ABSTRACT

THREE-NUCLEON TRANSFER REACTIONS AND CLUSTER STRUCTURE
IN THE A=15 TO A=19 NUCLEI

Louis Montague Martz
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We have studied the (6Li,t) and (6Li,3He) reactions on targets of 12C, 13C, 14N, 15N and 16O at E_{Lab}=44 MeV and \theta_{lab}=15^\circ. A preferential population of final states is exhibited in spectra for the A=15 to A=19 nuclei. The strong forward peaking of angular distributions in the 13C(6Li,t)16O and 13C(6Li,3He)16N reactions can be reproduced by DWBA calculations but not by the Hauser-Feshbach model. Given such indications of a primarily direct mechanism at forward angles, we use these three-nucleon transfer reactions to identify candidates for 3p-nh states. A comparison with other multi-nucleon transfer data, e.g. the (7Li,a) and (7Li,t) reactions on 13C and 15N targets, further tests dominant particle-hole configurations. The relationship between (6Li,t) and (6Li,3He) spectra reveals analog states, notably T=1, T_z=0 levels at high excitation in 16O. Through applications of nuclear theory, we investigate the role of triton clustering in such structure. The 2N+L=6 band predicted by a folded-potential model of 18O=15N+t shows an underlying correspondence to the experimental levels in triton-transfer data. Triton spectroscopic factors calculated from the SU(3) shell model further suggest the broad influence of clustering phenomena in this mass region. We find experimental evidence of systematic behavior in the triton binding energies of proposed p^n(sd)^3 configurations.
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At the Brookhaven National Laboratory, Dr. Carl B. Dover offered me a fine opportunity to work in nuclear theory and instructed me in the use of his folded-potential model. Dr. D. John Millener introduced me to the SU(3) shell model and allowed me to present his important calculations for $^{18}_0$.

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When questions arose concerning the computer system or target preparation, answers were always available from Dr. Martin W. Sachs and Dr. Edith Fehr respectively.

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CHAPTER 1 INTRODUCTION

The structure of light nuclei can be studied via the selectivity of multi-nucleon transfer reactions. In conjunction with the specialized predictions of nuclear models, experimental spectra reveal particle-hole configurations and clustering phenomena in final states. Such microscopic shell structure and macroscopic collective behavior are of interest as an indication of simplified properties and as a challenge to unified theories for the finite, many-body system. Although these simple features of excited states are generally blurred by a degree of impurity in the configuration or ambiguity in the parentage, the first step toward a precise understanding of nuclear structure lies in an identification and interpretation of the primary aspects.

1.1 Motivation

Important progress is being made through investigations of four-particle structure. Transfer reactions such as \( (\ell Li, t) \) (e.g. Co76) demonstrate a highly preferential population of final states in even-even, \( 4N \) nuclei such as \( {}^{16}O \) and \( {}^{20}Ne \). Cluster models, e.g. the folded-potential model (Bu75), predict energy levels in substantial agreement with these data. The result is a growing knowledge of \( 4p-nh \) configurations and alpha-particle clustering.

Three-particle structure is lesser known but generating interest. In early studies of the \( (\ell Li, t) \) and \( (\ell Li, {}^3He) \) reactions, for instance, a predominantly direct mechanism is indicated by excitation functions (Bi73b, Ba70), angular distributions (e.g. Bi75) and structural selectivity (e.g. Li72). This previous work, however, does not treat
many aspects such as $T=1$ states, accessible from odd-$A$ targets and relating $T_z=0$ to $T_z=1$ nuclei. Initial predictions for triton-cluster states in $^{15}$N from a folded-potential model (Bu75) encourage further applications to the interpretation of three-nucleon transfer data. The central goal of the present research, therefore, is twofold: to identify experimentally final states with dominant $3p$-$nh$ configurations and to indicate theoretically the role of three-nucleon clustering in the $A=15$ to $A=19$ nuclei.

A first question concerns the choice of a three-nucleon transfer reaction. The mechanism of the $(\alpha, p)$ reaction is relatively complex below an incident energy of 40 MeV, since backward peaking in the angular distributions near $E_\alpha=30$ MeV reflects a contribution from compound-nucleus formation, heavy-particle stripping and/or a knock-out process (Hi66). Without neutron detection, moreover, the $(\alpha, n)$ reaction into $N=Z$ and $N=Z-1$ nuclei cannot be observed. In heavy-ion-induced, three-nucleon transfer, e.g. by $^{10}$B, $^{12}$C or $^{13}$C (Ha76, Sc72, Pi77), high-resolution spectra are difficult to obtain. The intermediate choice is a lithium projectile. The $(^7\text{Li},\alpha)$ reaction has two disadvantages of its own, arising from Q-value effects. A large continuum in the alpha-particle spectrum is generated by Coulomb dissociation, which has a threshold of only 2 MeV, and a reduction in selectivity is caused by well-matched angular momenta, which allow the strong population of low-spin states. Three-nucleon transfer induced by $^6\text{Li}$, however, features low background and high-spin selectivity, because the Q-value for break-up equals $-16$ MeV and the mismatch $\Delta L$ is typically $6\hbar$. Although the parentage of $^6\text{Li}$ is less evident than $^7\text{Li}=\alpha+t$, a spectroscopic
factor for $^3\text{He}+t$ is found to be large and comparable to that for $\alpha+d$ (Ro76). A direct transfer of either $^3\text{He}$ or a triton can be observed from $^6\text{Li}$, with good energy resolution. Our experimental work, therefore, centers on the ($^6\text{Li},t$) and ($^6\text{Li},^3\text{He}$) reactions, which are measured on targets of $^{12}\text{C}$, $^{13}\text{C}$, $^{14}\text{N}$, $^{15}\text{N}$ and $^{16}\text{O}$ at $E_{\text{Li}}=40, 44$ or $46$ MeV and $\theta_{\text{lab}}=10^\circ$ or $15^\circ$.

1.2 Results

A preferential population of final states in the $A=15$ to $A=19$ nuclei leads to the identification of new candidates for $3p$-$n\hbar$ configurations. In $T_z=1$ nuclei, namely $^{16}\text{N}$ and $^{18}\text{O}$ (Table 1.1), high selectivity characterizes previously unobserved, triton-transfer reactions. A comparison with $^3\text{He}$ transfer into $T_z=0$ nuclei reveals distinct analog states in $^{16}\text{O}$ but a higher level density in $^{18}\text{F}$. In mirror spectra for $T_z=\pm1/2$ nuclei (Table 1.1), the largest cross sections occur at high excitation energy, i.e. $14.9$ MeV in $^{17}\text{F}/^{17}\text{O}$ and $\geq9$ MeV in $^{19}\text{Ne}/^{19}\text{F}$. The dominant structure of such states is checked when the ($^6\text{Li},t$) and ($^6\text{Li},^3\text{He}$) reactions are placed in the context of other multi-nucleon transfer data, such as ($^7\text{Li},\alpha$) and ($^7\text{Li},t$) spectra from $^{13}\text{C}$ and $^{15}\text{N}$ targets. In $p$-($sd$)$^3$ configurations, there exists tentative evidence of systematic behavior with respect to angular-momentum coupling and triton binding energy.

Angular distributions, measured for the $^{13}\text{C}(^6\text{Li},t)\,0$ and $^{13}\text{C}(^6\text{Li},^3\text{He})\,0$ reactions and compared with DWBA and Hauser-Feshbach predictions, confirm previous indications (Ba71a, Bi73b) of a predominantly direct mechanism at forward angles. Although relevant to analog assignments, these angular distributions do not uniquely determine transferred angular
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momenta (see also Bi75). Their structureless behavior implies that approximate, relative, spectroscopic information is contained in forward-angle spectra. From the selectivity exhibited in these spectra, we draw support for a one-step reaction mechanism; the influence of $^3$He- or triton-cluster transfer is suggested by a theoretical study of the final-state parentage.

Application of a folded-potential model to the prediction of triton-cluster structure provides a simplified interpretation of ($^6$Li, $^3$He) data. As in $^{19}$F (Bu77a), calculated (sd)$^3$ excitations show a significant, though approximate, correspondence to strongly populated states of $^{15}$N and $^{18}$O. A weak-coupling relationship between $^{18}$O = $^{15}$N + t and $^{19}$F = $^0$ + t (Table 1.1) appears to have substantial validity. Since the interaction of a triton with the valence neutron of $^{13}$C or with the spin 1$^+$ of $^{14}$N (Table 1.1) has experimentally unknown and potentially complex effects, $^{16}$N and $^{17}$O are at present beyond description by such a cluster model. More sophisticated calculations are obtained from a shell model with an SU(3) basis (Mi77). Spectroscopic factors predicted for a triton cluster in $^{18}$O prove to be well correlated with cross sections measured for the $N(Li, He)^0$ reaction. In addition to suggesting spin values, therefore, the SU(3) shell model supports evidence from the folded-potential model that triton clustering plays an important role in the structure of light nuclei.

The formalism of these nuclear models is discussed in Chapter 4, following a description of experimental apparatus and procedure (Chapter 2) and a survey of existing evidence on the mechanism of the ($^6$Li, t) and ($^6$Li, $^3$He) reactions (Chapter 3). The presentation of results is intro-
duced in Chapter 5 by the $A=15$ nuclei, which represent the focus of earlier study, but the description and interpretation of new data begin with the $A=19$ nuclei (Chapter 6), which provide an equally favorable case for three-nucleon cluster structure. We proceed downward in the sd shell (Chapters 7-9) and end with an analysis of angular distributions for the $A=16$ nuclei (Section 9.3). In Chapter 10, a comparison demonstrates the common features of nuclei in this mass region, and a summary integrates the new contributions outlined above with the body of previous work. After additional DWBA calculations (Appendix A), we include data for $^{20}\text{Ne}$, $^{20}\text{F}$ and $^{21}\text{F}$ (Appendix B), in which three-nucleon transfer reactions venture beyond p-shell targets.
CHAPTER 2 EXPERIMENT

2.1 Apparatus

Measurements on the \( ^6\text{Li},t \), \( ^6\text{Li},^3\text{He} \), \( ^7\text{Li},\alpha \) and \( ^7\text{Li},t \) reactions are performed using the MP-1 Tandem van de Graaff accelerator of the A.W. Wright Nuclear Structure Laboratory. In the Extrion sputtering source (Mi74), a \( \sim 400 \text{ nA} \) beam of \( \text{Li}^- \) ions is generated by bombarding an annular, cone-shaped sample of lithium with positive cesium ions. The lithium is pressed into a stepped copper cylinder, to increase thermal conductivity, and is placed quickly in vacuum to avoid oxidation. Common source parameters are an extraction voltage of \( \sim 30 \text{ kV} \) and an extraction current of \( \sim 1 \text{ mA} \). A flow of oxygen onto the lithium surface enhances the current output by \( \sim 50\% \), after the cone has been in use for a few hours. The oxygen leak rate is critical and very small, for the source pressure remains in the \( 10^{-7}-10^{-6} \) range. After negative ions are injected into the accelerator and foil-stripped at its terminal, \( \text{Li}^{3+} \) nuclei are analyzed by the 90° magnet. The emerging beam typically has an energy of 44 MeV, a spread of \( \sim 7 \text{ keV} \) and a current of \( \sim 400 \text{ nA} \), which is reduced to \( \sim 200 \text{ nA} \) by collimators in front of the target (see Section 2.2).

Both solid and gas targets are used in this series of experiments. 1/2"-diameter target frames support foils of \( ^{12}\text{C} \) (Yissum Corporation, Israel) or \( ^{13}\text{C} \) (AECL, Chalk River, Canada), the latter being isotopically enriched to \( \sim 96\% \). A gas cell (Co74) contains \( ^{14}\text{N}, ^{15}\text{N}, ^{16}\text{O}, ^{18}\text{O} \) (Monsanto Corporation) or \( ^{17}\text{O} \) (Miles Laboratories), for which the only observable impurity is \( \sim 4\% ^{16}\text{O} \) in the \( ^{17}\text{O} \) gas. The cell has a 1/4"-diameter entrance window of 20 \( \mu \text{inch} \) nickel and a wide exit window (see
Fig. 2.1) of 100 μinch Havar. Target characteristics are further discussed in Section 2.2.

Reaction products are observed with two Si(SB) detector telescopes, one designed for tritons, the other for \(^3\text{He}\) nuclei and alpha particles. Energy determination requires a total detector thickness capable of stopping the relevant nucleus; 4200 μ for \(^3\text{H}\) and 2000 μ for \(^3\text{He}/^4\text{He}\) are sufficient in our case. Particle identification depends upon the first detector in each telescope, which should provide an adequate but not excessive energy-loss signal. The criteria \(\Delta E > 1\text{ MeV}\) and \(\Delta E/E < 1/2\) are satisfied by a thickness of 200 μ for tritons with \(9 < E < 52\) and by 64 μ for \(^3\text{He}\) nuclei with \(11 < E < 74\). These two detectors, for example, allow measurement of the \(^{13}\text{C}(^6\text{Li},t)^{16}\text{O}\) and \(^{13}\text{C}(^6\text{Li},^3\text{He})^{16}\text{N}\) reactions from a laboratory angle of 10° to 70° for excitation energies up to 28 MeV in \(^{16}\text{O}\) and 15 MeV in \(^{16}\text{N}\).

The apparatus inside a 30"-diameter, Ortec scattering chamber is depicted in Fig. 2.1. The direction and size of a lithium beam from the accelerator are constrained by two tantalum collimators (Section 2.2), and the resulting scattering effects are reduced by an additional aperture close to the target. After passing through windows of the gas cell, the beam is collected by a magnetically shielded Faraday cup. Magnets are also attached to each snout in order to deflect electrons away from the detectors. The two detector telescopes can be moved independently but are limited to \(\theta_{\text{lab}} \geq 12.5°\). This angle between each pair of slits and the beam direction is calibrated to ±0.1° by optical alignment with the collimators. In the case of a solid target, we use rectangular rather than circular beam collimators and remove the slit.
Figure 2.1 Chamber set-up for a gas target
at the target end of each detector snout. In order to block the anti-scattering aperture from the view of the detectors, an additional snout is introduced between this aperture and the solid target. A 8"-square copper plate cooled by liquid nitrogen is positioned near a \(^{13}\text{C}\) target to reduce \(^{12}\text{C}\) build-up.

2.2 Energy Resolution

The beam collimation, target thickness and detector solid angle are designed to balance resolution with yield. These two competing characteristics are described by the following equations for a solid target normal to the beam:

\[
\Delta E_1 = \left( \frac{dE}{d\theta} \right) \Delta \theta
\]

\[
\Delta \theta = 180^\circ - \tan^{-1}\left(\frac{2R + b \sin \theta}{a + b \cos \theta}\right) - \tan^{-1}\left(\frac{2R - b \sin \theta}{a + b \cos \theta}\right) \quad (2.1)
\]

\[
\Delta E_2 = \left( \frac{dE}{dx} \right)_{\text{Li}} \cdot t = \Delta E_2 \quad \text{at small } \theta \quad (2.2)
\]

\[
Y \equiv n \left( pt \right) \frac{d\sigma}{d\Omega_{\text{c.m.}}} \Delta \Omega \quad \text{at small } \theta \quad (2.3)
\]

The kinematic broadening \(\Delta E_1\) is due to a variation in the energy \(E\) of the outgoing nucleus as a function of the laboratory angle of observation \(\theta\). In the expression for \(\Delta \theta\), relevant geometrical parameters are the width \(a\) of the detector slit, the width \(b\) of the beam spot on the target and the distance \(R\) between the two. The additional broadening \(\Delta E_2\) in the outgoing energy arises from a change \(\Delta E_{\text{Li}}\) of the incident energy as the beam passes through a target of given stopping power \((dE/dx)_{\text{Li}}\) and thickness \(t\). In the definition of the differential cross section \(\frac{d\sigma}{d\Omega_{\text{c.m.}}}\), \(Y\) is the yield of detected nuclei, \(n\) is the total number...
of Li$^{3+}$ ions collected, \( \rho t \) is the areal density of the target, \( \Delta \Omega_{\text{lab}} \) is the laboratory solid angle of the detector slit, and \( J \) is the Jacobian converting it into the center-of-mass system. The interdependence of these three equations is first evident in a proportionality of both \( \Delta E_{\text{Li}} \) and \( Y \) to the target thickness. The detection geometry, moreover, fixes \( \Delta \Omega_{\text{lab}} \) and affects \( \Delta \theta \); the beam collimation not only determines \( b \) but also influences \( n \). A lithium beam can be adequately focused through two collimators with dimensions \( w \times h = 0.040'' \times 0.120'' \) and positions 50'' and 20'' from the target. The resulting beam-spot height of 0.280'' is safely within the 1/2''-diameter solid target, and the value of \( b = 0.093'' \) is efficiently close to that of \( a = 0.062'' \) (see Eq. 2.1). A 1/16''-x 1/4'' detector slit at \( R = 10'' \) and \( \Theta = 10^\circ \) leads to \( \Delta \Theta = 0.88^\circ \) and \( \Delta \Omega_{\text{lab}} = 1.56 \times 10^{-4}\text{sr} \). With a 100 \( \mu \text{g/cm}^2 \) carbon target, the energy resolution is \( \sim 110 \text{ keV} \) for this experimental configuration.

A gas target introduces further interrelation between the above effects, because a double-slit detection geometry combines with the beam collimation to define an active target volume. Two 1/16''-diameter collimators placed 50'' and 20'' from the target assure that the beam passes cleanly through the 1/4''-diameter entrance window of the gas cell. Since the angle of observation \( \Theta \) depends on two detector slits and since the observed gas volume has significant length along the beam direction \( \hat{z} \), both \( \Theta \) and \( \Delta \Theta \) vary with \( \hat{z} \), as does \( E_{\text{Li}} \). Kinematic broadening therefore becomes interwoven with the loss of incident energy, and the two effects must be treated together (see Co74). The yield of detected nuclei is calculated from the following expressions (Si59):
In addition to symbols found in Eqs. 2.1 and 2.3, N is the number of
target nuclei per unit volume, and \( l_2 \) is the height of the back detector slit. \( G_{00} = 5.4 \times 10^{-5} \text{ cm-sr} \) is implied by slits with \( a_i \times l_i = 1/16'' \times 1/4'' \) at 1.65" and 7.65" from the target. Together with a \(^{15}\text{N}^\text{gas pressure of 1/8 atm, this configuration leads to an energy resolution of \( \sim 110 \text{ keV}. \)} Further contributions, however, arise from straggling in the gas and in
the windows of the cell. This broadening \( \eta \) (keV) can be estimated from
the relation (Bo15, Co66)
\[
\eta^2 = 435.1 \frac{z^2}{A} \rho t,
\]
where \( z \) is the atomic number of the moving nucleus, \( Z \) and \( A \) are the
atomic number and atomic weight of the medium, and \( \rho t \) is the areal
density of the medium (mg/cm\(^2\)). For lithium passing through the entrance window and the gas to the center of the cell, a common result
is \( \eta_{\text{Li}} = 42 \text{ keV} \) and \( \eta_{\text{Li}} = 25 \text{ keV} \) respectively. Energy straggling of the
outgoing nuclei is negligible in the gas but is typically \( \eta_{\text{Hb}} = 2\eta_{t} = 62 \text{ keV} \)
in the thick exit window.

2.3 Electronic Instrumentation

The energy signals from the two detector telescopes are differentiated, amplified, shaped, synchronized and gated, in the way described
by Fig. 2.2 for the helium telescope. Mutual gating occurs between the
energy loss \( \Delta E \) and the total energy \( E = \Delta E + E_{1} \). In order to reduce the
count rate at the computer interface, the gate on \( E \) by a \( \Delta E \) window removes elastically scattered lithium and some of the hydrogen signals.
In order to assure that valid $\Delta E-E$ pairs are transferred to the computer, the second gate removes $\Delta E$ signals which correspond to $E$ signals below the discriminator level of the biased amplifier. After $\Delta E$ and $E$ reach the analog-to-digital converters on the interface, EVENT 1 triggers their transfer to the computer. The integrated beam current, the number of events and the dead time are also stored. Duplicate hardware for the observation of tritons provides EVENT 2, $\Delta E'$, and $E' = \Delta E' + E_1' + E_2'$ signals free from helium and lithium contributions. By means of data acquisition and analysis software on an IBM 360/44, the information is sent both to magnetic tape for later analysis and to computer memory for on-line monitoring of the experiment.

2.4 Data Analysis

A two-parameter display of $\Delta E$ and $E$ (Fig. 2.3) allows precise isotope identification via a software gate which defines $\text{Min}(E) < \Delta E < \text{Max}(E)$. Data tapes are replayed after the gate has been refined from its preliminary form during the experiment. Although the separation of tritons from deuterons is rather clear-cut, an identification of $^3\text{He}$ requires this lengthy procedure. In Fig. 2.3, the $(^6\text{Li},\alpha)$ reaction generates a huge continuum through Coulomb dissociation but a negligible tail within the $^3\text{He}$ gate. No evidence of alpha particles appears in our $(^6\text{Li},^3\text{He})$ spectra.

The energy calibration of spectra from the $(^6\text{Li},t)$, $(^6\text{Li},^3\text{He})$ and $(^7\text{Li},\alpha)$ reactions is determined from known excitation energies in the $A=15$ and $A=19$ nuclei (see footnotes to Tables 5.1, 6.1). Calibration data are collected from $^{12}\text{C}$ and/or $^{16}\text{O}$ targets immediately before or after the study of a different target under the same experimental conditions.
Figure 2.2  Electronics for helium observation
PRE:  Pre-amplifier
AMP:  Main Amplifier
TSCA: Timing Single Channel Analyzer
LG:  Linear Gate and Stretcher
BIAS: Biased Amplifier

Figure 2.3  Identification of $^3$He
Counts within the dashed lines
are attributed to $^3$He nuclei.
For a gas target, the energy loss of an outgoing particle in the gas and in the exit window is given to sufficient accuracy by

\[
\frac{dE}{dx} = (\text{constant}) \left( \frac{1}{E} \right)
\]

(2.6)

where the constant is chosen to fit tabulated values of the stopping power (No70). After this correction of 200-400 keV for \(^3\)He and 50-100 keV for tritons, the outgoing energies are related to observed channels by a linear fit (Be69), as in the case of a solid target. Two sets of excitation energies, based on the \(^{12}\)C(\(^6\)Li, \(^3\)He)\(^{15}\)N and \(^{16}\)O(\(^6\)Li, \(^3\)He)\(^{19}\)F reactions respectively, are checked for consistency and are found to agree within 5 keV for final states in the \(^{15}\)N(\(^6\)Li, \(^3\)He)\(^{18}\)O reaction. In the (\(^6\)Li, t) reaction, the two standards apply to largely complementary regions of Q-value. Within the range of interpolation between known levels, a calibration generally has the estimated uncertainty of \(\Delta E = \pm 20\) keV (see Tables 5.1-9.1).

A final step in this analysis is the extraction of differential cross sections. A Gaussian distribution is fitted (Be69) to the continuum arising from Coulomb dissociation and is subtracted from the spectrum. In fitting individual peaks, we represent strongly overlapping states by a double or triple Gaussian. In addition to a refinement of the peak position and width, this procedure provides an area \(Y\) used in the calculation of \(d\sigma/d\Omega_{\text{c.m.}}\) for a given final state (Eqs. 2.3, 2.4). Statistical uncertainty in the yield and systematic error in the target thickness and slit width often add up to \(\sim 20\%\) of the absolute cross section. The error contribution arising from background subtraction varies widely but, in the case of angular distributions, consistency in the fitting procedure as a function of angle is checked.
CHAPTER 3 REACTION MECHANISM

If the \(^{6}\text{Li},t\) and \(^{6}\text{Li},^3\text{He}\) reactions are to be useful in the study of 3p-nh configurations, then they must proceed primarily via a direct mechanism. This chapter presents a survey of the existing experimental evidence, as it relates to theoretical expectations. We investigate the one-step nature of this direct transfer and end with a discussion of the most restrictive process, namely cluster transfer of \(^3\text{He}\) or a triton.

3.1 Excitation Functions

The behavior of cross sections as a function of incident energy provides a first test of the reaction mechanism. Formation of a compound nucleus, in isolated energy levels, would generate sharp resonances. Even in the case of strongly overlapping levels, narrow fluctuations can be produced by random phase variations in the contributing amplitudes, and broad structure is often observed in excitation functions. A smooth energy dependence is expected of a direct reaction, although it is not conclusive evidence.

Several measurements of excitation functions have been reported for lithium-induced, three-nucleon transfer reactions. The cross sections of the \(5/2^+\) and \(9/2^+\) states of \(^{19}\text{Ne}\) in the \(^{6}\text{Li},t\) reaction (see Fig. 6.1) demonstrate a flat energy dependence for \(E_{\text{Li}}=22.0,22.1,\ldots,24.6\) MeV and \(\Theta_{\text{lab}}=7.5^\circ\) (Bi73b). In a study of \(^{13}\text{C}(^{6}\text{Li},t)^{16}0^+(11.09)\) at \(E_{\text{Li}}=20,21,\ldots,32\) MeV and \(\Theta_{\text{lab}}=15^\circ\) (Ba70), only the barely observed, ground state has a structured excitation function and the strongly populated, 11.09 MeV doublet (see Fig. 9.1) has an especially smooth one.
The selectivity of the $^{12}\text{C}(^{6}\text{Li},t)^{15}\text{O}$ reaction is consistent for incident energies of 32 MeV (Ba70), 46 MeV (this work) and 60 MeV (Bi75). Experimental results are similar for the $(^{7}\text{Li},\alpha)$ reaction on a $^{12}\text{C}$ target from an energy of 28 MeV to 38 MeV (Ts73). For final states with large cross sections, therefore, these data show no effects of a compound-nucleus component in the reaction mechanism.

3.2 Angular Distributions

The relative contributions of direct and compound-nucleus processes can be estimated by comparing DWBA and Hauser-Feshbach predictions with measured angular distributions. We have observed the $^{13}\text{C}(^{6}\text{Li},t)^{16}\text{O}$ and $^{13}\text{C}(^{6}\text{Li},^{3}\text{He})^{16}\text{N}$ reactions from $\Theta_{\text{c.m.}}=15^\circ$ to $80^\circ$ at $E_{\text{Li}}=44$ MeV. Experimental angular distributions and theoretical curves are presented in Figs. 9.6-9.8 and are discussed in Section 9.3. The example of Fig. 3.1 illustrates the general conclusion that a strong forward peaking in the data can be reproduced by finite-range DWBA calculations but not by the Hauser-Feshbach model. The magnitude of the DWBA curve in Fig. 3.1 is normalized to the measured cross section at $\Theta_{\text{lab}}=10^\circ$, whereas an upper limit is placed on the overall magnitude of the Hauser-Feshbach predictions by the 10.353 MeV state of $^{16}\text{O}$ (see Fig. 9.7). The resulting difference between the absolute cross sections from statistical theory and from experiment indicates a negligible role for the compound-nucleus mechanism at small angles.

Another difference lies in the symmetry with respect to $\Theta_{\text{c.m.}}=90^\circ$ expected of an energy-averaged angular distribution from the decay of a compound nucleus. When the 11.09 MeV state of $^{16}\text{O}$ is observed out to $\Theta_{\text{c.m.}}=150^\circ$ in the $(^{6}\text{Li},t)$ reaction at $E_{\text{Li}}=28$ MeV (Ba71a), the angular
Figure 3.1  An example of (\(^6\)Li,t) angular distributions

Data for the 16.81 MeV, (3\(^+\)) state of \(^{16}\)O are compared with the angular distributions predicted by finite-range DWBA and Hauser-Feshbach theory.
distribution proves to be asymmetric, in contrast to the Hauser-Feshbach curve. Other reported work supplies further indication of a direct reaction. For a $^{16}\text{O}$ target (Ga72), the ($^{6}\text{Li},^{3}\text{He}$) reaction at $E_{\text{Li}}=24$ MeV produces a differential cross section for the $9/2^+$ state at $^{19}\text{F}^+(2.780)$ which falls even faster with angle than the zero-range DWBA prediction. At $E_{\text{Li}}=60$ MeV (Bi75), angular distributions for the three states most strongly populated by the $^{12}\text{C}(^{6}\text{Li},t)^{15}\text{O}$ reaction can be fitted by finite-range DWBA calculations. In the ($^{7}\text{Li},\alpha$) reaction (Ts73,74), strong forward peaking and asymmetry are again observed.

Angular distributions, therefore, together with excitation functions, provide strong evidence that the dominant mechanism of the ($^{6}\text{Li},t$) and ($^{6}\text{Li},^{3}\text{He}$) reactions is direct at forward angles. Since our spectra are measured at $E_{\text{Li}} \geq 40$ MeV and $\theta_{\text{lab}} \leq 15^\circ$, i.e. at incident energies higher than in all of the data referenced above (except Bi75), even less compound-nucleus formation is expected. The fraction of the exit-channel flux from a compound nucleus, moreover, is smaller for the ($^{6}\text{Li},t$) and ($^{6}\text{Li},^{3}\text{He}$) reactions than for ($^{7}\text{Li},\alpha$). In our Hauser-Feshbach calculation of the decay of $^{19}\text{F}$, 44% of the flux goes into the $^{15}\text{N}+\alpha$ channel but only 4% into $^{16}\text{O}+\alpha$.

3.3 Selectivity

A one-step, direct reaction transferring three nucleons as a group would lead to strong population of $3p$-$nh$ configurations in the $A=15$ to $A=19$ nuclei. Known final states in which $3p$-$nh$ structure is probable can test this aspect of the ($^{6}\text{Li},t$) and ($^{6}\text{Li},^{3}\text{He}$) reactions. In $^{19}\text{F}$ (Fig. 6.2, Bi71, We72), all high-spin members of the positive-parity, ground-state band are strongly populated. In contrast, the $7/2^+$ state
at 4.377 MeV and the $11/2^+$ states at 6.500, 7.937 and 9.267 MeV (Aj78, Sy77) are observed weakly if at all, despite the angular-momentum mismatch $\Delta L = 6$ of the \(^{16}\text{O}(^{6}\text{Li},^{3}\text{He})^{19}\text{F}\) reaction. The selectivity, therefore, is not merely of a high-spin nature characteristic of compound-nucleus reactions. Similarly, in the \(^{17}\text{O}(^{6}\text{Li},t)^{20}\text{Ne}\) spectrum (Fig. B.1), the $J^m = 5^-$, $6^-$ and $7^-$ members of the $K^m = 2^-$ band are clearly weak or absent at $E_x = 8.449$, 10.609 and 13.334 MeV respectively (Aj78). When one hole in the p shell is provided by the target nucleus, namely \(^{15}\text{N}\), low-lying negative-parity states of \(^{18}\text{F}\) and \(^{18}\text{O}\) are preferentially populated (Figs. 7.1, 7.2, Li72). The \(^{6}\text{Li},^{3}\text{He}\) reaction also produces large peaks corresponding to \(^{17}\text{O}^*(8.474,7/2^+\) and \(^{15}\text{N}^*(10.693,9/2^+)\) (Figs. 8.2, 5.2). These two states have the positive parity and high excitation energy expected of 3p-2h and 3p-4h configurations, as well as spin assignments which are too high for (sd) and \((p_{1/2})^{-2}(sd)\) configurations respectively. Overall, known candidates for 3p-nh states prove to be prominent in \(^{6}\text{Li},t\) and \(^{6}\text{Li},^{3}\text{He}\) spectra, a feature consistent with a one-step process of direct transfer.

In three-nucleon transfer data from a target with n holes, an absence of 4p-(n+1)h states would be evidence contrary to a two-step process involving both single-nucleon pick-up and alpha-particle transfer. A \(^{6}\text{Li},d\)(d,t) mechanism has been suggested as a possible explanation for the population of a proposed \(f_{7/2}\) neutron-hole state in the \(^{56}\text{Fe}(^{6}\text{Li},t)^{59}\text{Ni}\) reaction (Wo78). In absolute cross section, however, the \(^{6}\text{Li},d\) reaction on p-shell targets is comparable to the \(^{6}\text{Li},t\) reaction (Section 3.4) and weaker than the \(^{7}\text{Li},t\) reaction (Co76). We therefore consider a \(^{6}\text{Li},^{7}\text{Li}\)(\(^{7}\text{Li},t\)) process, which would also populate
final states with $4p-(n+1)h$ configurations and alpha-particle clustering. The lack of a consistent correlation in selectivity between the $(^7\text{Li},t)$ reaction and the $(^6\text{Li},t)$ or $(^6\text{Li},^3\text{He})$ reaction is documented by the following cases. The $4p-1h$, negative-parity band of $^{19}\text{F}$ (Fig. 6.3, Mi70) has a $13/2^-$ member at 8.288 MeV which is quite weakly populated in three-nucleon transfer (Figs. 6.2, 6.4). The $4^+$ state at $^{18}\text{F}^*(5.298)$, a member of the $4p-2h$, $K^*=1^+$ band (Ro73b, Co77), is almost absent in $^{15}\text{N}(^6\text{Li},t)^{18}\text{F}$ data (Fig. 7.1). The $(^6\text{Li},^3\text{He})$ reaction ignores the states at $^{17}\text{O}^*(18.15,19.24)$ which are strongly populated in alpha-particle transfer (Fig. 8.4) and appear to have $4p-3h$ configurations. Lastly, in the $^{13}\text{C}(^6\text{Li},t)^{16}\text{O}$ reaction (Fig. 9.1), there is only minor population of the $4^+$ state at 10.353 MeV and the $6^+$ state at 16.29 MeV, both belonging to the $4p-4h$, $K^*=0^+$ band of $^{16}\text{O}$ (e.g. Co76). These counterexamples for each target nucleus argue against the systematic effect expected of such a two-step mechanism. Special cases appear, however, in which a state such as $^{19}\text{F}^*(8.953,11/2^-)$ is strongly populated both in $(^7\text{Li},t)$ data and in the $(^6\text{Li},t)$ or $(^6\text{Li},^3\text{He})$ reaction. Given the above result, we attribute such exceptions to mixed structure in the final state, since impurity in the ground-state configuration of the target is generally small.

The consideration of a sequential transfer of three individual nucleons involves $2p-(n-1)h$ and $1p-(n-2)h$ states, where $n$ is the number of holes in the target nucleus. Although they are accessible to a one-step, direct reaction, weak population of these configurations could place an upper limit on the role of a sequential process. In a $(^6\text{Li},t)$ spectrum for $^{16}\text{O}^*(\leq16.2)$, some evidence has been pointed out (Ba71a)
for a mechanism of single-nucleon transfer into the p shell followed by transfer of a proton-neutron pair equivalent to the \((\alpha,d)\) reaction. A contrast in selectivity between these two reactions, however, is demonstrated by other nuclei. The 6.81 MeV state of \(^{18}\text{F}\) is prominent in \((\alpha,d)\) data (Ma68, Ri66) but not in \((^6\text{Li},t)\) data (Fig. 7.1). Similar counterexamples at \(^{17}\text{O}^+ (9.14)\) and \(^{15}\text{N}^+ (11.95)\) (Figs. 8.2, 5.2 and Lu69) show that this mechanism plays at most a minor role. The cases of corresponding selectivity in the \((^6\text{Li},t)\) and \((\alpha,d)\) reactions, e.g. 2p-(n-1)h states at \(^{15}\text{N}^+ (13.00,11/2^-)\) and \(^{16}\text{N}^+ (5.73,5^+)\) (Figs. 5.2, 9.2 and Lu69), can be adequately accounted for by a simple one-step process (see Section 5.3). In \((^6\text{Li},t)\) spectra from \(^{24}\text{Mg}\) and \(^{28}\text{Si}\) targets, evidence exists of a sequential mechanism populating 1p-(n-2)h states (Wo78). The relatively large cross section of the 4.45 MeV state of \(^{31}\text{S}\) is tentatively interpreted in terms of transfer of a proton pair into the lowest available level plus neutron transfer into the \(f_{7/2}\) shell. The only targets we have studied which contain two proton holes are \(^{12}\text{C}\) and \(^{13}\text{C}\). In the \(^{12}\text{C}(^6\text{Li},t)^{15}\text{O}\) reaction (Fig. 5.1), an inhibited population of the 1p-2h configuration (Li70) at \(^{15}\text{O}^+ (7.276,7/2^+)\) argues against this mechanism. In the \(^{13}\text{C}(^6\text{Li},t)^{16}\text{O}\) reaction (Fig. 9.1), a more prominent peak for the primarily 1p-1h state at \(^{16}\text{O}^+ (6.130,3^-)\) may therefore arise from an additional 3p-3h component (see De71). In general, features of the \((^6\text{Li},t)\) reaction mechanism suggested in the case of heavy nuclei (Wo78) do not appear to apply to these light nuclei.

In summary, the selectivity of the \((^6\text{Li},t)\) and \((^6\text{Li},^3\text{He})\) reactions contains much specific, experimental evidence in support of a one-step process of direct transfer. Final states which are expected a priori
to have 3p-nh configurations are indeed strongly populated by these 
three-nucleon transfer reactions, whereas several other known high-
spin states are populated weakly if at all. In the case of 4p-(n+1)h 
states as well as two-particle or one-particle structure, there exist 
counterexamples to a two-step mechanism involving alpha-particle, 
deuterium or neutron transfer respectively.

3.4 Clustering

The simplest and most restrictive reaction mechanism for the 
\((^6\text{Li}, t)\) or \((^6\text{Li}, ^3\text{He})\) reaction would be the direct transfer of a triton 
or \(^3\text{He}\) cluster, namely a group of three nucleons coupled to \(T=S=1/2\) 
and bound in their ground state. In the four-nucleon case, the \((^7\text{Li}, t)\) 
reaction behaves primarily as the cluster transfer of an alpha particle. 
The analogy to the three-nucleon system is not immediate because the 
triton or \(^3\text{He}\) has a binding energy of 8 MeV, small compared with the 
alpha-particle value of 28 MeV though larger than the deuteron binding 
of 2 MeV. The role of cluster transfer is influenced by the extent 
of three-nucleon clustering in the initial state of \(^6\text{Li}\) and is re-
flected by that in the final states of the residual nucleus.

The cluster structure of \(^6\text{Li}\) has been investigated in a wide 
variety of experiments (see Ha77). The \(t(^3\text{He}, \gamma_0)^6\text{Li}\) reaction yields 
a spectroscopic factor \(S(t)=0.7\) in one analysis (Yo70). The knock-out 
reactions \(^6\text{Li}(p, p^3\text{He})t\) and \(^6\text{Li}(p, p\alpha)d\) give \(S(t)=0.33\) and \(S(\alpha)=0.45\) 
for cluster wavefunctions, or \(S(t)=0.78\) and \(S(\alpha)=0.58\) for Woods-Saxon 
wavefunctions (Ro76). Although the parentage of \(^6\text{Li}\) is not unique, 
such results indicate that \(^3\text{He}+t\) structure is major and comparable to 
\(\alpha+d\) structure. Nonorthogonality of the cluster wavefunctions (C174)
may account for the duality of spectroscopic strength. Further evidence can be found in the comparable cross sections of the ($^6\text{Li},d$) and ($^6\text{Li},^3\text{He}$) reactions. For $^{12}\text{C}($6\text{Li},d$)^{16}\text{O}^*(10.353,4^+)$ at $E_{\text{Li}}=40\ \text{MeV}$ and $\theta_{\text{lab}}=10^\circ$ and for $^{16}\text{O}($6\text{Li},d$)^{20}\text{Ne}^*(10.261,5^-)$ at $E_{\text{Li}}=46\ \text{MeV}$ and $\theta_{\text{lab}}=15^\circ$, the differential cross section is $\sim600\ \mu\text{b/sr}$. Magnitudes of $\sim900\ \mu\text{b/sr}$ and $\sim300\ \mu\text{b/sr}$ are obtained for $^{12}\text{C}($6\text{Li},^3\text{He}$)^{15}\text{N}^*(10.693,9/2^+)$ and $^{16}\text{O}($6\text{Li},^3\text{He}$)^{19}\text{F}^*(8.953,11/2^-)$ respectively under the same experimental conditions (Tables 5.1, 6.1). Lastly, because triton clustering in $^7\text{Li}$ is more dominant than in $^6\text{Li}$, the selectivity of the ($^7\text{Li},\alpha$) reaction should be compared to that of ($^6\text{Li},^3\text{He}$). A substantial overlap does exist (Figs. 5.4, 7.4, 9.4) despite the large difference between these reactions in angular-momentum mismatch, e.g. $\Delta L=3$ and $\Delta L=6$ respectively. In view of these indications of $^6\text{Li}=^3\text{He}+t$ parentage, the ($^6\text{Li},t$) and ($^6\text{Li},^3\text{He}$) reactions could often proceed via cluster transfer.

The remaining question of final-state parentage is studied here by an application of nuclear models to the residual nuclei. In $^{19}\text{F}$, $^{18}_0$ and $^{15}_0\text{N}$, states strongly populated by the ($^6\text{Li},^3\text{He}$) reaction have a significant correspondence with triton-cluster states predicted by the folded-potential model and a more precise correlation with concentrations of triton-cluster spectroscopic strength predicted by the SU(3) shell model. For example, the prominence of $^{18}_0^*(8.10,5^-)$ in the ($^6\text{Li},^3\text{He}$) spectrum (Fig. 7.2) is in agreement with the substantial clustering expected in this state (Fig. 7.6). In contrast, no large peak appears for the $^5_3$ shell-model level predicted at 9.0 MeV, which has a dominant SU(3) component $(\lambda\mu)=(04)=(01)\times(03)$ involving three totally antisymmetric nucleons. Theoretical evidence on the structure of final states...
therefore suggests that cluster transfer plays a considerable part in the mechanism of the \(^{6}\text{Li}, \text{t})\) and \(^{6}\text{Li}, ^{3}\text{He})\) reactions. The formalism of the two models is introduced in the next chapter.
4.1 Folded-Potential Cluster Model

Clustering phenomena in the structure of light nuclei can be calculated to first order from a macroscopic model having microscopic origins. A triton cluster is assumed to exist in a potential derived from nuclear densities. The simplified approach of this theory leads to intuitive physical content and convenient numerical calculations. The limited scope of a triton-cluster model implies that predicted energy levels are to be compared with a special class of nuclear states, e.g. those selected by the \((^6\text{Li}, ^3\text{He})\) reaction.

The interaction between the cluster and the core nucleus is represented by the potentials of Fig. 4.2 using the coordinates of Fig. 4.1. The folded potential \(V_S(r)\) is a convolution of the densities of the cluster and core with an effective, nucleon-nucleon amplitude \(v_S\) (Do74, Va74, Bu75). The definition of \(v_S\) relates the adjustable strength \(\bar{f}\) of the finite-range interaction to the nucleon-nucleon, forward scattering amplitude. Applications to heavy-ion scattering have tested the form of \(V_S(r)\), with favorable results for elastic, inelastic and one-nucleon-transfer processes (Va73c, Do75, Mo77). The cluster density is determined by electron scattering (Co67) and normalized to \(A=3\):

\[
\rho_1(r) = \rho_0 \exp\left[\frac{-3}{2} \left(\frac{r}{a}\right)^2\right]
\]

\[
\rho_0 = 3\left(\frac{3}{2\pi a^2}\right)^{3/2},
\]

where \(a=1.64\) for a triton and \(a=1.77\) for \(^3\text{He}\). In the most influential factor of the folded-potential integrand, the core density, we use a theoretical mass density rather than an experimental charge density,
Figure 4.1 Coordinates of the folded potential

Figure 4.2 Potentials of the cluster-core interaction

1 = cluster
2 = core
\( \rho = \) density
\( M = \) nucleon mass
\( Y = 1 \text{ fm} \)
\( Z = \) atomic number
\( A = \) atomic weight
\( (h/m_{\text{\tiny \pi}}c)^2 = 2.0 \text{ fm}^2 \)
\( \Upsilon = \) relative orbital angular momentum
\( \frac{1}{2} \sigma^+ = \) intrinsic spin
\( \hat{j} = \) total angular momentum of the cluster
\( \hat{F}, V_{S01}, V_{S02} = \) strength parameters
CLUSTER COORDINATES

\[
\mathbf{r} + \mathbf{r}_1 - \mathbf{r}_2
\]

\[
\mathbf{r}_2
\]

\[
\rho_1
\]

\[
\rho_2
\]
CLUSTER POTENTIALS

FOLDED
\[ V_s(r) = \int d\hat{r}_1 \int d\hat{r}_2 \rho_1(\hat{r}_1) \nu_s(|\hat{r} + \hat{r}_1 - \hat{r}_2|) \rho_2(\hat{r}_2) \]

STRONG
\[ \nu_s = -\frac{2\pi \hbar^2}{M} \frac{f}{(\pi \gamma^2)^{3/2}} \exp \left( \frac{-|\hat{r} + \hat{r}_1 - \hat{r}_2|^2}{\gamma^2} \right) \]

COULOMB
\[ \nu_c = \frac{Z_1 Z_2}{A_1 A_2} e^2 \frac{1}{|\hat{r} + \hat{r}_1 - \hat{r}_2|} \]

SPIN-ORBIT
\[ V_{so1}(r) = -\left( \frac{\hbar}{m \pi c} \right)^2 \cdot \nu_{so1} \cdot \frac{l}{f} \left| \frac{1}{r} \frac{dV_s}{dr} \right| \hat{L} \cdot \hat{\sigma}_1 \]

HYPERFINE
\[ V_{so2}(r) = -\left( \frac{\hbar}{m \pi c} \right)^2 \cdot \nu_{so2} \cdot \frac{l}{f} \left| \frac{1}{r} \frac{dV_s}{dr} \right| \hat{j} \cdot \hat{\sigma}_2 \]
because Hartree-Fock calculations are more accurate in the important tail region and are consistent with electron scattering (Ne70).

In an alternate prescription from the shell model,

\[ \rho_2(r) = \sum_i W_i |\phi_i|^2, \]

(4.2)

where \( W_i \) is an occupation weight and \( \phi_i \) is a single-particle wavefunction resulting from well parameters fit to experimental binding energies (Mi73). Theoretical densities from these two sources generate similar predictions which, for example, differ by only 0.05 MeV for the spacing between the \( L=2 \) and \( L=4 \) levels of \(^{19}\)Ne (see Fig. 6.6).

Following the folded potential of the strong interaction in Fig. 4.2 are standard expressions for the Coulomb integral \( V_C(r) \) and for the Thomas term \( V_{S01}(r) \), which treats the spin-orbit coupling of a triton cluster. If the core has non-zero spin, we introduce a potential \( V_{S02}(r) \) proportional to the total angular momentum of the cluster coupled to the spin of the core. As in the spin-orbit case, an analogy exists to the electromagnetic coupling of an electron, since the hyperfine interaction with a nuclear dipole moment is also proportional to \( \mathbf{j} \cdot \mathbf{\sigma}_2 \). Both the spin-orbit interaction of the core and the spin-spin interaction are contained in \( \mathbf{j} \cdot \mathbf{\sigma}_2 = \mathbf{\hat{j}} \cdot \mathbf{\hat{\sigma}}_2 + \mathbf{\hat{\sigma}}_1 \cdot \mathbf{\hat{\sigma}}_2 \), but two assumptions are implicit in this prescription. The equal weight assumed for \( \mathbf{\hat{L}} \cdot \mathbf{\hat{S}}_2 \) and \( \mathbf{\hat{S}}_1 \cdot \mathbf{\hat{S}}_2 \) terms is necessary for the commutativity of \( V_{S01}(r) \) and \( V_{S02}(r) \). The weak coupling implied by \( \mathbf{j} = \mathbf{\hat{J}} + \mathbf{\hat{S}}_2 \) is valid only when the spin-spin interaction is small compared with the triton spin-orbit interaction. Strong coupling, i.e. \( \mathbf{\hat{S}} = \mathbf{\hat{S}}_1 + \mathbf{\hat{S}}_2 \) and \( \mathbf{\hat{J}} = \mathbf{\hat{L}} + \mathbf{\hat{S}}_2 \), would yield commuting operators \( \mathbf{\hat{L}} \cdot \mathbf{\hat{S}} \) and \( \mathbf{\hat{\sigma}}_1 \cdot \mathbf{\hat{\sigma}}_2 \), but a spin-orbit potential proportional to \( \mathbf{\hat{L}} \cdot \mathbf{\hat{S}} = \mathbf{\hat{L}} \cdot \mathbf{\hat{S}}_1 + \mathbf{\hat{L}} \cdot \mathbf{\hat{S}}_2 \) would require equal strength for the cluster and core terms, in contradiction to
experimental levels of $^{19}$F (see Bu77a).

With $V(r) = V_S(r) + V_C(r) + V_{S01}(r) + V_{S02}(r)$, solutions are obtained to the single-particle Schrödinger equation. While convergence upon bound states proceeds via the matching condition, a search occurs for unbound states in the calculated elastic scattering of a cluster projectile on a core target (Au76). A resonance in the cross section is identified where $\text{Im} S_L$ becomes negative (Fig. 4.3), since the scattering matrix is given by $S_L = \exp(2i\delta_L)$ and the amplitude by $f_L^{\infty}(S_L-1)$. Because of a Breit-Wigner shape (Bu75), the resonance has a width $\Gamma_{\text{c.m.}} = (\text{Im} S_L = -1) - E_{\text{c.m.}}(\text{Im} S_L = 1)$. The calculated energy levels are classified according to the configuration of the triton cluster. A $(sd)^3$ configuration corresponds to a $2N+L=6$ band, where

$$2N + L = \sum_{i=1}^{3} 2n_i + l_i \quad (4.3)$$

This particular restriction on the orbitals open to the three nucleons of the cluster trivially satisfies the Pauli principle for any p-shell core. Exchange effects, moreover, should be small owing to the large rms radius of the relative wavefunctions (Fig. 4.4). While the spatial localization of the cluster increases with the orbital angular momentum $L$, the rms separation from the core remains $\sim 3$ fm, illustrating that centrifugal stretching is balanced by the decreasing number $N$ of radial nodes. Although the folded potential is too deep at small radii, it is expected to be more valid than a Woods-Saxon well in the sensitive tail region, where most of the cluster probability density is located.

The free parameters of this triton-cluster model, which partially absorb many-body effects, are the strengths $\tilde{f}$, $V_{S01}$ and $V_{S02}$. In con-
Figure 4.3 Single-particle resonances

These predictions represent unbound, triton-cluster states of $^{19}\text{F}$.

Figure 4.4 Folded potential with probability densities

The arrows indicate the rms separation of a $(sd)^3$ triton cluster from a $^{15}\text{N}$ core.
contrast to a Woods-Saxon potential, the geometry of a folded potential is predetermined by the core density and, to a lesser extent, by the cluster density and nucleon-nucleon interaction. In addition, a single value of $\tilde{r}$ generates an entire cluster band, whereas a Woods-Saxon depth parameter must be readjusted to each experimental level (see Bu75). A $\sim 10\%$ renormalization of $\tilde{r}$, arising in part from a sensitivity to the choice of core density, is needed for $2N+L=6$ bands in different nuclei. The empirical result $\tilde{r}_{1.6}$ fm is consistent with the theoretical estimate in a Fermi-gas approach (Va74). A single value of $V_{S01}$ is used for all $2N+L=6$ calculations, and $V_{S02}=0$ except for a core of non-zero spin (see Sections 6.3, 7.3). Because the parameters are fit to experimental states, which inevitably contain some structural impurity, the model predicts energy levels representing not rigorous centroids, but rather, large concentrations of triton-cluster, spectroscopic strength.

4.2 SU(3) Shell Model

A more sophisticated calculation of clustering phenomena can be performed from a microscopic model having macroscopic connections. A shell model linked to SU(3) symmetry evaluates spectroscopic factors, in addition to facilitating spurious-state elimination and basis truncation. Greater complexity brings wider applicability, relative to the folded-potential model. Clustering is now predicted, instead of postulated.

The basis, i.e. the set of eigenvectors for a one-body central interaction, is labelled according to SU(3) symmetry (see He64, Ha68) and SU(4) quantum numbers. In the sd shell alone, $|[(\alpha \mu) \ell M]|$ and $|[(\tilde{r})_{BMT} S L M]|$ lead to $|[\alpha \beta (\lambda \mu) \ell M S L J T]|$, where $[\tilde{r}]$ represents the SU(6)
orbital symmetry, \((\lambda \mu)\) represents the SU(3) symmetry and \(\alpha, \beta\) and \(\kappa\) number multiplicities; a coupling with the p shell involves
\[
|p^n_1(\lambda_1 \mu_1)\beta_1 T_1 S_1, (sd)^n_2[f_2]\alpha_2 \beta_2 (\lambda_2 \mu_2)T_2 S_2; (\lambda \mu)_{LSJT}\rangle \quad (Mi72,76). \]
In the \(p^{-1}(sd)^3\) configuration of \(^{18}\)O, for example, \([\Lambda](\lambda \mu)=[3](60)\) represents maximum symmetry for the triton and couples with \([4443](01)\) of the \(^{15}\)N ground state to give \((01) \times (60) \rightarrow (61),(50)\). Truncation of the model space occurs in a natural, systematic way through the selection of high orbital symmetry and large values of the Casimir operator, both implying low excitation energy (Ha68). For instance, \([21](41)\) is included in a \((sd)^3\) basis, resulting in \((01) \times (41) \rightarrow (42),(50),(31)\) for \(^{18}\)O, whereas \([111](03)\) would be omitted first if a complete basis were not used. The model space is extended to include configurations having one nucleon in the fp shell (Mi77), e.g. an \((sd)(fp)\) configuration of \(^{18}\)O with \((20) \times (30) \rightarrow (50),(31),(12)\). The \((50)\) symmetry, which occurs in the above examples, can also be created by \(A^+_{c.m.}(10)\) acting on the \((sd)^2(40)\) configuration. Such spurious, center-of-mass motion can be removed rigorously through the construction of spurious wavefunctions followed by Schmidt orthogonalization (He71). Diagonalization of an effective, two-body residual interaction (Mi75, Ku66) is then carried out for an energy matrix as large as \(200 \times 200\) for a given \(J^n\).

Via the SU(3) labelling, spectroscopic factors can be extracted from the final shell-model wavefunctions. In the \(^{18}\)O case, a large \((61)\) or \((50)\) component indicates possible triton-cluster structure but does not guarantee a large spectroscopic factor, because amplitudes from several components may cancel each other or \((50)\) may result from a less symmetric decomposition noted above. Expression of a cluster wavefunction
in terms of the SU(3) basis \{\phi_i\} (lç73, He75) allows a calculation of its overlap with the shell-model wavefunction \(\psi\) of a given state:

\[
\psi = \sum_i a_i \phi_i
\]

\[
\psi_{\text{cluster}} = \sum_i b_i \phi_i
\]

\[
\theta = \langle \psi_{\text{cluster}} | \psi \rangle
\]

\[
S = \theta^2,
\]

where \(S\) is the spectroscopic factor and \(\theta\) the amplitude. The general form of the coefficients \(b_i\) (An74) becomes much simpler for a \(sd\)-shell cluster and a \(p\)-shell core, owing to the absence of fractional-parentage and recoupling coefficients. For \(^{18}\text{O}=^{15}\text{N}+\text{t}\) (Mi77),

\[
b_i = \left(\frac{18}{15}\right)^3 G(sd^2) \langle 01 \rangle \langle 60 \rangle L_L^{-} |(\lambda\mu)L\rangle \begin{pmatrix} 1 \frac{1}{2} \frac{1}{2} \\ L_L \frac{1}{2} J_L \end{pmatrix} (4.5)
\]

In order to transform a shell-model basis function into part of a triton-cluster wavefunction, the first factor converts to center-of-mass and relative coordinates for the cluster and core, and the second factor does the same for the three nucleons within the cluster. The SU(3) Clebsch-Gordan coefficient then decomposes \((61)\) or \((50)\) into \((01)\times(60)\), and the Wigner 9j symbol transforms \(LS\) into \(J'J_L\) coupling, where \((\lambda'\mu')=(01)\) and \(|L'S'J'>=|1\frac{1}{2}\rangle\) describe the \(^{15}\text{N}\) ground state, and \((60)\) and \(|L_L\frac{1}{2}J_L\rangle\) represent a triton cluster in the \(sd\) shell. An application of this theoretical formalism to experimental results begins with the next chapter.
5.1 \( ^{12}\text{C}(^6\text{Li},t)^{15}\text{O} \) and \( ^{12}\text{C}(^6\text{Li},^3\text{He})^{15}\text{N} \)

The selectivity exhibited by three-nucleon transfer into the \( A=15 \) nuclei has been a source of both experimental and theoretical interest. The \( (^{6}\text{Li},t) \) and \( (^{6}\text{Li},^3\text{He}) \) reactions on a \( ^{12}\text{C} \) target at \( E_{^6\text{Li}}=40 \text{ MeV} \) (Figs. 5.1, 5.2) demonstrate a preferential population of three states having \( J^\pi=9/2^+, 11/2^- \) and \( (13/2^+) \) respectively, a result consistent with measurements at \( E_{^6\text{Li}}=60 \text{ MeV} \) (Bi75) and with early studies at low incident energy (Ba70, Og73). Owing to the monotonic nature of angular distributions in these reactions (Bi75), forward-angle spectra constitute a source of qualitative information on relative spectroscopic strengths (see also Section 9.3). A one-to-one correspondence between \( T_z=\pm1/2 \) analog states in \( ^{15}O \) and \( ^{15}N \) implies that the dominant peak at \( 12.84 \text{ MeV} \) in \( ^{15}O \) is a narrow doublet, corresponding to \( ^{15}N^*\)\( (13.00,11/2^-;13.17) \). Before considering three-nucleon clustering in such states through an application of nuclear models, we study their properties experimentally via a comparison of the \( (^{6}\text{Li},t) \) and \( (^{6}\text{Li},^3\text{He}) \) reactions with diverse multi-nucleon transfer data.

5.2 Other Transfer Reactions

In forward-angle spectra for \( ^{15}N \), the \( (\alpha,p) \) reaction at \( E_{\alpha}=97 \text{ MeV} \) (Fa75) is almost identical to the \( (^{6}\text{Li},^3\text{He}) \) reaction at high incident energy (Bi75). Although the \( (13/2^+) \) state is dominant in these data, high-spin selectivity is even more pronounced in heavy-ion-induced, three-nucleon transfer. A semiclassical calculation of kinematic probability favors \( L=6 \) over \( L=4 \) by a factor of ten (An74), in the case of the \( ^{12}\text{C}(^{12}\text{C},^9\text{Be})^{15}O \) reaction at an incident energy of 114 MeV and at an
Final states of the $A=15$ nuclei, observed in triton and $^3\text{He}$ spectra at $E_{\text{Li}}=40$ MeV and $\theta_{\text{lab}}=15^\circ$, are given excitation energies from internal calibrations and spin values from references in Table 5.1. The standard levels and estimated uncertainties of the energy calibrations are listed in footnotes to Table 5.1. Assignments of $J^T=(9/2^+)$ and $(11/2^-)$ in $^{15}O$ are based on the analog relationship with $^{15}\text{N}$. 
excitation energy of 15 MeV. The observation of this reaction (Sc72), as well as the \(^{10}\text{B},^7\text{Li}\) and \(^{10}\text{B},^7\text{Be}\) reactions (Na73), reveals an almost exclusive population of the \(\frac{11}{2}^-\) state near 13 MeV and the \((\frac{13}{2}^+)\) state near 15 MeV. These different three-nucleon transfer data, therefore, provide supporting evidence of high angular-momentum transfer.

The \((^7\text{Li},\alpha)\) reaction serves an opposite dynamical function. For an excitation energy of 10 MeV in \(^{15}\text{N}\), incoming and outgoing orbital angular momenta at the nuclear surface are well matched, i.e. \(\Delta L=2\) in contrast to \(\Delta L=5\) of the \((^6\text{Li},^3\text{He})\) reaction. Because low-spin states are thus more accessible to the \((^7\text{Li},\alpha)\) reaction, less selectivity is observed in the spectrum for \(^{15}\text{N}\) at \(E_{^7\text{Li}}=40\) MeV (Fig. 5.3), which is consistent with previous measurements at \(E_{^7\text{Li}}=48\) MeV (Ze77), 35 MeV (Ts73) and 30 MeV (0g70,73). While the \(\frac{11}{2}^-\) state becomes secondary, levels at 12.55 MeV and 13.17 MeV receive enhanced relative cross sections in the \((^7\text{Li},\alpha)\) reaction, suggesting \(L\leq4\) (Fig. 5.4). The Q-value, which is 13 MeV more favorable than that of the \((^6\text{Li},^3\text{He})\) reaction, allows a strong population of additional states at high excitation energy, e.g. \(^{15}\text{N}^*(18.70,19.71)\). Owing to the opposing influences of linear- and angular-momentum matching, the relative strength of \(^{15}\text{N}^*(10.693,\frac{9}{2}^+)\) and \(^{15}\text{N}^*(15.41,\frac{13}{2}^+)\) in \((^7\text{Li},\alpha)\) data is almost unchanged from \((^6\text{Li},^3\text{He})\) data at \(E_{^7\text{Li}}=40\) MeV. In view of the unambiguous \(\alpha+t\) parentage of \(^7\text{Li}\), the repeated prominence of these two states confirms that they probably have 3p-4h configurations.

Identification of 2p-3h configurations follows from a study of the \(^{13}\text{C}(\alpha,d)^{15}\text{N}\) reaction at \(E_\alpha=40\) MeV (Lu69). On the basis of integrated cross section, angular distribution and Q-value, the dominant state at
Energy calibration of the alpha-particle spectrum at $E_{Li}=40$ MeV and $\theta_{lab}=15^\circ$ is independent of and consistent with $^{12}\text{C}(^{6}\text{Li},^{3}\text{He})^{15}\text{N}$ results. Additional excitation energies and spin values are included in Table 5.1.

Figure 5.3 $^{12}\text{C}(^{7}\text{Li},\alpha)^{15}\text{N}$

These three-nucleon transfer spectra from the ($^{6}\text{Li},t$), ($^{6}\text{Li},^{3}\text{He}$) and ($^{7}\text{Li},\alpha$) reactions are measured at the same incident energy and laboratory angle. Probable analog states and relative cross sections are also compared in Table 5.1. The large background in the ($^{7}\text{Li},\alpha$) reaction results from a Q-value favorable to Coulomb dissociation.
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* d²O/dQ² c.m. = 980 μb/σE Li = 44 MeV, θ lab = 15°

† d²O/dQ² c.m. = 1000 μb/σE Li = 44 MeV, θ lab = 15°

(1) calibrated from 15N (5.241, 8.284, 10.45, 12.835, 15.05)

ΔE ~ 20 keV

(2) ± 2° ~ 6%, statistical

(3) calibrated from 15N (5.270, 7.567, 8.571, 10.603)

ΔE ~ 20 keV, E X < 16 MeV

± 40 keV, E X > 16 MeV

(4) ± 3° ~ 8%, statistical
13.03 MeV is assigned \( J^\pi = 11/2^- \) and a \( (p_{1/2})^{-3}(d_{5/2})^{2} \) configuration. As a result, its prominence in \( ^{12}\text{C}(^6\text{Li},^3\text{He})^{15}\text{N} \) data (Fig. 5.2) probably reflects \( p(sd)^2 \) three-nucleon transfer. The 2p-3h state at \( ^{15}\text{N}^*(9.829,7/2^-) \) is also well populated (Fig. 5.2), but the proposed 9/2 member of the \( (p^{-3})_{1/2}^1(d^2)^{5+} \) doublet has very little cross section at 11.96 MeV in the \( (^6\text{Li},^3\text{He}) \) reaction, which thus demonstrates structural selectivity within this configuration. Because the levels of unknown spin at 12.55 MeV and 13.17 MeV (Fig. 5.3) are weak or absent in the \( (\alpha,\text{d}) \) spectrum, they emerge as additional good candidates for 3p-4h states. Overall, a comparison of \( (^6\text{Li},\text{t}) \) and \( (^6\text{Li},^3\text{He}) \) data with other transfer reactions increases the experimental sensitivity to transferred angular momenta and final-state configurations in the \( A=15 \) nuclei.

5.3 Model Predictions

We investigate the role of triton clustering in 3p-4h states of \( ^{15}\text{N} \) with calculations from a folded-potential model (Section 4.1). This potential generates a \( (sd)^3 \) cluster band with an approximately \( L(L+1) \) spacing (Fig. 5.5), whereas a Woods-Saxon potential of fixed depth would lead to almost degenerate energy levels or to an inverted sequence of orbital angular momenta (see Bu77a). Each level of given \( L \) is split by the triton spin-orbit interaction, where the strength parameter \( V_{S01} \) (Fig. 4.2) is equal to the value obtained in \( ^{19}\text{F} \) for the same \( (sd)^3 \) cluster configuration (Fig. 6.6). The only adjustable parameter in the present calculation, the strength \( \tilde{f} \) of the folded potential, is fitted to \( ^{15}\text{N}^*(10.693,9/2^+) \). In addition to having known spin (Be75), this normalization state is predicted in the shell model to have a pure 3p-4h configuration (Li70) and the largest \( (sd)^3 \) triton spectroscopic factor.
Figure 5.5 $^{15}\text{N}=^{12}\text{C}+t$

The folded-potential model predicts a $2N+L=6$ triton-cluster band of $^{15}\text{N}$, for comparison with final states from the $^{12}\text{C}(^6\text{Li},^3\text{He})^{15}\text{N}$ reaction at $E_{\text{Li}}=44$ MeV and $\theta_{\text{lab}}=10^\circ$. Peaks corresponding to $^{15}\text{N}^\pi(9.829,7/2^-;13.00,11/2^-)$ are disregarded in the list of observed levels. The dotted line represents experimental splitting; the star indicates a normalization state. With strength parameters of $\tilde{t}=1.694$ fm and $V_{S01}=0.016$, the following excitation energies (MeV) are calculated:

- $11/2^+$ 21.74
- $13/2^+$ 17.28
- $7/2^+$ 13.57
- $9/2^+$ 10.69
- $3/2^+$ 8.45
- $5/2^+$ 6.90
- $1/2^+$ 5.66
in $^{15}$N (An74). These expectations are supported by a large cross section in triton-transfer reactions. Triton-cluster states calculated from a normalized folded-potential model thus represent predicted positions of concentrated spectroscopic strength.

The correspondence between this simple cluster theory and transfer data in $^{15}$N is limited but significant (Fig. 5.5). Given that lp-2h components affect the experimental, positive-parity levels of the low-excitation region, we find the predictions with L=0 and L=2 to be quite reasonable. The model places 3p-4h, triton-cluster states near $^{15}$N$^*(5.299,1/2^+)$ and $^{15}$N$^*(8.571,3/2^+)$, but it suggests that 5/2$^+$ spectroscopic strength is divided experimentally between the levels at 5.270 MeV and 9.155 MeV. Both levels, as well as the 3/2$^+$ state, are observed in triton transfer via the ($^6$Li,$^3$He) reaction, although high-spin selectivity yields minor peaks. They all appear with more relative cross section in the ($^7$Li,$\alpha$) reaction (Fig. 5.3), in contrast to a near absence of $^{15}$N$^*(7.155,5/2^+;7.301,3/2^+;10.070,3/2^+)$. At higher excitation energy, the folded-potential model makes its most interesting prediction, a 7/2$^+$ triton-cluster state at 13.57 MeV. The only 7/2$^+$ states known in $^{15}$N (Aj76) are the lp-2h state at 7.567 MeV (Li70) and a 14.38 MeV level ignored by triton-transfer reactions. The only states of unknown spin which are well populated in the $^{12}$C($^6$Li,$^3$He)$^{15}$N spectrum lie at 12.56 MeV and 13.17 MeV (Fig. 5.5). Comparison to ($^7$Li,$\alpha$) and ($\alpha$,$d$) data indicates a 3p-4h configuration with L=4 in this pair of levels (Section 5.2). Angular distributions from the ($^7$Li,$\alpha$) reaction (Ts73) reflect a similarity to $^{15}$N$^*(10.693,9/2^+)$. The 13.17 MeV state is the favored candidate, with respect to excitation energy and ($^6$Li,$^3$He) cross section, for
spin $7/2^+$ and substantial triton-cluster structure. Predicted well above the 15.41 MeV level of $^{15}$N, the position of the $13/2^+$ cluster state indicates that additional spectroscopic strength at higher excitation energy may be important, as the second $13/2^+$ state of $^{19}$F demonstrates (Fig. 6.6). For the $11/2^+$ prediction, ($^6$Li,$^3$He) data is not available above $E_x=20$ MeV where, in any case, the cluster strength may fragment amidst a higher level density. Overall, application of the folded-potential model to $^{15}$N+$^{12}$C+t suggests that triton clustering does influence the structure of 3p-4h configurations selected by the $^{12}$C($^6$Li,$^3$He)$^{15}$N reaction. Useful predictive power, moreover, is illustrated by the case of spin $7/2^+$.

More detailed predictions, examining the degree of configuration mixing and the distribution of spectroscopic strength, are found in shell-model studies of the A=15 nuclei. Calculations from a SU(3) strong-coupling basis are reported (An74, see Section 4.2), in addition to results from a weak-coupling model which employs separate bases for the p and sd shells (Li70,71,76a, An74). Since the first $1/2^+$ state and the second $3/2^+$ state have larger 3p-4h components than other shell-model states with their respective spin values below $E_x=10$ MeV (Li70), the associated experimental levels at $^{15}$N$^*_x(5.299,8.571)$ are confirmed to be reasonable positions for the 3p-4h, triton-cluster states predicted by the folded-potential model (Fig. 5.5). A primarily 1p-2h configuration, however, is expected for $^{15}$N$^*_x(5.270,5/2^+)$ and a large (sd)$^3$ spectroscopic factor is calculated for $^{15}$N$^*_x(9.155,5/2^+)$ (An74), suggesting that the $5/2^+$ cluster state is rather low. 3p-4h triton clustering is most highly developed in the $9/2^+$ and $13/2^+$ shell-model states, in agreement
with strong population of the corresponding experimental levels by the 
\((^6\text{Li},^3\text{He})\) reaction. For the weak-coupling prediction of a \(7/2^+\) state, 
an excitation energy of 12.6 MeV and a spectroscopic factor of one-half 
the \(9/2^+\) value prove consistent with evidence in Fig. 5.5. More frag-
mentation of cluster strength occurs among the six shell-model states 
of spin \(11/2^+\) generated below \(E = 18\) MeV. Although the detailed distri-
bution of spectroscopic strength can be important in \(^{15}\text{N}\), the general 
outline of \((sd)^3\) triton-cluster structure indicated by the folded-
potential model receives considerable support from a comparison with 
shell-model calculations.

The influence of triton clustering upon negative-parity states of 
\(^{15}\text{N}\) is a relevant question, since \(2p-3h\) configurations at \(^{15}\text{N}^x(9.829,\) 
\(7/2^-;13.00,11/2^-)\) are responsible for major peaks in the \(^{12}\text{C}(^6\text{Li},^3\text{He})^{15}\text{N}\) 
spectrum (Fig. 5.2). A different cluster configuration of \(p_{1/2}\) \((sd)^2\) is 
expected to entail a change in the strength \(V_{SO1}\) of the triton spin-orbit 
interaction, as well as a renormalization of the strength \(\tilde{f}\) of the 
folded potential. Reliable determination of these parameters is pre-
cluded at present by the lack of an experimental candidate for the upper 
member of the \(L=3\) or \(L=5\) doublet, i.e. a \(5/2^-\) or \(9/2^-\) state populated by 
three-nucleon transfer at high excitation energy in \(^{15}\text{N}\). If a calcula-
tion is adjusted to the lower members of these doublets, the prediction 
for a \(3/2^-\) level of the \(2N+L=5\) band is encouraging (Bu75), but if a 
similar normalization procedure is followed for the \(2N+L=6\) band of \(^{15}\text{N},\) 
\(V_{SO1}\) is inconsistent with later results in \(^{19}\text{F}\) (Bu77a). In view of the 
uncertainty implied for the \(2N+L=5\) case, we turn from the folded-potential 
model to the shell model. Sizeable, three-nucleon spectroscopic factors
are indeed predicted for the $7/2^-$ and $11/2^-$ states of $^{15}\text{N}$ (An74), accounting for the large cross sections measured in the $(^{6}\text{Li},^{3}\text{He})$ reaction. As a result, $p_{1/2}(sd)^2$ clustering appears to be viable, outside a $^{12}\text{C}$ core.

In summary, the $(^{6}\text{Li},t)$ and $(^{6}\text{Li},^{3}\text{He})$ reactions, together with other transfer reactions into the $A=15$ nuclei, identify probable $p^{-4}(sd)^3$ configurations at $^{15}\text{N}^*(10.693,9/2^+;13.17;15.41,(13/2^+))$. The folded-potential model for $^{15}\text{N}=^{12}\text{C}+t$, through approximate correspondence with experiment and general support from the shell model, suggests that triton clustering plays a significant role in their structure.
The closed-shell target of $^{16}_0$, like the complete subshell of $^{12}_C$, should enhance the probability of clustering among transferred valence nucleons. Since $^{16}_0$ also has $J^\pi=0^+$, the spins and parities of triton-cluster states in $^{19}_F$ are expected to be the same as those in $^{15}_N$ (Table 1.1). In place of highly excited, 3p-4h states for $A=15$, however, the $(sd)^3$ configuration implies a 3p-0h, ground-state band in the $A=19$ nuclei.

6.1 $^{16}_0(\text{Li},t)^{19}_\text{Ne}$ and $^{16}_0(\text{Li},^3\text{He})^{19}_F$

In mirror spectra for these $T=\pm 1/2$ nuclei (Figs. 6.1, 6.2), three-nucleon transfer demonstrates a combination of structural and dynamic selectivity. Final states with $J^\pi=5/2^+, 9/2^+$ and $13/2^+$ have progressively enhanced cross sections, in contrast to the minor peak for a $7/2^- - 9/2^-$ doublet at $^{19}_F^\ast(4.01)$ and to the absence of several known high-spin states such as $^{19}_F^\ast(7.937, 11/2^+)$ (see Section 3.3). Since negative-parity levels become prominent above these positive-parity levels, the pattern immediately suggests a presence of $(sd)^3$ configurations followed by $(sd)^2 fp$ excitations. This choice of states in the $A=19$ nuclei by the $(^6\text{Li},t)$ and $(^6\text{Li},^3\text{He})$ reactions at $E_{Li}=46$ MeV is consistent with previous results, obtained at incident energies of 36 MeV (Pa72), 30 MeV (We72) and 24 MeV (Bi71, see Section 3.1) for excitation energies below 9 MeV. At higher excitation (Fig. 6.2), favored states of $^{19}_F$ are greater in strength but not in number. Consequently, analog assignments are clear in $^{19}_\text{Ne}$ (Fig. 6.1), although a shift in energy occurs at $^{19}_\text{Ne}^\ast(10.01)$ and a more negative Q-value reduces $(^6\text{Li},t)$ cross sections above $E_x=14$ MeV.
For these spectra measured at $E_{\text{Li}}=46$ MeV and $\theta_{\text{lab}}=15^\circ$, energy calibrations are described and spin values are referenced in Table 6.1. The extrapolation to high excitation in $^{19}\text{F}$ is generally consistent with a calibration of the $(\alpha,\text{p})$ reaction (Va76), and the energy of $^{19}\text{Ne}^*(8.94)$ agrees with a previous value from the $(^6\text{Li},t)$ reaction (We72). Given additional spins from the $(\alpha,\gamma)$ reaction (e.g. Sy77), $^{19}\text{F}$ is the source of tentative spin assignments for analog states in $^{19}\text{Ne}$.
$^{16}\text{O}(^{6}\text{Li},t)^{19}\text{Ne}$

$E_{\text{Li}} = 46$ MeV

$\theta_{\text{Lab}} = 15^\circ$
$^{16}O( ^6\text{Li}, ^3\text{He})^{19}\text{F}$

$E_{\text{Li}} = 46\text{MeV}$

$\theta_{\text{Lab}} = 15^\circ$
The angular-momentum mismatch $\Delta L=7$ of the $({}^6\text{Li},{}^3\text{He})$ reaction indicates high spin for high-lying levels. In view of the structural selectivity illustrated at lower excitation, they can be identified as additional candidates for $3p-0h$ states, perhaps involving several fp-shell excitations. Evidence of $(fp)^3$ structure in $^{20}\text{Ne}$ is presented in Appendix B.

6.2 Other transfer reactions

High angular-momentum transfer into $^{19}\text{F}^*(12.71,14.10,15.00)$ is confirmed by the large cross sections measured for these levels in the $(\alpha,p)$ reaction at $E_\alpha=40$ MeV (Va76), where $\Delta L=9$, and in the $(^{10}\text{B},^7\text{Be})$ reaction at $E_B=100$ MeV, where $\Delta L=5$ is expected semiclassically (Ha76a,c). As in the $A=15$ nuclei (Section 5.2), the known $13/2^+$ states of $^{19}\text{F}$ are most prominent in these two spectra. Additional states at high excitation energy are strongly populated by the $(^7\text{Li},\alpha)$ reaction at $E_{^7\text{Li}}=35$ MeV or 30 MeV, e.g. $^{19}\text{F}^*(9.6)$ (Ts74) and $^{19}\text{F}^*(13.3)$ (We73). Lower spin is probable for such levels, since $(^7\text{Li},\alpha)$ is $\sim 3h$ better matched than the $({}^6\text{Li},{}^3\text{He})$ reaction. If these dynamical differences between three-nucleon transfer reactions are taken into account, however, there is an underlying consistency in their selection of final states.

Candidates for $3p-0h$ configurations are more sensitively tested by a comparison of three-nucleon transfer with alpha-particle transfer. The $(^7\text{Li},t)$ reaction is predominantly direct at $E_{^7\text{Li}}=38$ MeV and $\theta_{lab}=15^\circ$ and highly selective in $^{16}\text{O}$, $^{18}\text{F}$ and $^{20}\text{Ne}$ (Co74,76,77). The $^{15}\text{N}(^7\text{Li},t)^{19}\text{F}$ reaction of Fig. 6.3, similarly, is expected to favor $4p-1h$ configurations with "alpha-cluster" structure, i.e. with large alpha-particle spectroscopic factors. Since this reaction has the same angular-momentum mismatch as $^{16}\text{O}(^6\text{Li},^3\text{He})^{19}\text{F}$, dynamical effects should have little
Final states of $^{19}$F are investigated here via alpha-particle transfer at $E_{Li} = 40$ MeV and $\theta_{lab} = 15^\circ$. Absolute differential cross sections are given in Table 6.1, together with relevant known levels of $^{19}$F.

The ($^6$Li,t) and ($^6$Li,${}^3$He) reactions indicate analog states in the A=19 nuclei, which are listed adjacently in Table 6.1. Below these three-nucleon transfer data is a contrasting alpha-particle transfer spectrum for $^{19}$F, measured at a similar incident energy and at the same laboratory angle.
\[ ^{15}\text{N}(^{7}\text{Li},t)^{19}\text{F} \]
\[ E_{\text{Li}}=40 \text{ MeV} \]
\[ \theta_{\text{Lab}}=15^\circ \]
### Table 6.1 \( A = 19 \)

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* or 12.63/12.77
† or 12.32/12.46/12.62
(1) calibrated from \(^{19}\text{Ne}^*(0.238, 2.795, 5.43)
consistent with \(^{16}\text{O}^*(5.241, 7.276, 10.45, 12.835, 15.05)
\( \Delta E \approx 20 \text{ keV}, E_x < 13 \text{ MeV} \)
\( \pm 30 \text{ keV}, E_x > 13 \text{ MeV} \)
(2) \( \pm (1\% - 4\%), \text{ statistical} \)
\( \pm \approx 10\%, \text{ absolute} \)
(3) calibrated from \(^{19}\text{F}^*(0.197, 2.780, 4.648, 6.925, 8.953, 10.411)
\( \Delta E \approx 15 \text{ keV}, E_x < 11 \text{ MeV} \)
\( \pm 30 \text{ keV}, E_x > 11 \text{ MeV} \)
(4) calibrated from \(^{19}\text{F}^*(2.780, 4.016, 8.953)
\( \Delta E \approx 15 \text{ keV}, E_x < 9 \text{ MeV} \)
\( \pm 30 \text{ keV}, 9 \text{ MeV} < E_x < 15 \text{ MeV} \)
\( \pm 50 \text{ keV}, E_x > 15 \text{ MeV} \)
(5) \( \pm (1\% - 5\%), \text{ statistical} \)
\( \pm \approx 15\%, \text{ absolute} \)
bearing on the comparison. Since angular distributions have a structureless behavior (Mi70, Ga72), forward-angle spectra contain approximate, relative, spectroscopic information. Final states strongly populated in the $^6\text{Li},^3\text{He}$ reaction but clearly inhibited in $^7\text{Li},t$, e.g. $^{19}\text{F}^\ast(2.78, 4.64, 6.92, 10.41, 14.10)$ (Fig. 6.4), demonstrate probable 3p-0h configurations. Mixing between 3p-0h and 4p-1h structure is evident in the 11/2$^-$ state at 8.953 MeV, where the two reactions yield similar relative cross sections despite their different population of the 13/2$^-$ state at 8.288 MeV. Alternate known levels for the peaks at $^{15}\text{N} (^7\text{Li},t)^{19}\text{F}^\ast(5.46, 9.92)$ (Table 6.1) make their origin more uncertain. Near 12 MeV and 15 MeV in excitation, multiplets further hinder a comparison with the $^{16}\text{O} (^6\text{Li},^3\text{He})^{19}\text{F}$ reaction, but primarily different states are suggested by the precise energies and widths (Table 6.1, Fig. 6.4). The $^6\text{Li},^3\text{He}$ and $^7\text{Li},t$ reactions into $^{19}\text{F}$, therefore, produce generally contrasting spectra but identify one major case of configuration mixing.

The resulting candidates for largely 4p-1h configurations, e.g. $^{19}\text{F}^\ast(4.02, 8.29, 14.50)$, become of interest through their relation to 4p-0h configurations in $^{20}\text{Ne}$. We will study, in the next chapter, the relation of 3p-1h to 3p-0h states by comparing $^6\text{Li},^3\text{He}$ spectra from $^{15}\text{N}$ and $^{16}\text{O}$ targets. We first investigate, as a simpler and better known case, the coupling of a $p_{1/2}$ hole to alpha-cluster structure by comparing $^7\text{Li},t$ data from $^{15}\text{N}$ and $^{16}\text{O}$ targets. Narrow, negative-parity doublets of $^{19}\text{F}$ (Fig. 6.5) exhibit a weak-coupling relationship to the $J^\pi=2^+, 4^+$ and $6^+$ members of the $(sd)^4$, ground-state band of $^{20}\text{Ne}$ (Mi70, Pi76, E170). Because the $8^+$ member at 11.95 MeV is hardly observed in the $^{16}\text{O} (^7\text{Li},t)^{20}\text{Ne}$ reaction, the $6^+$ state at 12.59 MeV may correspond to the pair at 12.57/
The $^{15}_N(7\text{Li},t)^{19}_F$ reaction is compared with $^{16}_O(7\text{Li},t)^{20}_\text{Ne}$ (Co74,76), where $E_{\text{Li}}=40$ MeV and 38 MeV respectively and $\theta_{\text{lab}}=15^\circ$. Excitation energies and spin values in $^{20}_\text{Ne}$ are obtained from Refs. Co76, Sa77, Aj78. The differential cross section of 4.1 mb for $^{19}_F^*(14.92/14.50)$ is comparable to the value of 3.3 mb for $^{20}_\text{Ne}^*(15.34)$. 
12.30 MeV in the \(^{15}\text{N}(^{7}\text{Li},t)^{19}\text{F}\) reaction. Comparison is more difficult for the low-spin members of the \(0^-\) band of \(^{20}\text{Ne}\) since, for example, \(^3\Omega\Omega 1/2^-\) strength appears fragmented among \(7/2^+\) states at \(^{19}\text{F}^\pm(6.070, 6.330, 7.56)\) (see also Bu77a). The \(5^-\) and \(7^-\) states of \(^{20}\text{Ne}\) do have good candidates in \(^{19}\text{F}\) near 10 MeV and 15 MeV respectively (Fig. 6.5). Although additional spin assignments in \(^{19}\text{F}\) are needed to confirm the relationship, weak coupling can at present describe \(4\text{p}-1\text{h}\), alpha-cluster structure. \(3\text{p}-1\text{h}\), triton-cluster structure may therefore involve the same phenomenon (Section 7.3).

6.3 Model Predictions

Theoretical investigation of triton clustering in \(3\text{p}-0\text{h}\) states is complemented by extensive experimental information on \(^{19}\text{F}\). In particular, an application of the folded-potential model to the \((\text{sd})^3\) configuration is aided by current knowledge of the ground-state band of \(^{19}\text{F}\) (Fig. 6.6). In contrast to the case of \(^{15}\text{N}\) (Fig. 5.5), a \(7/2^+\) state is assigned to this band (Bi72) and a second \(13/2^+\) state is identified at high excitation energy, together with a \(11/2^+\) state (Sy77). Low-lying \(3\text{p}-0\text{h}\) configurations, moreover, are free from the mixing with single-particle excitations which affects \(3\text{p}-4\text{h}\) structure at low excitation in \(^{15}\text{N}\) (Section 5.3). Since the \((^{6}\text{Li},^{3}\text{He})\) reaction (Fig. 6.6) and the \(\text{SU}(3)\) shell model (St73) indicate enhanced triton clustering in the \(7/2^+\) and \(9/2^+\) states of \(^{19}\text{F}\), they provide a good normalization for the strength \(V_{50}\) of the triton spin-orbit interaction and the strength \(\tilde{f}\) of the folded potential.

Theoretical triton-cluster states show a remarkable correspondence to experimental levels of \(^{19}\text{F}\). A calculated \(5/2^+-3/2^+\) doublet is in
Figure 6.6  $^{19}\text{F}=^{16}\text{O}+t$

A $2N+L=6$, triton-cluster band from the folded-potential model is compared with triton-transfer data from the $^{16}\text{O}(^{6}\text{Li},^{3}\text{He})^{19}\text{F}$ reaction (see also Fig. 6.2, Table 6.1). The list of experimental levels excludes the strongly populated states at $^{19}\text{F}^* (6.925,7/2^-;8.953,11/2^-;9.872,11/2^-)$. Using $\tilde{f}=1.514$ fm and $V_{S01}=0.016$, we calculate the following excitation energies (MeV):

11/2$^+$  11.46  
13/2$^+$  7.30  
7/2$^+$  5.46  
9/2$^+$  2.78  
3/2$^+$  1.63  
5/2$^+$  0.20  
1/2$^+$  -0.57.
precise agreement with known excitation energies (Fig. 6.6). In addition to a reasonable result for the ground state of $^{19}$F, an average position of $13/2^+$ spectroscopic strength is predicted between the pair of $13/2^+$ states strongly populated in triton-transfer data. For the $11/2^+$ triton-cluster state, an experimental candidate at $^{19}$F*(11.217, 11/2^+) has a relatively small cross section, despite the high-spin selectivity of the ($^6$Li, $^3$He) reaction. This observation suggests an important distribution of $11/2^+$ cluster strength among additional levels, perhaps including a state of unknown spin at 9.90 MeV which is resolved by the ($\alpha$,p) reaction (Ko77). The overall correlation, however, between a cluster band predicted by the folded-potential model and the ground-state band known in $^{19}$F is evidence that (sd)$^3$ triton clustering is highly developed outside the closed-shell, $^{16}$O core.

This conclusion is supported by spectroscopic factors calculated from the SU(3) shell model, e.g. large concentrations of triton-cluster strength in the $13/2^+_1$ and $13/2^+_2$ levels as well as in $11/2^+_1$ (St73, Sy77). A result similar to the 2N+L=6 band of Fig. 6.6, moreover, is obtained from a 'cosh-potential' model (Bu77a), i.e. a triton-cluster model based on a symmetrized Woods-Saxon well. Once the radius and diffuseness parameters are fit to the ground-state band of $^{19}$F, this potential is found to be similar in shape to a folded potential (Fig. 4.4) and is applied also to excited triton-cluster configurations (Bu77a). A normalization problem, however, analogous to that in the 2N+L=5 band of $^{15}$N (Section 5.3), arises in the 2N+L=7 band of $^{19}$F. Although a (sd)$^2$fp configuration (see Eq. 4.3) is indicated at $^{19}$F*$^\kappa$(6.925, 7/2^-) by triton-transfer reactions (Fig. 6.2, Ts74), the 5/2^- member of the doublet is
more uncertain. If the parameter $V_{S01}$ were fit to a $5/2^-$ state at 9.819 MeV, which is weakly observed in a high-resolution ($\alpha$,p) spectrum (Ko77), the resulting predictions would include a $15/2^-$ triton-cluster state near $^{16}_0(\alpha,\alpha) \, \, ^{19}\text{F}^{\ast}$ (14.10). Mixing is expected, however, in the case of $J^{\pi}=15/2^-$ or $11/2^-$, because of the theoretical proximity of triton- and alpha-cluster states (Bu77a). A detailed description of the competition between such (sd)$^2$fp and p$^{-1}$(sd)$^4$ structure is attempted by the SU(3) shell model. Large spectroscopic factors for both the triton and alpha clusters are calculated in a $11/2^-$ state at 8.9 MeV (Mi77), in agreement with the strong population of $^{19}\text{F}^{\ast}$ (8.953,11/2$^-$) by both the ($^6\text{Li},^3\text{He}$) and ($^\text{Li},t$) reactions (Fig. 6.4). A $15/2^-$ state, predicted with similar mixing at 12.5 MeV, may correspond to a member of the tentative doublets observed at $^{19}\text{F}^{\ast}$ (12.63/12.77) in triton transfer and at $^{19}\text{F}^{\ast}$ (12.62/12.46) in alpha-particle transfer (Table 6.1). (sd)$^2$fp triton clustering is thus expected to be influential in $^{19}\text{F}$, just as p(sd)$^2$ clustering exists in the shell model of $^{15}\text{N}$ (see Section 5.3).

In summary, three-nucleon transfer reactions identify candidates for 3p-0h states at $^{19}\text{F}^{\ast}$ (0.197,5/2$^+$;2.780,9/2$^+$;4.647,13/2$^+$;5.465,7/2$^+$;10.411,13/2$^+$) and $^{19}\text{F}^{\ast}$ (6.925,7/2$^-$;9.872,11/2$^-$;12.77;14.10;15.00). The ($^7\text{Li},t$) reaction, via contrast, generally confirms this configuration. The folded-potential model, through correspondence, suggests that (sd)$^3$ triton-cluster structure is important in the former states. The latter levels appear to represent fp-shell excitations.
CHAPTER 7 A=18

The previous two chapters concern $T=1/2$ states of odd-$A$, mirror nuclei. In this chapter, we investigate the spectrum of $T=1$ states in the even-$A$, $N=Z+2$ nucleus of $^{18}O$ and compare it with the spectrum of interspersed $T=1$ and $T=0$ states in the $N=Z$ nucleus of $^{18}F$ (Table 1.1). Since an unexcited $^{15}N$ core has $J^\pi=1/2^-$, triton-cluster states of spin $j\otimes1/2^-$ are expected in $^{18}O$, where $j$ is the total angular momentum of the triton. Their relationship to states of spin $j$ in $^{19}F=^{16}O+t$ (Fig. 6.6) shows the influence of weak coupling.

7.1 $^{15}N(6\text{Li},t)^{18}F$ and $^{15}N(6\text{Li},^3\text{He})^{18}O$

Identification of probable 3p-1h states in the $A=18$ nuclei begins with the role of low-lying, negative-parity states in three-nucleon transfer spectra. Above the (sd)$^2$ ground-state band of $^{18}F$, such known levels are selectively populated by the $(^6\text{Li},t)$ reaction at $E_{Li}=40$ MeV (Fig. 7.1), in accordance with results at $E_{Li}=30$ MeV for $E<7$ MeV (Li72). The precedence of a $p^{-1}(sd)^3$ configuration over (sd)(fp) is supported by diverse experimental evidence (see Ro73c); e.g. the first negative-parity state of $^{18}F$ has spin zero (see Li72), which cannot arise from a $d_5/2f_7/2$ coupling. Further candidates for 3p-1h structure, led by a $T=0$ state at 9.52 MeV, are plentiful at high excitation in $^{18}F$. In $^{18}O$, where $T=1$ states of spin $1^-$, $3^-$ and $5^-$ appear with increasing strength (Fig. 7.2), $J^\pi=7^-$ or $6^-$ may apply to the leading peaks at 11.10 MeV and 14.61 MeV. A correspondence to 3p-0h states of $^{19}F$ with $J^\pi=1/2^+$, $5/2^+$, $9/2^+$ and $13/2^+$ is indicated by their similar progression of relative cross sections in the $(^6\text{Li},^3\text{He})$ reaction (see Fig. 10.1a,b). An analog relationship to
At \( E_{\text{Li}} = 40 \text{ MeV} \) and \( \Theta_{\text{lab}} = 15^\circ \), outgoing tritons and \(^3\text{He}\) nuclei from standard targets of \(^{12}\text{C}\) and \(^{16}\text{O}\) provide an energy calibration for these spectra. Known final states of \(^{15}\text{N}\) and \(^{19}\text{F}\) observed in the \(^{6}\text{Li}, ^3\text{He}\) reaction generate consistent excitation energies for \(^{18}\text{O}\). High energy levels of \(^{18}\text{F}\) are determined by interpolation from the \(^{12}\text{C}(^{6}\text{Li}, t)^{15}\text{O}\) reaction instead of extrapolation from \(^{16}\text{O}(^{6}\text{Li}, t)^{19}\text{Ne}\) (see footnotes to Table 7.1). The broad contaminant peak under \(^{18}\text{O}^* (3.555)\) is from the \(^{1}H(^{6}\text{Li}, ^3\text{He})^4\text{He}\) reaction. The large peak at \(^{18}\text{F}^* (4.85)\), where \( \Delta L = 5 \) in the \(^{6}\text{Li}, t\) reaction, does not appear to arise from a \(^1(\sim)\) level at 4.860 MeV.
$^{15}\text{N}(^{6}\text{Li}, ^{3}\text{He})^{18}\text{O}$

$E_{\text{Li}} = 40 \text{ MeV}$

$\theta_{\text{Lab}} = 15^\circ$
T=1 states of $^{18}\text{F}$, which lie at $E_x \gtrsim 1.04 \text{ MeV}$, is complicated by their proximity to T=0 levels of equal prominence (Fig. 7.4). Although isospin mixing is relevant in general, the location of large T=1 components in $^{18}\text{F}$ can be suggested on the basis of excitation energies in $^{18}\text{O}$, which are listed adjacently in Table 7.1. More definite T=1, T_z=0 assignments are obtained from the ($^6\text{Li},t$) and ($^6\text{Li},^3\text{He}$) reactions into the A=16 nuclei (Section 9.1).

7.2 Other Transfer Reactions

The ($^{12}\text{C},^9\text{Be}$) and ($^{13}\text{C},^{10}\text{B}$) reactions at incident energies near 100 MeV (P177) preferentially populate the states at $^{18}\text{F}^*(7.24,9.52)$ and $^{18}\text{O}^*(11.10,11.67)$, confirming their high-spin character. The ($^7\text{Li},\alpha$) reaction identifies additional states of lower spin at high excitation, e.g. $^{18}\text{O}^*(16.73,17.92,20.4)$ (Figs. 7.3, 7.4). In comparison to ($^6\text{Li},t$) and ($^6\text{Li},^3\text{He}$) data for the A=18 nuclei, therefore, these other three-nucleon transfer reactions have differences equivalent to those found in the A=15 and A=19 nuclei, where we discuss their dynamical origins (see Sections 5.2, 6.2).

An overall difference in structural selectivity is expected from the ($^7\text{Li},t$) and ($\alpha,d$) reactions, favoring 4p-2h and 2p-0h configurations respectively in the A=18 nuclei. A T=1, $J^\pi=6^+$ state dominant at $^{14}\text{C}^*(7.6,11.69)$ (Mo70), however, also appears to be well populated in the $^{15}\text{N}(^6\text{Li},^3\text{He})^{18}\text{O}$ reaction (Fig. 7.2). Since this similarity may be interpreted as mixing between $p^{-2}(sd)^4$ and $p^{-1}(sd)^2fp$ structure, an analogy exists to the $11/2^-$ state at $^{19}\text{F}^*(8.953)$, where such competition between triton and alpha-particle clustering is indicated by both experiment (Fig. 6.4) and theory (Section 6.3). A T=0, $J^\pi=(6^+)$ state is
Excitation energies for these data are determined from the $^{12}_{\text{C}}(^{7}_{\text{Li}},\alpha)^{15}_{\text{N}}$ reaction (Fig. 5.3).

Three-nucleon transfer via the $(^{6}_{\text{Li}},t)$, $(^{6}_{\text{Li}},^{3}_{\text{He}})$ and $(^{7}_{\text{Li}},\alpha)$ reactions, all measured at $E_{\text{Li}}=40$ MeV and $\theta_{\text{lab}}=15^\circ$, selects final states of the $A=18$ nuclei. A large background from Coulomb break-up is subtracted from this $(^{7}_{\text{Li}},\alpha)$ spectrum.
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(1) – (6) see next page
TABLE 7.1 (continued)

(1) calibrated from $^{19}\text{Ne}$ $^\ast$ $(0.238, 2.794, 5.43)$, $E_x < 10$ MeV

from $^{15}\text{O}$ $(5.241, 8.284, 10.45, 12.835, 15.05)$, $E_x > 10$ MeV

$\Delta E \approx \pm 20$ keV, $E_x < 11$ MeV

$\pm 30$ keV, $E_x > 11$ MeV

(2) $\pm (1\% - 5\%)$, statistical

$\sim \pm 15\%$ absolute, $E_x < 10$ MeV

$\sim +40\%$ absolute, $E_x > 10$ MeV

(3) calibrated from $^{19}\text{F}$ $^\ast$ $(0.197, 2.780, 4.648, 6.925, 8.953, 10.411)$

$\Delta E \approx \pm 15$ keV, $4$ MeV $< E_x < 15$ MeV

$\pm 30$ keV, $E_x > 15$ MeV

(4) $\pm (1\% - 5\%)$, statistical

$\sim \pm 15\%$, absolute

(5) calibrated from $^{15}\text{N}$ $^\ast$ $(5.270, 7.567, 8.571, 10.693)$

$\Delta E \approx \pm 20$ keV, $E_x < 16$ MeV

$\pm 40$ keV, $E_x > 16$ MeV

(6) $\pm (2\% - 10\%)$, statistical

$\sim \pm 15\%$ absolute, $E_x < 10$ MeV

$\sim \pm 25\%$ absolute, $E_x > 10$ MeV
identified at 9.58 MeV in the $^{14}\text{N}(^{7}\text{Li},t)^{18}\text{F}$ reaction as a candidate for the 4p-2h, $1^+$ band of $^{18}\text{F}$ (Co77). Although other members of this band are clearly negligible in $^{15}\text{N}(^{6}\text{Li},t)^{18}\text{F}$ data, the peak at 9.52 MeV (Fig. 7.1) could contain a $(6^+)$ contribution. A more probable explanation of this peak, however, lies in a correspondence to the level observed at $E=9.494$ MeV ± 15 keV in the $^{16}_0(\alpha,d)^{18}\text{F}$ reaction (Ma68).

While the large cross section in two-nucleon transfer suggests a $(d_{5/2}f_{7/2})_6^-$ component (Ri66), mixing with $p^{-1}(sd)^3$ structure would be implied by the dominance of the same state in three-nucleon transfer. Several other states of $^{18}\text{F}$, e.g. at 10.541 MeV and 11.384 MeV (Ma68, Ri66), reflect a limited overlap between $^{6}\text{Li}(t)$ and $(\alpha,d)$ spectra. The $(sd)(fp)$ configuration, therefore, appears to play a significant role in these high-lying, $T=0$ levels of $^{18}\text{F}$.

7.3 Model Predictions

Interpretation of triton-transfer data for $^{18}_0$ by means of a calculation of $p^{-1}(sd)^3$, triton-cluster structure involves a coupling of three angular momenta. The folded-potential model of $^{18}_0=^{15}\text{N}+^t_0$ (Fig. 7.5) predicts orbital angular-momentum states, which are first split by the triton spin-orbit interaction. Levels of $^{19}\text{F}=^{16}_0+t$ (Fig. 6.6) fix the strength parameter $V_{S01}$ in the $(sd)^3$ cluster configuration. In order to describe the effect of a $^{15}\text{N}$ core with $J^n=1/2^-$, we introduce a second spin-dependent interaction $V_{S02}(r)$, defined and discussed in Section 4.1. When its strength $V_{S02}$ is adjusted approximately to the separation of $^{18}_0^*(5.098,3^-;5.530,2^-)$, the resulting narrow doublets prove consistent with a "hyperfine" interaction (Fig. 4.2) rather than a strong spin-spin coupling. A third parameter, the strength $\tilde{F}$ of the folded potential $V_S(r)$,
Triton-cluster states in the 2N+L=6 band of $^{18}_0$ are calculated from the folded potential of Fig. 4.4 and compared with the $^{15}_N(6 Li, 3 He)^{18}_0$ spectrum of Fig. 7.2. Peaks identified with positive-parity states, namely $^{18}_0(7.117,4^+; 11.69,6^+; 12.53,6^+ )$ (Aj78), are absent from the list of experimental levels. With $\bar{r}=1.532$ fm, $V_{S01}=0.016$ and $V_{S02}=0.0032$, we obtain the following theoretical excitation energies (MeV):

<table>
<thead>
<tr>
<th>$^+$</th>
<th>Energy (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5$^-$</td>
<td>17.76</td>
</tr>
<tr>
<td>6$^-$</td>
<td>16.99</td>
</tr>
<tr>
<td>6$^-$</td>
<td>13.57</td>
</tr>
<tr>
<td>7$^-$</td>
<td>12.62</td>
</tr>
<tr>
<td>3$^-$</td>
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</tr>
<tr>
<td>4$^-$</td>
<td>10.89</td>
</tr>
<tr>
<td>4$^-$</td>
<td>8.74</td>
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<tr>
<td>5$^-$</td>
<td>8.12</td>
</tr>
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<td>7.30</td>
</tr>
<tr>
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<td>7.08</td>
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</tr>
<tr>
<td>3$^-$</td>
<td>5.60</td>
</tr>
<tr>
<td>0$^-$</td>
<td>5.02</td>
</tr>
<tr>
<td>1$^-$</td>
<td>4.91</td>
</tr>
</tbody>
</table>
is fitted to the known $5^-$ state (Le67) strongly populated by the $^{15}_{\text{N}}(^{6}_{\text{Li}},^{3}_{\text{He}})^{18}_{\text{O}}$ reaction. We then find that $V_s(r)$ for $^{15}_{\text{N}}t$ is almost identical to the potential for $^{16}_{\text{O}}t$, which generates a triton-cluster band in close correspondence to the ground-state band of $^{19}_{\text{F}}$. Consequently, this normalization of the folded-potential model for $3p-1h$ structure in $^{18}_{\text{O}}$ is equivalent to a weak-coupling procedure, which joins a $p_{1/2}$ hole to $(sd)^3$ states of $^{19}_{\text{F}}$. A theoretical approach relating these two nuclei is also taken by the weak-coupling shell model, with similar results for $E_x < 8$ MeV (E170), and by the cosh-potential cluster model, with different interactions and normalization (Bu78). Experimental evidence of weak coupling is well established in the case of a $p_{1/2}$ hole plus $sd^4$ states of $^{20}_{\text{Ne}}$ (Fig. 6.5, Mi70).

Weak-coupling effects are subtle but observable in $p^{-1}(sd)^3$ configurations. In addition to the known $3^- - 2^-$ doublet of $^{18}_{\text{O}}$ (Fig. 7.5), the $4^-$ member of a $9/2^+ - 1/2^-$ doublet predicted by the folded-potential model has a good experimental candidate at 8.47 MeV. This level of $^{18}_{\text{O}}$ is assigned unnatural parity ($0171$) and is prominent in triton-transfer spectra (see also Fig. 7.3). The predicted position of the $1^- - 2^-$ triton-cluster states suggests a distribution of spectroscopic strength among $^{18}_{\text{O}}\ ^\ast (6.196, 1^-; 6.351, 2^-; 7.620, 1^-; 7.75)$ (Aj78). Although population of these known levels is dynamically inhibited in the $(^{6}_{\text{Li}},^{3}_{\text{He}})$ reaction (Fig. 7.2), low-spin states such as $^{18}_{\text{O}}\ ^\ast (6.882, 0^-)$ do appear in the $(^{7}_{\text{Li}},\alpha)$ spectrum (Fig. 7.3). Between $E_x = 8.47$ and 10.60 MeV, all levels observed in the two reactions have natural parity ($0171$); at 10.60 MeV, indefinite parity and adequate cross section provide the first candidate for a $4^- = 7/2^+ - 1/2^-$ prediction. The $7^-$ triton-cluster state represents an
average position of spectroscopic strength which may be divided experi-
mentally, e.g. between the leading peaks at $^{18}_0(11.10;14.61$ or $15.95)$
(Fig. 7.5), just as $13/2^+$ cluster strength is found to be split between
$^{19}_F(4.647;10.411)$ (Fig. 6.6). Through an underlying correspondence to
triton-transfer data for $^{18}_O$, therefore, the folded-potential model
shows useful predictive power and suggests influential clustering
phenomena.

A more evident correlation between theory and experiment is ob-
tained with the SU(3) shell model. Predicted spectroscopic factors
detail the distribution and degree of triton clustering in negative-
parity states of $^{18}_O$ (Mi77) which, in Section 4.2, serve as examples
of SU(3) techniques. At $E = 7.84$ MeV, a state of unknown spin and
natural parity (0171), which is strongly populated in triton-transfer
reactions and unaccounted for by the folded-potential model (Fig. 7.5),
can be associated with the first $5^-$ state calculated by the shell
model (Fig. 7.6). The $5_2^-$ prediction then corresponds to a known level
at $^{18}_0(8.10,5^-)$. In addition to this unexpected splitting of $5^-$ spec-
troscopic strength, a suspected division of the $7^-$ triton-cluster state
(Fig. 7.5) is confirmed by the shell model, which thereby supports an
identification of the $7_1^-$ and $7_2^-$ states with the prominent experimental
levels at $^{15}_N(6^Li,3^He)^{18}_O(11.10;14.61$ or $15.95)$. The magnitude of the
above spectroscopic factors, together with the strength of $1_1^-$ and $3_1^-$
(Fig. 7.6), demonstrates the importance of triton clustering in "stretched"
angular-momentum couplings, where orbital angular momentum, cluster spin
and core spin are aligned to maximum J (see Fig. 7.5). Enhanced cross
sections for such states are found in the $(6^Li,3^He)$ reaction which, for
Preliminary triton spectroscopic factors for negative-parity states of $^{18}O$ (Mi77) are predicted from Eq. 4.5 and plotted if $S>0.05$ (center). They are calculated for a $p^{-1}(sd)^3$ configuration and a $J^\pi = j\otimes 1/2^-$ coupling which corresponds to the triton-cluster states predicted by the folded-potential model (Fig. 7.5). Excitation energies for the latter states are plotted on the left-hand side of the present diagram. Above the relevant known levels of $^{18}O$ (right), which also include $^{18}O^*(7.620,1^-;7.75)$ (Aj78), the experimental levels of unknown spin are obtained from the $^{15}N(^6Li,^3He)^{18}O$ reaction. Peaks at $^{18}O^*(7.10,11.67,12.53)$ in Fig. 7.2 are associated with positive-parity states and are omitted from the present diagram, although $^{18}O^*(11.67)$ may be related in part to the $6^-_2$ prediction. Normalization at $^{18}O^*(4.456,1^-)$ determines the absolute excitation energies of shell-model levels.
example, favors $^{18}O^*(5.098,3^{-})$ over $^{18}O^*(5.530,2^{-})$.

The SU(3) shell model predicts, rather than postulates, weak-coupling effects in triton-cluster structure. In agreement with a $9/2^+\otimes 1/2^-$ doublet from the folded-potential model, a $4^-_2$ level is calculated near the 8.47 MeV state of $^{18}O$ (Fig. 7.6). Further theoretical evidence of weak coupling exists in a $4^-_{6/10}$ doublet and a $6^-_{7/15}$ pair, although a higher level density reduces the concentration of spectroscopic strength in these unaligned angular-momentum couplings. Mixing between doublets is found to be minor in the shell-model states of Fig. 7.6, except for comparable $5/2^+\otimes 1/2^-$ and $3/2^+\otimes 1/2^-$ components in both $2^-_1$ and $2^-_3$. Despite a basis including (sd)(fp) configurations, the admixture into $3p-1h$ structure is predicted to be small, aside from a 11% component in the $6^-_4$ state. For this exception, constructive addition occurs for the spectroscopic amplitudes of a $p(sd)fp$ and a $(sd)^3$ triton cluster. The expected cross section is observed at $^{18}O^*(14.61)$ (Fig. 7.2), but $^{18}O^*(13.79)$ is closer to the predicted excitation energy. Overall, the SU(3) shell model of negative-parity states in $^{18}O$ confirms the theoretical framework of triton clustering from the folded-potential model and corresponds to the experimental results of triton transfer from the ($^6Li,^3He$) reaction. In detail, calculated triton spectroscopic factors reveal division of cluster strength and favor alignment of angular momenta, but they remain influenced by weak coupling.

In summary, the ($^6Li,^3He$) reaction identifies major $p^{-1}(sd)^3$ structure at $^{18}O^*(5.098,3^{-};7.84;8.10,5^{-};11.10;14.61;15.95)$. The folded-potential model and the SU(3) shell model indicate substantial triton clustering in these levels. Three-nucleon transfer data are more complex for $^{18}F$, where $T=0$ states and (sd)(fp) configurations play an important role.
CHAPTER 8 A=17

As an extension of the doublet structure in $^{18}_0$, $^{01}_1$ triplets are expected in $^{17}_0$, where a triton cluster has total angular momentum $j$ and an unexcited $^{14}_N$ core has spin one and positive parity (Table 1.1). Mixing becomes probable among these triplets since, for example, $J''=3/2^+$ can originate from $j=1/2^+$, $5/2^+$ or $3/2^+$ (Fig. 6.6). Strong-coupling effects, evidenced in $4p-2h$ configurations of $^{18}_F$ (Ro73b), may also reduce the influence of weak coupling in $3p-2h$ structure. Such theoretical complexity is beyond the scope of a folded-potential model of triton clustering. If spectroscopic strength is enhanced for aligned angular momenta, however, relative simplicity should emerge in experimental spectra.

8.1 $^{14}_N(\text{Li},t)^{17}_F$ and $^{14}_N(\text{Li},^3\text{He})^{17}_0$

Three-nucleon transfer into the A=17 nuclei is dominated by three states at 8.5, 10.7 and 14.9 MeV (Figs. 8.1, 8.2). Their excitation energies suggest a relation to $^{15}_N^*(5.270/9.155,5/2^+;10.693,9/2^+;15.41,(13/2^+))$ (Fig. 5.5, Ha76b). Their relative population at $E_{\text{Li}}=46$ MeV, consistent with results for $E_x<14$ MeV at $E_{\text{Li}}=30$ MeV (Ba72, see also Bi73a), follows the behavior of the first 5/2+, 9/2+ and 13/2+ states of $^{19}_\text{Ne}$ or $^{19}_F$ (Figs. 6.1, 6.2). Because the pair of p-shell holes in a $^{14}_N$ target has spin $1^+$, coupling to these $^{(sd)}_3$ states of the A=19 nuclei is expected to generate nine levels in $^{17}_F$ or $^{17}_0$. A preference for one member of each triplet would then account for the observation of three leading peaks. Their absolute, differential cross sections reflect such an enhancement; e.g. $^{17}_F^*(10.71)$ carries 70% of the total strength present in $^{19}_\text{Ne}^*(2.80,9/2^+)$ (Tables 8.1, 6.1). If $^{17}_F^*(8.43)$ arises from a $5/2^+\otimes 1^+$...
Excitation energies of the \(A=17\) nuclei are determined from known levels of the \(A=19\) and \(A=15\) nuclei, also observed at \(E_{\text{Li}}=46\) MeV and \(\theta_{\text{lab}}=15^\circ\). The \(^{16}\text{O}(^{6}\text{Li},t)^{19}\text{Ne}\) and \(^{12}\text{C}(^{6}\text{Li},t)^{15}\text{O}\) reactions provide calibrations which agree within 15 keV for the energy levels of \(^{17}\text{F}\). Since the low-excitation region of \(^{17}\text{O}\) is beyond the Q-value of \(^{16}\text{O}(^{6}\text{Li},^{3}\text{He})^{19}\text{F}(\text{g.s.})\), an internal calibration for \(E_x<6\) MeV supplements the independent energies at higher excitation (see Table 8.1). The peaks at \(^{17}\text{F}^*(8.43)\) and \(^{17}\text{O}^*(8.48)\) are both nearest in energy to \(7/2^+\) states, known at 8.416 MeV \(\pm 10\) keV and 8.474 MeV \(\pm 3\) keV respectively (Aj77).
$^{14}\text{N}(^6\text{Li},t)^{17}\text{F}$

$E_{\text{Li}}=46$ MeV

$\theta_{\text{Lab}}=15^\circ$
coupling, moreover, its spin assignment of \( J^T = 7/2^+ \) illustrates the alignment of angular momenta. As in \(^{18}\text{O} \) (Section 7.3), low level density would then favor a large spectroscopic factor for this state and a small admixture of \( j=9/2^+ \) or \( 7/2^+ \) structure. Further evidence concerning transferred angular momenta and \( 3p-2h \) configurations is found in a comparison of the \((^{6}\text{Li},t)\) and \((^{6}\text{Li},^3\text{He})\) reactions with various multinucleon transfer data for the \( A=17 \) nuclei.

### 8.2 Other Transfer Reactions

In the \((\alpha,p)\) reaction at \( E_\alpha = 34 \text{ MeV} \) (Va75) and in the \((^{10}\text{B},^7\text{Be})\) reaction at \( E_{^B\text{B}} = 100 \text{ MeV} \) (Ha76b), the most strongly populated state is \(^{17}\text{O}^* \) (14.9). Since a \( 13/2^+ \) state has this property in \(^{19}\text{F} \) and tentatively in \(^{15}\text{N} \) (Sections 5.2, 6.2), a spin of \( 13/2^+ \otimes 1^+ = 15/2^+ \) in \(^{17}\text{O} \) is proposed by these authors. The sizeable peak at 10.7 MeV could similarly arise from a \( 9/2^+ \otimes 1^+ = 11/2^+ \) state (Ha76b). In correspondence to the minor cross section of \(^{16}\text{O}(^{10}\text{B},^7\text{Be})^{19}\text{F}^* (0.20,5/2^+) \) (Ha76a,c), the known \( 7/2^+ \) state at 8.474 MeV is weakly populated by the \(^{14}\text{N}(^{10}\text{B},^7\text{Be})^{17}\text{O} \) reaction. This indication of relatively low angular-momentum transfer (see Section 5.2) confirms the existence of a \( L=2, \; 5/2^+ \otimes 1^+ \) stretched coupling. From the dynamic differences between three-nucleon transfer reactions, therefore, and from the similarities between \( A=17 \) data and results for \( A=19 \) and \( A=15 \), we conclude that the three dominant peaks of Fig. 8.1 represent probable \( L=2, \; 4 \) and \( 6 \) members of a \( 3p-2h \) band. In support of this interpretation, the folded-potential model for a \( 2N+L=6 \) band of \(^{17}\text{O}^{14}\text{N}+t \) predicts a moment of inertia which is consistent to 20% with the experimental \( L(L+1) \) spacing.
Negative-parity states of $^{17}O$ are found in two- and four-nucleon transfer data. The $(\alpha,d)$ reaction (Lu69) identifies $2p$-$1h$ configurations at $^{17}O^{*}(7.75,11/2^-;9.15,9/2^-)$, which have little strength in the $(^6Li,^3He)$ reaction and appear analogous to minor peaks at $^{14}N(^6Li,t)^{17}F^{*}(7.97,9.40)$ (Figs. 8.1, 8.2). This contrast to the major role of a $2p$-$3h$, $11/2^-$ state in the $^{12}C(^6Li,^3He)^{15}N$ reaction (Fig. 5.2) illustrates that $p(sd)$ transfer is dependent upon the number of holes available in the $p$ shell. A probable negative-parity state of $^{17}O$ which has different structure, however, proves important in three-nucleon transfer data. The dominant state in a $^{13}C(^7Li,t)^{17}O$ spectrum (Fig. 8.3) also has significant cross section at $^{14}N(^6Li,^3He)^{17}O^{*}(13.53)$, a unique behavior suggesting $p^{-2}(sd)^2fp$ admixture into a $p^{-3}(sd)^4$ configuration (see also Section 7.2). In the case of the three candidates for positive parity at $^{17}O^{*}(8.48,10.70,14.89)$, a sharp reduction of relative strength in alpha-particle transfer (Fig. 8.4) and a near absence of yield in two-nucleon transfer (Lu69) constitute further evidence of their largely $p^{-2}(sd)^3$ configurations.

The identification of this $3p$-$2h$ structure in $^{17}O$ leads to an interpretation of the $(^7Li,t)$ reaction. A population of the above states at $^{17}O^{*}(10.70,14.89)$ (Fig. 8.4c) can be attributed to a mechanism of $p(sd)^3$ alpha-particle transfer and/or a configuration with $(sd)^3fp$ admixture. Despite a primary role in $J^{\pi}=5^-$ and $7^-$ structure of $^{16}O$ (see Section 9.2), alpha-particle clustering of either type appears secondary in these suggested $11/2^+$ and $15/2^+$ states of $^{17}O$ (Fig. 8.4b). The other prominent peaks in $^{13}C(^7Li,t)^{17}O$ data (Fig. 8.4c) represent candidates for $p^{-3}(sd)^4$ configurations, beginning with a $7/2^-$ state at
For these data measured at $E_{Li} = 40$ MeV and $\theta_{lab} = 10^\circ$, energy calibrations are based on the $^{12}_C(^7Li,t)^{16}_O$ reaction. Owing to a small discrepancy in amplifier gain between the $E_1$ and $E_2$ signals (Fig. 2.2), separate calibrations are required above and below an excitation energy of 10 MeV (see Table 8.1). A contribution from $^{12}_C$ impurity in the target to the $^{13}_C(^7Li,t)^{17}_O$ spectrum is eliminated by a subtraction of the calibration spectrum, weighted according to yields for $^{16}_O^*(g.s., 6.1)$.

Three-nucleon transfer via the ($^6Li,t$) and ($^6Li,^3He$) reactions demonstrates the mirror relationship between $^{17}_F$ and $^{17}_O$. Below, alpha-particle transfer is observed at a similar incident energy but at a more forward angle. This ($^7Li,t$) spectrum for $^{17}_O$ includes the $^{16}_O$ contamination subtracted in Fig. 8.3.
$^{13}\text{C}(^7\text{Li},t)^{17}\text{O}$

$E_{\text{Li}} = 40$ MeV

$\theta_{\text{Lab}} = 10^\circ$

$O^{16\,*}$ subtracted

EXCITATION ENERGY (MeV)

COUNTS
$^{14}\text{N}(^{6}\text{Li},t)^{17}\text{F}$
$E_{Li}=4.6$ MeV
$\theta_{Lab}=15^\circ$

$^{14}\text{N}(^{6}\text{Li},^{3}\text{He})^{17}\text{O}$
$E_{Li}=4.6$ MeV
$\theta_{Lab}=15^\circ$

$^{13}\text{C}(^{7}\text{Li},t)^{17}\text{O}$
$E_{Li}=4.0$ MeV
$\theta_{Lab}=10^\circ$
<table>
<thead>
<tr>
<th>$J^p$</th>
<th>Energy</th>
<th>$E_X (MeV)$</th>
<th>$E_X (^{14}N, ^6Li, ^{17}F)$</th>
<th>$E_X (^{14}N, ^6Li, ^{3}He)$</th>
<th>$E_X (^{15}Cl, ^7Li, ^{17}O)$</th>
<th>$E_X (^{17}O)$</th>
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<tr>
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<td>3.81</td>
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<tr>
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<td>7.03</td>
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<tr>
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<td>etc.</td>
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</tbody>
</table>

(1) calibrated from $^{19}F (0.238, 2.794, 5.43)$

(2) $\pm (1\% - 4\%)$, statistical
$\pm 10\%$, absolute

(3) calibrated from $^{17}O (g.s., 3.841, 8.474), E_X < 6 MeV$

(4) $\pm (1\% - 7\%)$, statistical
$\pm 10\%$, absolute

(5) calibrated from $^{16}O (g.s., 6.917, 10.353), E_X < 10 MeV$

$\Delta E = \pm 20 keV$
8.972 MeV (Aj77). The first 1/2\(^{-}\), 5/2\(^{-}\) and 3/2\(^{-}\) states of \(^{170}\) (Fig. 8.3) are also observed in alpha-particle transfer, indicating 4p-3h components (Be70, Go71), but shell-model calculations depict strong mixing with 2p-1h configurations (see Le72). Using theoretical states with unmixed 4p-3h structure for L=0 and L=2 (E170), we find that the experimental doublets have a L(L+1) spacing for L=4, 6 and 8 (Fig. 8.5). This evidence reveals a tentative 2N+L=8, alpha-cluster band of \(^{170}\).

A comparison can be made to the 4p-4h, 0\(^{+}\) band of \(^{160}\), selectively populated by the \(^{12}\)C(\(^{7}\)Li,t)\(^{160}\) reaction (Co76). Weak coupling of a \(p_{1/2}\) particle to the 6\(^{+}\) state at \(^{160}\)\(^{+}\)(16.29) would generate a 11/2\(^{-}\)-13/2\(^{-}\) doublet, in accordance with peaks at \(^{170}\)\(^{+}\)(12.41,13.55) (Fig. 8.4c). In the \(^{7}\)Li,t reaction at \(E_{Li}=40\) MeV and \(\theta_{lab}=10^\circ\), the absolute differential cross section of the 13.55 MeV state equals 40\% that of \(^{160}\)\(^{+}\)(16.29); in the \(^{6}\)Li,d reaction at \(E_{Li}=34\) MeV, their angular distributions are consistent (C178). Good candidates for the 8\(^{+}\)\(\otimes\)1/2\(^{-}\) coupling appear at \(^{170}\)\(^{+}\)(18.15,19.24). The same 1 MeV splitting, moreover, characterizes the effect of a \(p_{1/2}\) neutron on two-particle structure, i.e. a 2p-3h doublet at \(^{15}\)N\(^{+}\)(11.95,(9/2\(^{-}\);13.00,11/2\(^{-}\)) arises from the \((p_{1/2})^{4}(d_{5/2})^{2}\) configuration at \(^{14}\)N\(^{+}\)(8.961,5\(^{+}\)) (Lu69, Ri66). Although confirmation requires more spin assignments, we conclude that present evidence of \(p^{-3}(sd)^{4}\) structure in \(^{170}\) exhibits the influence of weak coupling. In contrast to the nearly equal excitation energies of 4p-1h and 4p-0h states (Fig. 6.5), however, an increase in the moment of inertia accompanies the formation of 4p-3h doublets (Fig. 8.5). A \(p_{1/2}\) particle also appears to generate greater splitting than does a \(p_{1/2}\) hole. Corresponding phenomena may affect 3p-3h configurations described in the next chapter.
Figure 8.5 Weak coupling in 4p-3h configurations

In this plot of $E_x$ vs. $L(L+1)$, the candidates for $p^{-3}(sd)^4$ configurations (solid points) are obtained from $^{13}_C(^7Li,t)^{17}_{170} \times (8.972, 7/2^-, 9.87; 12.41; 13.55; 18.15; 19.24)$ (Fig. 8.4c). The positions of unmixed 4p-3h states with $J^\pi=1/2^-, 5/2^-$ and $3/2^-$ are calculated from the weak-coupling shell model (E170). A comparison with $p^{-4}(sd)^4$, alpha-cluster structure (open points) is provided by $^{12}_C(^7Li,t)^{16}_{160} \times (6.049, 0^+; 6.917, 2^+; 10.353, 4^+; 16.29, 6^+)$ (Co76, Aj77) and by $^{12}_C(^{12}_C, ^8Be)^{16}_{160} \times (22.5, 8^+) \langle \alpha_0 \rangle ^{12}_C$ (Sa77).
In summary, triton-transfer reactions classify $^{17}O (8.474, 7/2^+; 10.70; 14.89)$ as probable members of a $p^{-2}(sd)^3$ band. Alpha-particle transfer data for $^{17}O$ lead us to expect a similarity between triton-transfer spectra from $^{13}C$ and $^{12}C$ targets.
CHAPTER 9 A=16

As in the A=18 nuclei, three-nucleon transfer into T=1 states of 16N draws an analogy to the spectrum of 16O, which contains both T=1 and T=0 states (Table 1.1). Since the ground state of 13C has J″=1/2−, triton clustering in 16N involves the same theoretical spins and parities as 180=15N+t (Fig. 7.5). A lack of experimental spin assignments in 16N, however, prevents normalization of the folded-potential model for 3p-3h configurations. Evidence of a relationship to 3p-4h states of 15N (Table 1.1) exists despite the effect of a p1/2 valence neutron.

9.1 13C(6Li,t)16O and 13C(6Li,3He)16N

The dominant peaks at 160*(20.49) and 16N*(7.65) in three-nucleon transfer spectra (Figs. 9.1, 9.2) represent T=1 analog states with Tz=0 and Tz=1 respectively, for their difference in excitation energy agrees with the separation between 160*(12.969,2−,T=1) (Aj77) and 16N(g.s.,2−). Further T=1 assignments can be made for levels at 22.6, 23.9 and 24.6 MeV in 16O, which correspond in relative cross section to those at 9.68/9.8, 11.2 and 11.8 MeV in 16N (Fig. 9.4a,b). At lower excitation, an analog relationship between the J″=3(+) states (Ja77) at 160*(16.81) and 16N*(3.97) is indicated by an energy difference equal to that of the dominant peaks and by a population of the 17.14 MeV state in the 14N(a,d)16O reaction (Zi70), which prefers T=0 states. In addition to a correspondence between 160*(18.01,3) and 16N*(5.15,(2,3)−) (Ch77, Ma78), there are two candidates at 18.44/18.61 MeV in 16O for the analog of a 5+ state at 5.73 MeV in 16N. A comparison of angular distributions from the (6Li,t) and (6Li,3He) reactions favors the upper member of the
Figure 9.1 \( ^{13}C(^{6}Li, t)^{16}O \)

Figure 9.2 \( ^{13}C(^{6}Li, ^{3}He)^{16}N \)

For these A=16 spectra at \( E_{Li} = 44 \text{ MeV} \) and \( \theta_{lab} = 10^\circ \), the \( ^{6}Li, t \) and \( ^{6}Li, ^{3}He \) reactions on a \( ^{12}C \) target provide a calibration of excitation energies and an identification of contaminant peaks (see Table 9.1). Since \( ^{15}O^{*}(5.241) \) is equivalent to \( ^{16}O^{*}(16.1) \) in Q-value, an extrapolation to the low-excitation region of \( ^{16}O \) is replaced by known energy levels below 9 MeV (Aj77). The \( J^{\pi}=(3^{+}) \) and \( 5^{+} \) assignments in \( ^{16}N \) are obtained from Refs. Aj77 and Lu69 respectively. The peak centered at \( ^{16}N^{*}(5.15) \) is analyzed as a multiplet in Table 9.1.
doublet and supports the $T=1$ character of $^{16}_0(16.81,20.49,24.63)$ (see Fig. 9.6). In overall contrast to $^{18}_F$ (Section 7.1), a shift in excitation energy and an enhancement in cross section lead to the unambiguous identification of several $T=1$ states of unknown spin above $E_x=20$ MeV in $^{16}_0$.

9.2 Other Transfer Reactions

Three-nucleon transfer into $T=0$ states of $^{16}_0$ is interpreted within the context of different multi-nucleon transfer data. In the low-excitation region of the ($^6$Li,$t$) spectrum (Fig. 9.1), which is consistent with results at lower incident energy (Ba69,70,71a,0g70), the most prominent states are $^{16}_0(11.095,4^+;14.40;14.815,6^+;16.24)$. Since the ($\alpha,d$) reaction (Ba70,Zi70) identifies them as primarily $2p-2h$ configurations, $p(sd)^2$ transfer appears to be important for the ($^6$Li,$t$) reaction on a $^{13}_C$ target. Relatively little cross section (Fig. 9.1) is found in the positive-parity, $T=0$ states of $4p-4h$ character at $^{16}_0(10.353,4^+;16.29,6^+)$. The broad, negative-parity states at $^{16}_0(14.59,5^-;20.9,7^-)$ (e.g. Sa77), which are strongly populated by the ($^7$Li,$t$) reaction (Co76), may have significant cross section in three-nucleon transfer (Table 9.1). Whatever their mixture of $p^{-3}(sd)^3$ and $p^{-4}(sd)^3 fp$ configurations, alpha-particle clustering is favored in such $T=0$ states of an even-even $4N$ nucleus, an effect most evident in $^{20}_{Ne}$ (Appendix B). Three-nucleon clustering is expected to develop more highly in $T=1$ states of $^{16}_0$, which indeed dominate the ($^6$Li,$t$) spectrum. We focus, therefore, on the analogous $T=1$ states of $^{16}_{N}$.

The rather simple spectrum from the $^{13}_{C}(^6_{Li},^3_{He})^{16}_{N}$ reaction (Fig. 9.2) is further clarified by an identification of positive-parity
levels. In the $^{14}\text{C}(\alpha,d)^{16}\text{N}$ reaction, the 3.96 MeV state with spin $3^+$ is confirmed to have a primarily 2p-2h configuration, and the 5.73 MeV state is assigned $(p_{1/2})^{-2}(d_{5/2})^{2+}$ structure (Lu69). This $L=5$ level of $^{16}\text{N}$ is strongly populated by the $(^6\text{Li},^3\text{He})$ reaction but not by $(^7\text{Li},\alpha)$ (Fig. 9.3), where angular momenta are well matched (Section 5.2). A corresponding reduction in cross section at $^{13}\text{C}(^7\text{Li},\alpha)^{16}\text{N}$ (11.21) (Fig. 9.4) may have similar origin. Although peaks at $E_x=5.14, 6.59$ and 7.65 MeV in the $^{14}\text{N}(^{10}\text{B},^8\text{He})^{16}\text{N}$ reaction suggest a $(p_{1/2})^{-2}(d_{5/2})^{2+}$ triplet (Ha78), the strength of $^{16}\text{N}^*(5.15,7.65)$ in the $(^7\text{Li},\alpha)$ reaction indicates an observation of primarily different states in triton transfer. The presence of known doublets at $^{16}\text{N}^*(5.130/5.150,7.637/7.675)$ (Aj77) and the absence of $^{16}\text{N}^*(6.59)$ from the $(^6\text{Li},^3\text{He})$ spectrum support this view. We are left, therefore, with four good candidates for $p^{-3}(sd)^3$ configurations, selected by both triton-transfer reactions (Fig. 9.4) at $^{16}\text{N}^*(5.15,7.65,9.81,11.81)$.

An interpretation of these states of $^{16}\text{N}$ emerges from experimental evidence of the correspondence to better known levels of $^{18}\text{O}$ and $^{15}\text{N}$. Triton clustering outside a spin $1/2^-$ core is expected to lead to a similarity between $^{16}\text{N}$ and $^{18}\text{O}$ (Table 1.1, Fig. 7.5). In addition to known $1^-$ states at 4.387 MeV in $^{16}\text{N}$ and at 4.456 MeV in $^{18}\text{O}$, a $3^-$ state at 5.15 MeV in $^{16}\text{N}$ (Ma78) appears related to $^{18}\text{O}^*(5.098,3^-)$ (Figs. 9.4, 7.4). With respect to excitation energy and relative population in $(^{6}\text{Li},^{3}\text{He})$ and $(^7\text{Li},\alpha)$ data, this tentative correspondence can be extended to $^{16}\text{N}^*(7.65)$ and $^{18}\text{O}^*(7.84,(5^-);8.10,5^-)$ and to $^{16}\text{N}^*(11.81)$ and $^{18}\text{O}^*(11.10,(7^-))$ (Fig. 10.1), where spin values in parentheses are suggested by the SU(3) shell model (Fig. 7.6). A similarity between $^{16}\text{N}$ and
Figure 9.3 $^{13}\text{C}(^7\text{Li},\alpha)^{16}\text{N}$

The energy calibration and contaminant peaks are determined from $^{12}\text{C}(^7\text{Li},\alpha)^{15}\text{N}$ data, also measured at $E_{\text{Li}}=40$ MeV and $\theta_{\text{lab}}=10^\circ$.

Figure 9.4 Comparison

Three-nucleon transfer into the $A=16$ nuclei proceeds via the $(^6\text{Li},t)$, $(^6\text{Li},^3\text{He})$ and $(^7\text{Li},\alpha)$ reactions at similar incident energies. The laboratory angle of $10^\circ$ represents a change from $\theta_{\text{lab}}=15^\circ$ for $A=15, 19, 18$ and 17.
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(1) calibrated from $^{15}$O$^+$\((5.241, 7.276, 10.45, 12.835, 15.05)\)
$\Delta E = \pm 30$ keV

(2) \(\pm (2\% - 6\%)\), statistical
\(~ \pm 10\%, absolute\)

(3) calibrated from $^{15}$N\((5.270, 7.567, 10.693, 13.02, 15.41)\)
$\Delta E = \pm 20$ keV

(4) \(\pm (1\% - 5\%)\), statistical
\(~ \pm 10\%, absolute\)

(5) calibrated from $^{15}$N\((5.270, 8.571, 12.55, 15.40)\)
$\Delta E = \pm 40$ keV

(6) \(\pm (1\% - 5\%)\), statistical
\(~ \pm 20\%, absolute\)
$^{15}$N would arise from weak coupling of a $p_{1/2}$ particle to $3p$-$4h$ states (Table 1.1). Both $^{16}_N(11.81)$ and $^{15}_N(15.41, (13/2^+))$ (Figs. 9.4, 5.4) are within 1 MeV of the triton threshold (Bu76); both $^{16}_N(7.65)$ and $^{15}_N(10.693, 9/2^+)$ have absolute differential cross sections of 1 mb/sr in the ($^6$Li, $^3$He) reaction at $E_{Li}=44$ MeV and $\theta_{lab}=10^\circ$ (Fig. 10.1). As in alpha-cluster structure (Fig. 8.5), a smaller level spacing for the case of a $^{13}$C core is implied by such a comparison of triton-cluster states. In contrast to the $^{13}_C(7_Li,t)^{17}_0$ reaction, however, doublets with 1 MeV splitting are not found in the $^{13}_C(6_Li,^3He)^{16}_N$ reaction, where a $2^-/3^-$ pair at 5.05/5.15 MeV provides the only available evidence of $J^\pi 1/2^-$ doublet structure. An alternative to the above interpretation would associate $^{16}_N(5.13, 7.65)$ with the $5^-$ and $7^-$ states respectively. The present choice of the 7.65 MeV and 11.81 MeV states, however, is more consistent with triton-transfer data for $^{18}_0$ and $^{15}_N$. Further discussion of systematic behavior in $p$-$n$(sd)$^3$ configurations of the A=15 to A=19 nuclei is presented in Section 10.1.

In summary, the ($^6$Li, $^3$He) reaction, together with other transfer reactions into $^{16}_N$, identifies candidates for $p$-$3$(sd)$^3$ configurations at $^{16}_N(5.15, 7.65, 9.81, 11.81)$. The ($^6$Li,t) reaction assigns $T=1$, $T_z=0$ analog structure to $^{16}_0(18.01, 20.49, 22.46, 24.63)$.

9.3 Angular Distributions

For a given final state, an angular distribution is relevant to the reaction mechanism, angular-momentum transfer, spectroscopic factor and analog assignment. A predominantly direct mechanism is consistently indicated by the previous measurements of angular distributions in the ($^6$Li,t) and ($^6$Li, $^3$He) reactions (see Section 3.2). Angular-momentum
transfer into the A=15 nuclei (Bi75) is found to be ambiguous in an analysis of such data. The structureless behavior of these angular distributions, moreover, implies that the forward-angle spectra are sufficient for qualitative information on relative spectroscopic strengths. Although analog assignments can also be deduced from the mirror spectra of Tz=±1/2 nuclei (Figs. 5.4, 6.4, 8.4), the presence of both T=0 and T=1 states in 160 and 18F (Table 1.1) demonstrates a need for further experimental evidence of the correspondence to 16N and 18O respectively. The high level density of 18F (Fig. 7.4a) would hinder an extraction of angular distributions, but the T=1 candidates of 16O remain relatively distinguishable at large angles of observation (Fig. 9.5). In this section, therefore, we investigate angular distributions only in the 13C(6Li,t)16O and 13C(6Li,3He)16N reactions.

A T=1, Tz=0 state of 16O, which is analogous to a Tz=1 state of 16N, should have an angular distribution of similar shape (see Ga72, Bi75) and of reduced magnitude. A change by a factor of 2.1 in cross section is implied by the expression (e.g. Ce64, Ga73)

$$\frac{d\sigma}{d\Omega} \propto k_b |<T,T,T,T,B>B|^2,$$

(9.1)

where the reaction A(a,b)B transfers c=a-b. These two properties are exhibited in Fig. 9.6 by 16N* (7.65) and 16O* (20.49) and by 16N* (11.81) and 16O* (24.63), confirming their analog relationship. Experimental values of 1.7 and 2.1 respectively are obtained for the ratio of the Tz=1 to Tz=0 cross section, averaged over 14°<θc.m.<35°. In contrast to T=0 states at 16O* (8.872, 10.353), the 16.81 MeV state of 16O corresponds closely in angular distribution to the 3.96 MeV state of 16N, as expected from Section 9.1. The comparison of 16N* (5.73, 5+) to both
Figure 9.5  \( \Theta_{\text{lab}} = 45^\circ \)

This \(^{13}\text{C}(^6\text{Li},^3\text{He})^{16}\text{N}\) spectrum is calibrated in energy from the \(^{12}\text{C}(^6\text{Li},^3\text{He})^{15}\text{N}\) reaction at \( \Theta_{\text{lab}} = 45^\circ \). An analogous procedure applies to \(^{13}\text{C}(^6\text{Li},t)^{16}\text{O}\) data for \( E_x > 16 \text{ MeV} \), but low excitation energies are determined from the \(^{12}\text{C}(^6\text{Li},t)^{15}\text{O}\) reaction at \( \Theta_{\text{lab}} = 10^\circ \).

Figure 9.6  Angular distributions

Differential cross sections are plotted for the \(^{13}\text{C}(^6\text{Li},t)^{16}\text{O}\) reaction (open points) and the \(^{13}\text{C}(^6\text{Li},^3\text{He})^{16}\text{N}\) reaction (solid points) at \( E_{\text{Li}} = 44 \text{ MeV} \) and \( \Theta_{\text{lab}} = 10^\circ, 15^\circ, \ldots, 60^\circ \). Since \(^{16}\text{O}^\ast(23.94)\) is obscured by contamination from \(^{15}\text{O}^\ast(12.84)\) at \( 15^\circ < \Theta_{\text{lab}} < 40^\circ \), the angular distribution of \(^{16}\text{N}^\ast(11.21)\) appears without analogous data for \(^{16}\text{O}\) (Fig. 9.4). Points are omitted from the angular distribution of \(^{16}\text{O}^\ast(18.44)\) (Fig. 9.1) at angles where this state is not resolved from \(^{16}\text{O}^\ast(18.61)\) (Fig. 9.5).
members of the 18.44/18.61 MeV doublet in $^{16}$O illustrates a potentially
decisive test of analog assignments. The angular distribution of
$^{16}$O*(18.61), though a little high in magnitude, better approximates the
curve of $^{16}$N data. Overall, for the ($^{6}$Li,t) and ($^{6}$Li,$^3$He) reactions,
the measurement of angular distributions proves to be a worthwhile
source of experimental information on analog states.

A prediction of the compound-nucleus contribution to these angular
distributions provides further support for the conclusion (Section 3.2)
that the two reactions proceed primarily via a direct mechanism. The
Hauser-Feshbach model of a statistical process gives the energy-averaged,
differential cross section by (Fe60, Vo64, St72)

$$
\frac{d\sigma}{d\Omega} = \sum_{L} \frac{1}{4k_{\alpha}^2} \frac{1}{\eta(2I+1)(2i+1)} \left( \sum_{l',s'} T_{l'}^{l} \right) \left( \sum_{c'} \frac{T_{l'}^{c'}_{l}}{T_{l}^{c}} \right) Z(lj'lj; sL) Z(lj'lj; sL) (-1)^{s-s'} P_{L}(\cos \theta_{c.m.}),
$$

(9.2)

where $\alpha$ represents the entrance channel, $\alpha'$ the observed exit channel and
$\alpha''$ any relevant outgoing channel with quantum numbers $c''$. Letting $I$ and
$I'$ be the spin values of the projectile and target, we have $s=I+I'$ and
$j=i+s$. The central quantities are the transmission coefficients $T$, the
$Z$-coefficients (Fe60) and the Legendre polynomials $P_{L}$. Using the code
STATIS (St72), we calculate the formation of a compound nucleus $^{19}$F from
the incoming channel $^{13}$C+$^{6}$Li and treat its decay into six outgoing chan-
nels: $^{13}$C+$^{6}$Li, $^{16}$O+t, $^{18}$F+n, $^{18}$O+p, $^{17}$O+d and $^{15}$N+$\alpha$. Above the known
discrete spectrum of each heavy fragment, the level density is expressed
as (La63, St72)
An effective excitation energy \( U = E_x - b \delta \) determines the nuclear temperature \( T \) via \( U = a t^2 - t \), where \( b \delta \) is the pairing energy and \( a \) is the level density parameter. A spin cut-off is obtained from \( \sigma = \frac{I_r}{\hbar^2} \), where \( I_r \) is the rigid-body moment of inertia.

The resulting compound-nucleus calculation (Fig. 9.7) can largely account for the experimental cross section of \( ^{16}O \otimes (10.353, 4^+) \) in the \(^{6}\text{Li}, t\) reaction (Ba71a). The dominant 4p-4h component of this state (e.g. Co76) is expected to be inaccessible to direct, one-step, three-nucleon transfer. For the 1p-1h state at \( ^{16}O \otimes (8.872) \) (E170), the probable 2p-2h configurations at \( ^{16}O \otimes (16.81, 18.61) \) (Lu69, Section 9.1), and the proposed 3p-3h states at \( ^{16}O \otimes (20.49, 24.63) \) (Section 9.2), the magnitude of each theoretical curve is well below the data points. Even the slopes predicted for \( J^m = 5^- \) and \( 7^- \) are minor relative to the strong forward peaking of measured angular distributions. At forward angles and \( E_{\text{Li}} = 44 \) MeV, therefore, a negligible compound-nucleus contribution is indicated by the Hauser-Feshbach model for the \( ^{13}\text{C}(^{6}\text{Li}, t)^{16}O \) reaction into these five states.

An application of direct reaction theory is relevant both to the confirmation of this result and to the study of angular-momentum transfer. The transition matrix for a direct mechanism (Au70)

\[
T_{\text{direct}}^{\alpha \beta} = \langle \hat{\psi}_{\alpha}^{\gamma_1} \hat{\psi}_{\beta}^{\gamma_2} (r) | \mathbf{V} - U_B | \sum_{\gamma} \hat{\psi}_{\gamma_1} \hat{\psi}_{\gamma_2} (r) \rangle
\]

(9.4)
is calculated in the finite-range, distorted-wave, Born approximation (FRDWBA) from
Although the assumption of $J^m = 5^-, 7^-$ for $^{16}O_{18.61}$ $(20.49, 24.63)$ is highly tentative (Section 9.2), the 18.61 MeV state is a probable analog of $^{16}N_{5^+} (5.73, 5^+)$ (Fig. 9.6), and the 16.81 MeV state is assigned spin $(3^+)$ independently (Ja77). These compound-nucleus calculations are carried out for the $^{13}C(6Li, t)^{16}O$ reaction rather than $^{13}C(6Li, ^3He)^{16}N$, because $^{16}O_{10.353, 4^+}$ provides a check on the overall normalization. The predicted curves reach this upper limit in magnitude when the level density parameter has the value $a=0.152$ (Ha74).

With optical potentials from Table A.1, Ref. Pi74 (#T2) and Ref. Co76, we use the code ABACUS (Au76) to compute transmission coefficients for Eq. 9.2.
where $\alpha$ represents the entrance channel, $\beta$ the exit channel and $\gamma$ any possible outgoing channel. In addition to assuming that terms with $\gamma \neq \alpha$ are negligible, this expression approximates a relative wavefunction $\xi_\alpha$ with the distorted wave $\chi_\alpha^{(+)}$ produced by an optical potential $U_\alpha$. $\psi_{1\alpha}$ and $\psi_{2\alpha}$ are the internal wavefunctions of the projectile and target; $V_{\beta}^{2\alpha}$ is the total nuclear interaction. Although a zero-range interaction is assumed by the code DWUCK (Appendix A), the code PTOLEMY (G176) calculates the full, six-dimensional integral. An initial wavefunction representing the 1s state of $^6\text{Li}+^3\text{He}+t$ is generated by a Woods-Saxon potential having $r_0=1.73$ and $a=0.45$ (Th67, Bi75), where the radius is given by $R=r_0A^{1/3}$ and the depth is fitted to the experimental binding energy. Optical potentials for the entrance channel $^6\text{Li}+^{13}\text{C}$ and the exit channel $^3\text{He}+^{16}\text{N}$ are listed in Table A.1, where the alternate parameter set can be shown to have little effect upon the shape of FRDWBA curves. Predicted angular distributions are more dependent upon the radius parameter of the Woods-Saxon potential which generates a final wavefunction for the bound state of $^{16}\text{N}=^{13}\text{C}+t$. With $a=0.65$, $r_0=1.7$ is the minimum value yielding a good result for $^{16}\text{N}^* (3.96, (3^+))$. Convergence checks were made for other parameters involved in the PTOLEMY code.

These FRDWBA calculations succeed in reproducing the steep slope of experimental angular distributions from the $^{13}\text{C}(^6\text{Li}, ^3\text{He})^{16}\text{N}$ reaction (Fig. 9.8). In view of the failure of the Hauser-Feshbach model to account for such strong forward peaking (Fig. 9.7), this result is clear evidence for a primarily direct mechanism (see also Ga72, Bi75). Data for the $J^m=(3^+)$ state at $^{16}\text{N}^*(3.96)$, moreover, are well described to $\theta_{\text{c.m.}}=45^\circ$.
Figures 9.8a,b Finite-range DWBA calculations

Because of a relative s-state in $^6$Li-$^3$He+$t$, L-transfer in the $^{13}$C($^6$Li,$^3$He)$^{16}$N reaction is equal to the orbital angular momentum of a $^{16}$N+$^{13}$C+$t$ bound state. The number of nodes $N$ in a final-state wavefunction depends upon the configuration of the triton cluster. In Fig. 9.8a, we consider p(sd)$^2$ transfer corresponding to $2N+L=5$, because a 2p-2h configuration characterizes $^{16}$N$^*$($3.96,5.73$) (Lu69) and may also apply to $^{16}$N$^*$($11.21$), which behaves similarly in Fig. 9.4. In Fig. 9.8b, we assume (sd)$^3$ transfer, i.e. $2N+L=6$, for the probable 3p-3h states of $^{16}$N (Section 9.2). Analog states of $^{16}$O (Fig. 9.7) have similar angular distributions in the ($^6$Li,$t$) reaction (Fig. 9.6).
by a L=3 curve from PTOLEMY, which is normalized in magnitude at \( \theta_{\text{c.m.}} = 14^\circ \). A calculation from DWUCK, however, is better able to fit a L=5 curve to the angular distribution measured for the \( 5^+ \) state at \( ^{16}\text{N}^\ast (5.73) \) (see Appendix A). Although L=4, 5 and 6 lead to predictions of similar shape (Fig. 9.8), the \( \theta_{\text{c.m.}} = 14^\circ \) point favors L=4 for \( ^{16}\text{N}^\ast (7.65) \) and the \( \theta_{\text{c.m.}} = 40^\circ \) region favors L=6 for \( ^{16}\text{N}^\ast (11.81) \). When coupled to the spin 1/2\(^+\) of the transferred triton and to the spin 1/2\(^-\) of the \(^{13}\text{C} \) target, these orbital angular momenta would imply \( J^\pi = (3,4,5)^- \) and \( (5,6,7)^- \) for the 7.65 MeV and 11.81 MeV states respectively, in agreement with the interpretation chosen in Section 9.2. The 11.21 MeV state of \(^{16}\text{N} \), where parity is more uncertain, illustrates that transferred angular momenta differing by only one unit (Bi75) are not distinguished by angular distributions in the \((^6\text{Li},^3\text{He}) \) reaction.

A final question concerns the evaluation of spectroscopic factors. The coefficient which normalizes a FRDWBA curve to \(^{13}\text{C}(^6\text{Li},^3\text{He})^{16}\text{N} \) data (Fig. 9.8) represents a product of spectroscopic factors \( S_i (^6\text{Li}=^3\text{He}+t) \times S_f (^{16}\text{N}=^{13}\text{C}+t) \). Using L=3 and L=5 for \( ^{16}\text{N}^\ast (3.96, (3^+); 5.73, 5^+) \) and assuming L=4, 5 and 6 for \( ^{16}\text{N}^\ast (7.65, 11.21, 11.81) \) (Section 9.2), we obtain \( S_i S_f = 0.037, 0.035, 0.073, 0.037 \) and 0.051 respectively. The overall magnitude is reasonable, since \( S_i = S_f \sim 1/4 \) could account for the two largest products. The relative strength is more meaningful, however, since theoretical cross sections are sensitive to the radius parameter of the \( ^{16}\text{N}=^{13}\text{C}+t \) potential. Setting \( S=1 \) for \( ^{16}\text{N}^\ast (7.65) \), we note that \( S_{\text{rel}} = 1/2 \) for \( ^{16}\text{N}^\ast (3.96, 5.73, 11.21) \) favors a common classification of these states, namely as \( 2p-2h \) configurations (Section 9.2). The larger value \( S_{\text{rel}} = 2/3 \) for \( ^{16}\text{N}^\ast (11.81) \) supports an association with \( ^{16}\text{N}^\ast (7.65) \) and \( 3p-3h \) struc-
ture. Approximate spectroscopic information contained in the forward-angle spectrum of $^{16}_N$ (Fig. 9.2), therefore, is qualitatively confirmed by relative spectroscopic factors extracted from the angular distributions.

In summary, although a search for further information on analog structure motivated their measurement, angular distributions from the ($^6$Li, t) and ($^6$Li, $^3$He) reactions on a $^{13}$C target also provide supporting evidence on the reaction mechanism, transferred angular momenta and spectroscopic factors.
CHAPTER 10  Conclusion

In the preceding five chapters, individual discussion of the A=15 to A=19 nuclei entails frequent consideration of pairs differing in mass. We compare, in Section 10.1, experimental results over the entire mass region, as evidence of systematic behavior in three-particle structure. In Section 1.2, a summary of this research focuses on new findings. We integrate, in Section 10.2, the present results with previous information on three-nucleon transfer reactions and cluster structure.

10.1 Systematics

A consistent identification of \((sd)^3\) configurations is obtained from the \((^6\text{Li},^3\text{He})\) reaction on targets having from zero to four holes in the p shell (Fig. 10.1). A coupling of target spin to the total angular momentum \(j=L \otimes l/2\) of the transferred triton (Table 1.1) determines final-state spin values. In the A=15 to A=19 nuclei, corresponding states with \(J^P=5/2^+,3^-,7/2^+,3^-\) and \(5/2^+\) exhibit a spin sequence based on the alignment of angular momenta. Candidates for \(3p\)-nh, \(j=9/2^+\) structure regularly appear with larger cross sections and with excitation energies about 3 MeV higher than those of the \(j=5/2^+\) states (Fig. 10.1). Since the SU(3) shell model predicts a splitting of \(5^-\) strength (Fig. 7.6), two levels at \(^{18}\alpha(7.84;8.10,5^-)\) are associated with the \(9/2^+\) state of \(^{19}\text{F}\). The level at \(^{17}\alpha(10.70)\) is equal in excitation to the \(9/2^+\) state of \(^{15}\text{N}\), while the peak at \(^{16}\alpha(7.65)\) is similar in cross section to the pair in \(^{18}\alpha\). Reflecting the angular-momentum mismatch \(\Delta L=6\) of the \((^6\text{Li},^3\text{He})\) reaction, the most strongly populated states of positive parity in \(^{19}\text{F}\) have spin \(13/2^+\). A corresponding \(p^-\alpha\)(sd)^3_5/2+ configuration is probable.
The \((^6\text{Li},^3\text{He})\) reaction on targets of \(^{12}\text{C},^{13}\text{C},^{14}\text{N},^{15}\text{N}\) and \(^{16}\text{O}\) selects final states of the \(A=15\) to \(A=19\) nuclei. These data are measured at similar energies of \(E_{\text{Li}}=40,44,46,40,46\) MeV respectively and at the same angle of \(\theta_{\text{lab}}=15^\circ\). As reference points for relative \(Q\)-values, contaminant peaks arise from the \(^1\text{H} (^6\text{Li},^3\text{He})^4\text{He(g.s.)}\) reaction. Excitation energies and known spin values are given for probable \(p^{-}\text{N}(sd)^3_j\) configurations with \(j=5/2^+,9/2^+\) and \(13/2^+\). The candidates for \(j=9/2^+\) structure are lined up. Table 9.1 analyzes the broad peak at \(^{16}\text{N}^\star (5.15)\); Section 5.3 interprets the two \(5/2^+\) states at \(^{15}\text{N}^\star (5.270,9.155)\). Information on the unlabelled peaks is contained in Figs. 5.2-9.2 and Tables 5.1-9.1.
for the major states at $^{18}O^+(11.10)$, $^{17}O^+(14.89)$, $^{16}N^+(11.81)$ and $^{15}N^+(15.41)$. Shell-model calculations for $^{15}N$ and $^{18}O$ (An74, Fig. 7.6) support this interpretation and predict a second $13/2^+\otimes 1/2^-=7^-$ state of $^{18}O$ near 15 MeV. The separation of $^{19}F^+(10.41,13/2^+)$ from the first $j=13/2^+$ state is well reproduced by $^{18}O^+(15.95)$ and $^{17}O^+(20.2)$, although the 14.61 MeV level of $^{18}O$ is another candidate. Through a tentative but nearly one-to-one correspondence between aligned angular-momentum couplings, therefore, triton-transfer spectra reveal common structure in the A=15 to A=19 nuclei, based on $p^-n(sd)^3$ configurations with $j=5/2^+$, $9/2^+$ and $13/2^+$.

This conclusion is supported by evidence of a consistent trend in triton binding energies (Fig. 10.2). For the above three-particle structure (Fig. 10.1), the increase in binding with mass is continuous, except at $^{17}O^+(10.70)$. The $^{17}O$ levels are expected to have relatively low energy, because the higher spin $\sigma_2=1^+$ of an unexcited $^{14}N$ core implies stronger $j^+\sigma_2$ interaction with an aligned triton cluster (see Fig. 4.2). From $^{15}N$ to $^{19}F$, the increase in moment of inertia is characterized by a gradual level compression for $j=9/2^+$ and $13/2^+$. This trend is not observable in the $5/2^+-9/2^+$ level spacing, where two mixing effects are relevant. Admixture of $3p$-nh structure into single-particle excitations at $^{15}N^*(5.270,5/2^+)$ and $^{16}N^*(0.297,3^-)$ (e.g. Li70) is expected to lower the $p^-n(sd)^3$ centroid below the points plotted at $^{15}N^*(9.155,5/2^+)$ and $^{16}N^*(5.15,3^-)$. In $^{17}O=^{14}N+t$, moreover, the relative position of the $5/2^+\otimes 1^+=7/2^+$ coupling could be influenced by mixing with $9/2^+\otimes 1^+$ structure. Allowing for such complications, we conclude that triton binding energies exhibit reasonably smooth behavior in the A=15 to A=19 nuclei.
Figure 10.2 Binding energies

\[ E_{\text{c.m.}} = E - E_{\text{threshold}} \] is plotted versus \( A_{\text{target}} \) for deuteron (d), triton (t) and alpha (a) transfer. The \((a,d), (^6Li,^3He)\) and \((^7Li,t)\) reactions identify candidates for \(p^-(sd)^n\) configurations, where \(n=0\) to \(4\) and \(n'=2\) (dotted lines), \(3\) (solid) and \(4\) (dashed). Given the angular momentum and parity \(j^\pi\) of a transferred cluster, coupling to the spin \(1/2^-\) of \(^{13}C\) and \(^{15}N\) or to the spin \(1^+\) of a \(^{14}N\) target occurs in final states. Table 10.1 lists the excitation energies and spin assignments of levels selected for this figure. In two-particle structure, only aligned angular-momentum couplings are shown for \(^{16}_0=^{14}N+d\) and \(^{17}_0=^{15}N+d\) since, for example, ambiguity arises from the population of both \(^{17}_0^*(5.215, (9/2^-); 9.15, 9/2^-)\) by the \((a,d)\) reaction (Lu69). In three-particle structure, only the known \(5^-\) state is plotted for \(^{18}_0=^{15}N+t\), although model predictions suggest spin \(5^-\) and \(4^-\) for \(^{18}_0^*(7.84, 8.47)\) respectively (Fig. 7.6). We do not include the candidates for a second \(j=13/2^+\) configuration (Fig. 10.1). In four-particle structure, the \(2^+1/2^-\) states of \(^{17}O=^{13}C+\alpha\) are omitted because of strong mixing (see Le72). Only couplings to spin \(j\) are shown for \(^{18}F=^{14}N+\alpha; j=8^+\) states are unknown in \(^{18}F\) and \(^{19}F\).
TABLE 10.1 $p^{-n}(sd)^n$ Candidates

<table>
<thead>
<tr>
<th>Threshold</th>
<th>$L=2$</th>
<th>$L=4$</th>
<th>$L=6$</th>
<th>$L=8$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{12}\text{C}+d=^{14}N$ (10.272)</td>
<td>6.444,3$^+$</td>
<td>8.961,5$^+$</td>
<td></td>
<td></td>
<td>Ri66</td>
</tr>
<tr>
<td>$^{13}\text{C}+d=^{15}N$ (16.160)</td>
<td>9.829,7/$^2$;...</td>
<td>11.95,9/$^2$;13.00,11/$^2$;</td>
<td></td>
<td></td>
<td>Lu69</td>
</tr>
<tr>
<td>$^{14}\text{N}+d=^{16}O$ (20.737)</td>
<td>11.095,4$^+$;...</td>
<td>14.815,6$^+$;...</td>
<td></td>
<td></td>
<td>Zi70</td>
</tr>
<tr>
<td>$^{15}\text{N}+d=^{17}O$ (14.049)</td>
<td>5.698,7/$^2$;...</td>
<td>7.75,11/$^2$;...</td>
<td></td>
<td></td>
<td>Lu69</td>
</tr>
<tr>
<td>$^{16}\text{O}+d=^{18}F$ (7.526)</td>
<td>0.937,3$^+$</td>
<td>1.121,5$^+$</td>
<td></td>
<td></td>
<td>Ma68</td>
</tr>
<tr>
<td>$^{12}\text{C}+t=^{15}N$ (14.848)</td>
<td>9.155,5/$^2$;...</td>
<td>10.693,9/$^2$;...</td>
<td>15.41,(13/$^2$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{13}\text{C}+t=^{16}N$ (12.394)</td>
<td>5.15,3$^-$;...</td>
<td>7.65;...</td>
<td>11.81;...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{14}\text{N}+t=^{17}O$ (18.625)</td>
<td>8.474,7/$^2$;...</td>
<td>10.70;...</td>
<td>14.89;...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{15}\text{N}+t=^{18}O$ (15.834)</td>
<td>5.098,3$^-$;...</td>
<td>8.10,5$^-$;...</td>
<td>11.10;...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{16}\text{O}+t=^{19}F$ (11.700)</td>
<td>0.197,5/$^2$;...</td>
<td>2.780,9/$^2$;...</td>
<td>4.647,13/$^2$;...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{12}\text{C}+\alpha=^{16}O$ (7.162)</td>
<td>6.917,2$^+$</td>
<td>10.353,4$^+$</td>
<td>16.29,6$^+$</td>
<td>22.5,(8$^-$)</td>
<td>Sa77</td>
</tr>
<tr>
<td>$^{13}\text{C}+\alpha=^{17}O$ (6.361)</td>
<td>...</td>
<td>8.972,7/$^2$;9.87</td>
<td>12.41;13.55</td>
<td>18.15;19.24</td>
<td>Fig. 8.5</td>
</tr>
<tr>
<td>$^{14}\text{N}+\alpha=^{18}F$ (4.416)</td>
<td>2.523,2$^+$;...</td>
<td>5.298,4$^+$;...</td>
<td>9.58,(6$^+$);...</td>
<td>...</td>
<td>Co77</td>
</tr>
<tr>
<td>$^{15}\text{N}+\alpha=^{19}F$ (4.014)</td>
<td>1.346,5/$^2$;1.459,3/$^2$;</td>
<td>3.999,7/$^2$;4.032,9/$^2$</td>
<td>8.288,13/$^2$;8.953,11/$^2$;</td>
<td>...</td>
<td>Fig. 6.3</td>
</tr>
<tr>
<td>$^{16}\text{O}+\alpha=^{20}\text{Ne}$ (4.731)</td>
<td>1.634,2$^+$</td>
<td>4.247,4$^+$</td>
<td>8.776,6$^+$</td>
<td>11.95,8$^+$</td>
<td>Co76</td>
</tr>
</tbody>
</table>

Aj76,77,78
A lack of complete spin information and multiplet identification, however, makes the systematic behavior of three-particle structure a tentative result, inviting comparison with the better known phenomena of two- and four-particle structure. Moreover, \( (d_{5/2})^2 \) deuteron binding supplies a trend free from dependence upon the subshell configuration, and alpha-particle clustering offers a case free from spin-spin interaction with the core. Reflecting these simplifications, \( j=5^+ \) states of 2p-nh character (Lu69) and \( j=6^+ \) states of 4p-nh character exemplify a smooth increase in binding energy as a function of mass (Fig. 10.2).

We find a similarity in overall slope for \( j=13/2^+ \) and \( j=8^+ \) and for \( j=9/2^+ \) and \( j=5^+ \). Although level spacing is rather irregular in the probable \( p^n(sd)^2 \) configurations, the 2N+L=8 band demonstrates a nearly monotonic increase in moment of inertia. Limited evidence exists on the nature of multiplet structure. For a \(^{13}\text{C}\) target of spin \( 1/2^- \), dual peaks with 1 MeV splitting are observed in deuteron and alpha-particle transfer (Lu69, Fig. 8.4c) but not in triton transfer (Fig. 9.2). For a \(^{14}\text{N}\) target of spin \( 1^+ \), a triplet appears in 2p-2h states at \(^{16}\text{O}^+ (14.40; 14.82, 6^+ ; 16.24)\) (Zi70) but stronger coupling characterizes a 4p-2h band in \(^{18}\text{F}\) (Ro73b). Indications of weak coupling in \(^{18}O=^{15}\text{N}+t\) (Fig. 7.5) are supported by the presence of narrow doublets in \(^{19}\text{F}^{15}\text{N}+\alpha\) (Fig. 6.5).

Overall, greater knowledge of two- and four-particle structure provides a standard for trends in three-particle structure. The \( p^n(sd)^3 \) configurations of Fig. 10.1 show fundamental consistency with this broader context.

Other configurations also play a role in the \((^6\text{Li}, ^3\text{He})\) reaction (Fig. 10.3). A strong population of the \( 7/2^- \) and \( 11/2^- \) states of \(^{15}\text{N}\) is attributed in the shell model to their large spectroscopic factors for a
Figure 10.3 Relation to other transfer reactions

Triton-transfer spectra from the ($^6$Li,$^3$He) reaction are re-labelled in this figure but are still aligned as in Fig. 10.1, where additional details are given. Comparison with the ($\alpha$,d) reaction (Lu69) distinguishes peaks arising from p$^-n$(sd)$^2$ configurations of known spin in $^{15}$N, $^{16}$N and $^{17}$O. $^{18}O^*$($3.555,4^+$) dominates a ($\alpha,^2$He) spectrum (Ja76). Comparison with the ($^7$Li,t) reaction identifies mixing into p$^-n$(sd)$^4$ configurations at high excitation in $^{19}$F (Fig. 6.3), $^{18}$O (Mo70b) and $^{17}$O (Fig. 8.3). $^{18}O^*$($7.117,4^+$) may correspond to $^{16}N^*(11.21)$. 
p(sd)\(^2\) triton cluster (An74). For corresponding two-particle multi-hole configurations in \(^{16}\text{N}, {17}\text{O}\) and \(^{18}\text{O}\), a trend exists toward smaller cross section and lower excitation energy, relative to 3p-nh states, as progressively fewer p-shell holes are present in the target. Substantial (sd)\(^2\) but larger p\(^{-2}\)(sd)\(^4\) components are predicted (E170) in the second 4\(^+\) state of \(^{18}\text{O}\). There is a possible link between this 7.117 MeV state of \(^{18}\text{O}\) and the 11.21 MeV state of \(^{16}\text{N}\), because both levels lie about 1 MeV above the alpha-particle threshold and have little cross section in the (\(^7\text{Li},\alpha\)) reaction (Figs. 7.3, 9.3). Both alpha-particle and triton transfer data contain large peaks at \(^{19}\text{F}\/entities/upsilon^\pi(8.953,11/2^\pm\)) (Fig. 6.4), which are interpreted in the shell model as a case of mixing between p\(^{-1}\)(sd)\(^4\) and (sd)\(^2\)fp configurations (Mi77). Since corresponding (sd)\(^4\)\(^\pi\)\(^6\) structure is found at \(^{18}\text{O}\/entities/upsilon^\pi(11.69,6^+\)) (Mo70) and tentatively at \(^{17}\text{O}\/entities/upsilon^\pi(13.55\)) (Fig. 8.3), the prominence of these states in (\(^6\text{Li},\text{^3He}\)) spectra (Fig. 10.3) reflects consistent admixture with [(sd)\(^2\)fp]\(^{11/2}\) structure. In relation to different multi-nucleon transfer reactions, therefore, p(sd)\(^2\) and (sd)\(^2\)fp triton transfer into the A=15 to A=19 nuclei also has systematic features.

10.2 Summary

We conclude with an overview of the investigation into three-nucleon transfer reactions and cluster structure for light nuclei. In the previous work of others and in the present research, there is a consistent indication that the (\(^6\text{Li},t\)) and (\(^6\text{Li},\text{^3He}\)) reactions proceed via a predominantly direct mechanism. This result applies at least to final states strongly populated at \(E_{\text{Li}}\geq 40\) MeV and \(\theta_{\text{lab}}\leq 15^\circ\). Diverse supporting evidence is found in excitation functions, angular distributions and
forward-angle spectra. For incident energies varied in fine steps or over a wide range, the energy dependence of cross sections is essentially featureless. Strongly forward-peaked angular distributions are adequately described by DWBA calculations but not by the Hauser-Feshbach model. From the relative population of final states at $\theta_{\text{lab}}=15^\circ$, selectivity within the class of high-spin states can be documented experimentally. Theoretical evidence on the origin of this structural selectivity suggests that cluster transfer plays an influential role in the reaction mechanism.

The $(^6\text{Li},^3\text{He})$ reaction therefore leads to an identification of probable $3p$-$nh$ configurations in the $A=15$ to $A=19$ nuclei. Its relationship to the $(^6\text{Li},t)$ reaction allows an assignment of analog states, especially in the mirror spectra for $T_z=\pm 1/2$ nuclei. Although $T=1,T_z=0$ states of $^{18}\text{F}$ are difficult to distinguish from the $T=0$ levels, dominant states at high excitation in $^{13}\text{C}(^6\text{Li},t)^{16}\text{O}$ data show a clear correspondence to the $T=1$ spectrum of $^{13}\text{C}(^6\text{Li},^3\text{He})^{16}\text{N}$. Comparison with other three-nucleon transfer reactions demonstrates an underlying consistency in structural selectivity and a useful variety of dynamic effects. Whereas the $(\alpha,p)$ and $(^{10}\text{B},^7\text{Be})$ reactions surpass the $(^6\text{Li},^3\text{He})$ reaction in high-spin enhancement, the well-matched $(^7\text{Li},\alpha)$ reaction populates additional levels of lower spin at high excitation energies. The contrast to two- and four-nucleon transfer data provides a check on candidates for $3p$-$nh$ structure. While the $(\alpha,d)$ reaction identifies $2p$-$(n-1)h$ states, the $(^7\text{Li},t)$ reaction indicates admixture into $4p$-$(n+1)h$ states. The largely $p^{-n}(sd)^3$ configurations proposed from the above comparisons exhibit systematic behavior with respect to angular-momentum coupling
An application of specialized nuclear models to \((^6\text{Li}, ^3\text{He})\) data reflects the important influence of triton-cluster structure in this mass region. As a first approximation in a macroscopic approach, the folded-potential model of triton-cluster states makes limited but significant predictions. Good agreement between theoretical excitation energies for the \((\text{sd})^3\) configuration of \(^{16}\text{O}+\text{t}\) and known experimental levels in the ground-state band of \(^{19}\text{F}\) constitutes evidence of triton clustering outside a closed-shell core. An approximate correspondence of predicted \(2N+L=6\) structure to triton-transfer spectra reveals weak-coupling effects in \(^{18}\text{O}\) and \(J^\pi=7/2^+\) candidates in \(^{15}\text{N}\). As a higher-order calculation from a microscopic approach, the SU(3) shell model provides a more rigorous interpretation of experimental results. A correlation between predicted triton spectroscopic factors and measured \((^6\text{Li}, ^3\text{He})\) cross sections leads to suggested spin values in \(^{18}\text{O}\). Despite the detailed splitting of spectroscopic strength, the SU(3) shell model confirms the general outline of triton-cluster structure given by the folded-potential model.

Through experiment and theory, therefore, particle-hole configurations and clustering phenomena emerge as relatively simple features common to the structure of light nuclei.
In Section 9.3, we discuss the distorted-wave, Born approximation and present a finite-range prediction of angular distributions for the $^{13}C(^6Li,^3He)^{16}N$ reaction (Fig. 9.8). We investigate here the adequacy of a zero-range interaction, which reduces the calculation to a three-dimensional integral over \( \hat{r}_\beta = (M_{2\alpha,2\beta}) \hat{r}_\alpha \) (Eq. 9.5). The assumption $\hat{r}(^6Li) = \hat{r}(^3He) = \hat{r}(t)$ neglects internal structure but may approximate a relative s-state of the projectile (Au70).

Because of a high sensitivity to adjustable parameters (Ga72), zero-range calculations via the code DWUCK (Ku69) require substantial normalization to the $^{13}C(^6Li,^3He)^{16}N$ data of Fig. A.1a. The resulting predictions of Fig. A.1b favor $L=6$ over $L=4$ for $^{16}N_1^\ast$ (11.81) but appear inconclusive for $^{16}N_0^\ast$ (7.65). These theoretical angular distributions show a qualitative similarity to finite-range results (Fig. A.2). Although the zero-range assumption leads to more structured curves, it can partially absorb finite-range effects through an increase in the radius parameter of the final-state potential. ZRDWBA allows a better fit to the data for $^{16}N_0^\ast$ (5.73); FRDWBA better reproduces the experimental angular distribution of $^{16}N_0^\ast$ (7.65). For the ($^6Li,^3He$) reaction, therefore, a zero-range interaction proves to be a reasonable approximation in DWBA calculations.

Appendix A ZRDWBA
Figures A.1a,b  Zero-range DWBA calculations

The values of N and L for final states in the $^{13}$C($^{6}$Li,$^{3}$He)$^{16}$N reaction are explained in the caption to Fig. 9.8. The optical potentials are listed in Table A.1, where alternate parameters from Refs. Sc73 and Ga73 lead to poor fits for the $5^+$ state at 5.73 MeV and the $(3^+)$ state at 3.96 MeV respectively. In order to reduce the amplitude of oscillation in a L=5 or L=6 curve for the high-spin state at 11.21 MeV (Section 9.2), a large value of the radius parameter $r_0^=$ 2.2 is chosen for the Woods-Saxon potential generating a $^{16}$N=$^{13}$C+t bound state.

Figure A.2  Comparison of zero-range to finite-range predictions

Theoretical curves from Fig. A.1 are plotted with corresponding results from Fig. 9.8. Although optical potentials are the same, different radius parameters of $r_0^=$ 2.2 and $r_0^=$ 1.7 are used in the respective calculations. In addition to L=3 and L=5 for $^{16}$N$^<(3.96,(3^+);5.73,5^+)$, we consider L=4 and L=6 for $^{16}$N$^<(7.65,11.81)$ (Section 9.2).
### TABLE A.1  OPTICAL POTENTIALS

\[
V(r) = -V_f f(r) - i V_f f(r) + V_c(r), \text{ where } f(r) = \left[ 1 + \exp \left( \frac{r - r_0 A^{1/3}}{a} \right) \right]^{-1}
\]

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<th>(V_r)</th>
<th>(r_0r)</th>
<th>(a_r)</th>
<th>(V_i)</th>
<th>(r_{0i})</th>
<th>(a_i)</th>
<th>(r_{0c})</th>
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<td>(^6)Li</td>
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<td>0.50</td>
<td>6.5 + 0.177E</td>
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**Alternate**

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Three-nucleon transfer data from targets of $^{17}\text{O}$ and $^{18}\text{O}$ lie beyond the scope of a search for $p^{-n}(sd)^3$ configurations. Three-nucleon clustering in the $A=20$ and $A=21$ nuclei, moreover, is expected to be reduced when valence neutrons of the target interact with transferred nucleons in the sd shell. An identification of $(fp)^3$ transfer, however, is relevant to the classification of highly excited states in $^{20}\text{Ne}$. The coupling of a $d_{5/2}$ neutron to states of $^{19}\text{F}$ is involved in $^{20}\text{F}$; little-known $T_z=3/2$ structure is presented in $^{21}\text{F}$.

The $^{17}\text{O}(^6\text{Li},t)^{20}\text{Ne}$ reaction (Fig. B.1) largely populates $T=0$ configurations with two protons and two neutrons outside a closed p shell. Such states of an even-even, 4N nucleus are favorable to alpha-particle clustering. Identification of alpha-cluster states in the $^{16}\text{O}(^7\text{Li},t)^{20}\text{Ne}$ reaction (Co76, see Fig. 6.5) is complemented by recent spin assignments from a $^{16}\text{O}(^{12}\text{C},^{8}\text{Be})^{20}\text{Ne}^*(\alpha)^{16}\text{O}(\text{g.s.})$ correlation study (Sa77), which summarizes the band structure of $^{20}\text{Ne}$. In three-nucleon transfer data, sizeable peaks occur for high-spin members of the $0^+_1$ ground-state band, including a $8^+$ state absent from the $(^7\text{Li},t)$ reaction (Va73). Although the $(^6\text{Li},t)$ reaction also selects a $0^-_1$ band beginning at $^{20}\text{Ne}^*(5.784,1^-)$ (Fig. B.1), the relative strength of this band is greater in alpha-particle transfer data, e.g. at $^{20}\text{Ne}^*(15.34,7^-)$ (Fig. 6.5). The consistent presence of such alpha-cluster structure in a $^{17}\text{O}(^6\text{Li},t)^{20}\text{Ne}$ spectrum reflects strong binding of the target neutron to the transferred $^3\text{He}$. Since this effect should be weaker in a $(sd)(fp)^3$ configuration, we investigate negative-parity states at high excitation. The $9^-$ state at 21.09 MeV is dominant in $^3\text{He}$ transfer but not in alpha-particle
Excitation energies and contaminant peaks in the $^{20}\text{Ne}$ spectrum are determined from the $^{16}\text{O}(^{6}\text{Li},t)^{19}\text{Ne}$ reaction. Since $^{19}\text{Ne}^*(0.238)$ is equivalent to $^{20}\text{Ne}^*(13.0)$ in Q-value, known energy levels (Aj78) are substituted below 8 MeV in excitation. Triton transfer into $^{20}\text{F}$ shows analogous contamination from the $^{16}\text{O}(^{6}\text{Li},^{3}\text{He})^{19}\text{F}$ reaction, but data for $^{21}\text{F}$ reflect only hydrogen impurity in the target. Additional excitation energies are listed in Table B.1; spin assignments are from Refs. Aj78, En73. $^{20}\text{Ne}^*(21.09)$, $^{20}\text{F}^*(9.90)$ and $^{21}\text{F}^*(8.79)$ have $d\sigma/d\Omega_{\text{c.m.}}=100\ \mu\text{b/sr}$. 

Figure B.1 $^{17}\text{O}(^{6}\text{Li},t)^{20}\text{Ne}$

Figure B.2 $^{17}\text{O}(^{6}\text{Li},^{3}\text{He})^{20}\text{F}$

Figure B.3 $^{18}\text{O}(^{6}\text{Li},^{3}\text{He})^{21}\text{F}$
$^{17}\text{O}(^{6}\text{Li},^{3}\text{He})^{20}\text{F}$

$E_{\text{Li}} = 46$ MeV

$\theta_{\text{Lab}} = 15^\circ$
TABLE B.1  \( A = 20, 21 \)

\[
\begin{array}{l}
\begin{array}{ll}
17^6\text{Li, } 3^7\text{He} & 20^8\text{F} \\
18^6\text{Li, } 3^7\text{He} & 21^8\text{F}
\end{array}
\end{array}
\]

\( E_{\text{Li}} = 46 \text{ MeV} \)

\( \theta_{\text{lab}} = 15^\circ \)

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\(^{(1)}\) calibrated from \( ^{19}\text{F} \) (0.197, 2.780, 4.648, 6.925, 8.953, 10.411)

\( \Delta E = \pm 20 \text{ keV}, 2 \text{ MeV} < E_x < 14 \text{ MeV} \)

\( \pm 40 \text{ keV}, E_x < 2 \text{ MeV}, E_x > 14 \text{ MeV} \)
transfer. Together with a relative enhancement of $^{20}\text{Ne}^*(16.62,7^-)$ in the former reaction, this observation supports a classification of the two states within a $0^+$ band (Sa77) and suggests an existence of large (sd)(fp)$^3$ components. Moreover, the minor role of $^{20}\text{Ne}^*(12.59,6^+; 17.30,8^+)$ in the ($^6\text{Li},t$) reaction is consistent with a consideration of (fp)$^4$ structure (Sa77).

The $^{170}(^6\text{Li},^3\text{He})^{20}\text{F}$ reaction (Fig. B.2) strongly populates a $T=1$ state at 9.90 MeV. As a candidate for the $T_z=0$ analog state, $^{20}\text{Ne}^*(19.9)$ approximates the separation which $^{20}\text{Ne}^*(10.272,2^+,T=1)$ establishes from $^{20}\text{F}(\text{g.s.},2^+)$ (Aj78), and it satisfies a criterion that the cross section be one-half the $T_z=1$ value (Section 9.3). On the basis of excitation energies, peaks at $^{20}\text{Ne}^*(14.81,15.92)$ may also correspond in part to $^{20}\text{F}^*(4.54,5.37)$. The first two states of $^{20}\text{F}$, known to have $J^\pi=2^+$ and $3^+$ respectively, could arise from the coupling of a $d_{5/2}$ neutron to the $1/2^+$ ground state of $^{19}\text{F}$. Although $^{19}\text{F}^*(0.197,5/2^+)$ could similarly account for the $4^+$ and $5^+$ states of $^{20}\text{F}$ (Fig. B.2), the monotonic sequence of spins suggests strong coupling. The first two states of $^{21}\text{F}$, with $J^\pi=5/2^+$ and $1/2^+$, also appear related to the above states of $^{19}\text{F}$. Since levels of $^{21}\text{F}$ are known only below 6 MeV in excitation (En73), the ($^6\text{Li},^3\text{He}$) reaction identifies new states of this $T_z=3/2$ nucleus, notably at 8.79 MeV and 12.71 MeV. Owing to small absolute cross sections and unknown spin values in $^{20}\text{F}$ and $^{21}\text{F}$, the interpretation of triton-transfer data from $^{170}$ and $^{180}$ targets is a matter for the future.
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