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MASTER

COMPLEX SINGLE-NUCLEON STRIPPING

AND PICKUP REACTIONS $[(\alpha, t), (d, \text{He}^3), \text{etc.}]^*$

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The subject of my talk is the study of nuclear spectroscopy with the less common single-nucleon stripping reactions (He^3, d) , (α, t) , and (α, He^3) , and the inverse pickup reactions. These are the analogs of the (d, n) and (d, p) reactions and their inverses, but there are special features which sometimes make them more attractive than the simpler reactions. For example, the (He^3, d) and (α, t) reactions transfer a proton to the target nucleus, as does the (d, n) reaction, but involve an outgoing charged particle, with the associated ease and efficiency of detection and energy resolution capability. As another example, the study of the (He^3, α) reaction may in some cases be preferable to that of the (p, d) or (d, t) reactions because of its much higher reaction Q (18.3 MeV and 14.3 MeV higher, respectively). A similar argument holds for the (t, α) reaction versus the (n, d) reaction.

Let me illustrate a few of the more recent applications of some of these reactions to level structure studies. Fisher and Whaling,¹ at the California Institute of Technology, have investigated the level structure of B^9 by observing the (He^3, α) reaction on B^{10} . Using a 10-MeV He^3 beam, they were able to search from zero excitation to

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17 MeV. They located one new B^9 state at 11.62 MeV. Clayton,² also at the California Institute of Technology, investigated the level structure of N^{14} in the 4-8 MeV range of excitation by means of the (He^3, α) reaction on N^{15} , taking advantage of the 9.7-MeV Q of this reaction. In this case the He^3 beam energy was about 3 MeV. Of particular interest was the possible existence of a level near 7.6 MeV of excitation, since such a state could serve as a resonance for the $C^{13}(p, \gamma)N^{14}$ reaction for low-energy protons. Such a resonance is of interest to cosmologists, since the rate of this (p, γ) reaction is instrumental in determining the amount of C^{13} that can persist in stellar interiors. No such level was found from the (He^3, α) reaction, and the conclusion could then be drawn that the so-called "CNO" cycle adequately explains the observed C^{12}/C^{13} abundance ratio in stars.

Taylor,³ at Manchester, has compared the spectra of Ar^{38} and K^{38} , obtaining the level positions by observing the $K^{39}(t, \alpha)Ar^{38}$ and $Ca^{40}(d, \alpha)K^{38}$ reactions. He made $T = 1$ assignments to states of K^{38} on the basis of low cross sections from the (d, α) reaction and the positions of these states relative to the low-lying ($T = 1$) states in Ar^{38} .

Hinds, Marchant, and Middleton⁴ at Aldermaston have investigated the energy levels of several of the light-to-medium mass nuclei by means of one or more of the reactions under discussion. An example of the kind of results they have achieved is shown in Table I. Note that the high Q of the (t, α) reaction allows an additional 2 MeV of excitation to be studied, at which point the level density becomes too great for suitable analysis. In another experiment, Hinds and Middleton⁵ have

located a previously undetected state in C^{11} , at 6.345 MeV, by means of the (He^3, d) reaction on B^{10} . This state had been the subject of several searches via the (d, n) reaction. (It had been obscured by a strong transition to the 6.476-MeV level.)

When one examines the mechanism by which these reactions proceed, the situation for low-mass targets and low bombarding energies is somewhat confused. It seems likely that in at least some cases clustering effects in the nuclei are important, and the reactions may proceed by knockon and heavy-particle stripping.⁶ However, at higher energies, say, above 5 or 6 MeV, and for heavier nuclei, say, above Ne, the dominant mechanism should be one of simple stripping or pickup. It is mainly to a discussion of these cases that I shall confine the remainder of my talk.

Although distorted-waves (DW) calculations are being used in increasing frequency in the analysis of stripping and pickup reactions, there are many laboratory groups who still analyze their data by means of the plane-wave (Butler) calculation, most often because they do not have ready access to a large computer or to a friend who does. In addition, there is frequently insufficient information on the optical-model parameters used in the DW calculation. This gap, however, is rapidly being filled. There is also the criticism that an optical-model calculation lacks validity for the lighter nuclei. In principle, it should be possible to analyze the reactions under discussion by means of a plane-wave calculation and extract information of the same quality as has been obtained in the past for (d, p) and (d, t) reactions. However, even for (d, p) and (d, t) reactions the results are often conflicting, and in the more complicated reactions there are additional

difficulties. I shall discuss some of these difficulties, but I would first like to say that I would advise trying to get either a computer or a friend.

I shall first consider the possible application of a plane-wave analysis to the (d, He^3) pickup reaction; the extension to the other reactions will be obvious. One would like to obtain a normalization factor between the (d, He^3) reaction and the corresponding (n, d) reaction in order to extract spectroscopic factors from the angular distributions. This is done for the (d, t) and (p, d) reactions and their inverses, and an average normalization value of $\Lambda \approx 200$, in the notation of Macfarlane and French,⁷ is obtained. There is, however, a great amount of scatter; individual cases often vary by a factor of 2 or more from this value.^{7,8} One should not expect to use the value $\Lambda \approx 200$ for (d, He^3) reactions, largely because of the difference in the Coulomb field. Indeed, the normalization factor for this reaction is in many cases four or five times lower than for the (d, t) reaction; there is presently insufficient information to allow the establishment of a preferred value.

Also, because the classical Coulomb barrier is twice as high for the outgoing He^3 particle as for an outgoing singly-charged particle of the same energy, the cross section for a (d, He^3) reaction will begin to drop off at a higher energy than that for a (d, t) reaction on the same nucleus. A few MeV below the Coulomb barrier the cross section may be quite small. For example, Cujec⁹ found that it was not possible to observe the $\text{Zr}^{90}(d, \text{He}^3)\text{Y}^{89}$ reaction at a deuteron energy of 14 MeV. From the inverse of this reaction, to be discussed later, the ground

state transition is known to be strong, but in Cujec's experiment the ground-state He^3 particles emerged with an energy approximately 5 MeV below the Coulomb barrier. The study of Williams and Irvine¹⁰ of the excitation functions for the (d, He^3) reaction on Ar^{40} and Zn^{68} provides another example. At the high-energy end of the excitation functions, the maximum energy available for the He^3 particle was about equal to the classical Coulomb barrier height. (See Fig. 1.) As the incoming deuteron energy was lowered, the cross section fell, and had dropped two orders of magnitude in 4 MeV. In all these cases, the deuteron energy was well above the barrier.

The importance of the Coulomb barrier has sometimes been ignored. Table II shows the results of some (n, d) and (d, He^3) reaction studies on Al^{27} . Note that to all three states of Mg^{26} the orbital angular momentum transfer is $\ell = 2$. In the last three columns of the table are shown ratios of spectroscopic factors for the excited-state transitions relative to the ground-state transition. The results in the fourth column are from a plane-wave analysis of a 14-MeV (n, d) study, those in the fifth column are from a plane-wave analysis of a 12.8-MeV (d, He^3) study, and those in the final column are from a DW analysis of a 15-MeV (d, He^3) study. For the (d, He^3) reaction to the 2.97-MeV state, the value from the plane-wave analysis is only half that obtained from the DW analysis. It seems reasonable to attribute the difference mainly to the fact that the Coulomb barrier for the outgoing He^3 particle is about 8 MeV, which is about 1 MeV higher than the actual energy of the He^3 particle from this level in the 12.8-MeV experiment.

A further difficulty with plane-wave analyses appears in studies of the (He^3, α) and (t, α) reactions or their inverses. It has been shown that for these reactions which involve an incoming or outgoing alpha particle, the cross sections for transitions in which the orbital angular momentum is changed by three or four units are enhanced over those for which $\ell = 0$ or 1,^{11,12,13} in contrast to the behavior of the simple reactions such as (d, p) and (d, t) . Figure 2 shows an example of this behavior. The spectroscopic factor for the $\ell = 1$ transition to the ground plus first excited states is approximately equal to that for the $\ell = 3$ transition to the 3-MeV group, but the cross section is lower by a factor of two or three in the first 40° of angular distribution. This behavior is adequately predicted by a DW calculation, but if one analyzes such data by means of a plane-wave calculation, one will have to use values of the single particle reduced-width, $\theta_0^2(\ell)$, much different than those used for (p, d) or (d, t) reactions.

This rather unique behavior of the (He^3, α) and (t, α) reactions and their inverses has not been greatly exploited. Experimentally, the detection of the alpha particles from these two pickup reactions can be accomplished by means of the magnetic spectrograph-nuclear emulsion technique nearly as easily as protons from a (d, p) reaction, by proper choice of emulsions and/or development techniques. Later in the program, a contributed paper on the experimental results and DW analysis of the $^{16}\text{O}(\text{He}^3, \alpha)^{15}\text{O}$ ground-state reaction, by Alford, Blau, and Cline,¹⁴ will be presented.

¶ Let us return to the (d, He^3) and (He^3, d) reactions. Although the (d, He^3) reaction should provide information about ground-state wave functions and proton hole states in the same way that (d, t) reactions provide information about neutron configurations, it has been studied far less than the (d, t) reaction, partly because of experimental difficulties. Included among the rather few recent studies is the work of Cujec,⁹ at the University of Pittsburgh, who has obtained angular distributions of low-lying states from the (d, He^3) reaction on a variety of nuclei from O^{16} to Cu^{63} . She has extracted spectroscopic factors with the aid of DW calculations, and from these has deduced information on proton configurations for the target ground states. At the Argonne Laboratory, the (d, He^3) reaction has been studied by Zeidman, Yntema, and co-workers.^{15,16} Target nuclei have included F^{19} , Al^{27} , and the nuclei near $Z = 28$. Among the results of the studies has been the indication that the 28-proton shell in the Ni nuclei is not well closed. This is to be contrasted to neutron-pickup results for the $N = 28$ nucleus Fe^{54} , which indicate a well-closed $N = 28$ shell.^{13,17,18}

There have been several (He^3, d) experiments performed lately, but I shall restrict myself to some recent work at Los Alamos. We are studying the (He^3, d) reaction on the Mg isotopes; four of the $N = 28$ nuclei, the four even Ni isotopes, Y^{89} , and a few others.

A deuteron spectrum at 27° laboratory angle from the $\text{Ni}^{62}(\text{He}^3, d)\text{Cu}^{63}$ reaction is shown in Fig. 3. The He^3 beam energy is 22 MeV. The curves through the datum points are the results of a digital-computer-program fit to the spectrum. This program fits peaks with skewed Gaussians plus

exponential tails, and computes the area under each peak.¹⁹ Note especially the relatively large cross section of the first and second excited states, at 0.67 and 0.96 MeV.

Figure 4 shows the angular distributions of dueterons from the ground and first few excited states of Cu^{63} . The curves through the datum points represent the results of a distorted-wave calculation for the reaction, normalized in magnitude to the experimental distributions at their peaks in the region of 20 to 30 degrees. The orbital angular-momentum transfers are indicated adjacent to the curves. The calculation comes from a computer program based on the Gibbs-Tobocman program,²⁰ modified at Los Alamos.²¹ The interaction between the proton and the deuteron in the He^3 particle is taken to be a delta-function interaction in the calculation, but a finite range of interaction is partially simulated by cutting off the integration of the wave functions near the surface of the nucleus.^{22,23} The optical-model parameters used in the calculation are those obtained from fits to elastic-scattering data.

It can be seen that the DW calculation yields curves which are in good agreement with the angular distributions. In the spectra, the third and fourth excited states are not well resolved, and the analysis of the spectra yields some scatter of points in their angular distributions. However, the observed energies of the peaks are within 10 keV of the energies quoted in the literature and indicated on Fig. 3. At nearly all angles the analysis indicates that the higher state at 1.41 MeV is excited three to four times as strongly as the lower state at 1.33 MeV. The distribution labeled 1.4 MeV in the figure is the sum distribution

of the two states. It is probably entirely $\ell = 3$ in character. The spin and parity of the stronger state at 1.41 MeV is thus restricted to $5/2^-$ or $7/2^-$, as is, with somewhat less certainty, that of the 1.33-MeV state. Thus, these results are consistent with the recent assignment²⁴ of $7/2^-$ for the 1.33-MeV state, but in disagreement with the often-proposed assignment of $3/2^-$ for the 1.41-MeV state.^{25,26}

Figure 5 shows the next several excited-state distributions and the DW fits. A distribution peaking at about 25° and corresponding to an $\ell = 4$ DW calculation is found at 2.51 MeV. Two more distributions and the DW fits are shown in Figure 6. The distribution for the 3.48-MeV group peaks further out in angle than any observed $\ell = 1, 3$, or 4 distribution, and is tentatively assigned as an $\ell = 2$ transition. It is possible that the expected minimum of the $\ell = 2$ distribution at approximately 27° is filled in by a weaker $\ell = 1$ or $\ell = 4$ transition to a group at approximately the same energy.

These figures show the DW fits to the strongest deuteron groups up to approximately 4 MeV of excitation. Most of the weaker groups have been similarly analyzed.

To obtain quantitative results for spectroscopic factors from the present experiment is somewhat more difficult. The DW calculation does not yet yield absolute cross section predictions for the (He^3, d) reaction, and the normalization factor is now known very accurately. We have chosen to assume that all observed $\ell = 1$ transitions but that to the ground state are $p_{1/2}$. We also assume that we have actually identified all of the important $\ell = 1$ transitions. The assumptions are probably

correct in the main; from the analysis of the (He^3, d) reaction on the $N = 28$ nuclei, currently being studied by Armstrong,²⁷ it seems likely that the transition strengths obtained from the present reaction are accurate to within 30%.

Table III shows the results of the data analysis on the basis just outlined. The first column lists the single-particle states, and the second column shows the observed states and their single-particle assignment. The quantity actually extracted from the normalization of the DW curves to the experimental distributions is NC^2S , where S is the spectroscopic factor, and C is the isobaric-spin Clebsch-Gordan coefficient. N is the factor multiplying the calculated DW curves such that the calculated cross section equals the experimental cross section for a full single-particle transition, i.e., for a transition having $C^2S = 1$. We have also assumed Λ cross-section dependence on $\ell \cdot s$ for the captured proton of about $\pm 15\%$, as $j = \ell \pm \frac{1}{2}$, respectively, as indicated by recent work of Satchler.²³

The sum of the $p_{1/2}$ transition strengths is actually expected to be slightly less than unity, as shown in the final column. The reasons for this are that, first, the value of the isobaric-spin coupling factor C^2 is $6/7$, and secondly, a correction must be made for the partial occupation of the $p_{3/2}$ neutron states in the Ni^{62} nucleus. The other 8% of the full $p_{3/2}$ strength will lie in $T = T_z + 1$ states, many MeV higher in excitation.

Thus, we adjust the value of the normalizing constant, N , such that the sum of the $p_{1/2}$ transitions, when compared to the DW calculation,

yields a total strength of 0.92. This value of N will then be used for all the other transitions, and for the other Ni isotopes. The experimental values for the transition strengths for each state or group are given in column 3 and their sums in column 4.

The experimental strength of 0.53 obtained for the $p_{3/2}$ ground state is to be compared to the expected value of 0.96 if the full strength were available to this state. This discrepancy can be partially accounted for in several ways, but the two which are probably the most important are 1) some of the higher $\ell = 1$ transitions may actually be $p_{3/2}$, rather than $p_{1/2}$, and 2) there is configuration mixing of $p_{3/2}$ protons in the ground-state wave function of Ni^{62} . Previous evidence for this latter observation has already been mentioned. If one assumes that the low value of the ground-state transition strength is due completely to this latter factor, one can calculate the occupation number of $p_{3/2}$ protons in the Ni^{62} ground-state wave function. The result is that on this basis the $p_{3/2}$ proton orbital is approximately 40% full. This value can be considered as an approximate upper limit to the amount of $p_{3/2}$ admixture.

If the $p_{3/2}$ orbital were 40% full, it follows that the $f_{7/2}$ orbital would be 20% empty (the $p_{3/2}$ orbital can hold four protons; the $f_{7/2}$ can hold eight). Thus, a fraction of the $\ell = 3$ transitions must be $f_{7/2}$, rather than $f_{5/2}$. I have already mentioned that the third excited state at 1.33 MeV has recently been assigned spin and parity of $7/2^-$. In our work, although this state is not well resolved from the stronger transition to the 1.41-MeV state, we can still deduce an approximate

value for its strength. The number so obtained is about 7% of the full $f_{7/2}$ single-particle strength, as indicated in Table III. Thus, we conclude on the basis of the present analysis that the $f_{7/2}$ orbital is at least 7% empty, and probably not more than 20% empty; i.e., the $p_{3/2}$ orbital is between 14% and 40% filled in the Ni^{62} ground state. If we take an average between these numbers, we obtain the predicted $p_{3/2}$ strength shown in parentheses. (To be consistent, we must say that a small additional fraction of the $\ell = 3$ transfers labeled as $f_{5/2}$ must be $f_{7/2}$, and this accounts for the number in parentheses in the $f_{5/2}$ row.) The agreement for the $p_{3/2}$ and $f_{5/2}$ states is satisfactory.

The present analysis also yields 0.64 for the $g_{9/2}$ transition strength to the 2.51-MeV level, approximately three-quarters of the predicted full strength of 0.86. The $d_{5/2}$ transition at 3.48 MeV includes only about one-quarter of the total predicted $d_{5/2}$ strength. These results are reminiscent of the work on the location of single-particle neutron states by Fulmer et al.²⁸ In their study of (d,p) reactions in this region of the periodic table, they found that the $g_{9/2}$ neutron strength was nearly entirely concentrated in one, or at the most, two nuclear levels, while the $d_{5/2}$ neutron strength was split over many nuclear levels.

The results from the reaction on Ni^{58} , Ni^{60} , and Ni^{64} are quite similar. For all four Cu isotopes, large fractions of the available $p_{1/2}$ and $f_{5/2}$ single-particle strengths are found in the first two excited states. On the other hand, the results of proton inelastic-scattering experiments by Perey et al.,²⁵ alpha-particle inelastic-

scattering experiments by Bruege et al.,²⁹ and Harvey et al.,³⁰ and Coulomb-excitation and resonance fluorescence experiments,²⁴ are consistent with a nuclear model which essentially couples a $p_{3/2}$ proton to an excited core, with very little, if any, coupling of $p_{1/2}$ and $f_{5/2}$ protons. The reconciliation between these results and those of the present (He^3, d) study has not yet been made.

The $\text{Ni}^{58}(\text{He}^3, d)\text{Cu}^{59}$ reaction is interesting in a further respect. Figure 7 shows a spectrum of this reaction. In the 4-MeV excitation region, in the neighborhood of channels 130-140 in the figure, strong peaks appear which are missing in the spectra of the three other Cu nuclei. At least a part of this difference can probably be attributed to the excitation of $T = T_z + 1$ isobaric states. In Cu^{59} , where there is only one more neutron than proton, the isobaric analog to the Ni^{59} ground state lies quite low in energy, namely at about 3.9 MeV of excitation. It is expected to be fairly strongly excited in the (He^3, d) $3/2^-$ reaction. By definition, the state has the spin and parity of the Ni^{59} ground state. Indeed, there is a transition at 3.9 MeV, and its angular distribution, shown in Fig. 8, most strongly resembles an $\ell = 1$ transition. The state is unbound, so that no DW calculations are available, but its maxima and minima fall in the correct place, and, because of its low Q , its structure should be washed out considerably from that of the $\text{Ni}^{62}(\text{He}^3, d)\text{Cu}^{63}$ distributions. It has approximately the expected cross section. Other transitions a few hundred keV higher in excitation may be roughly identified as analogs of the lowest excited states in Ni^{59} .

In the case of $\text{Mg}^{26}(\text{He}^3, \text{d})\text{Al}^{27}$, a transition has similarly been seen which can be identified as proceeding to the analog of the Mg^{27} ground state.

Another interesting application of the (He^3, d) reaction has been in the study of the low-lying states of Zr^{90} . One of the successes of the shell-model theory has been its ability to account in a quantitative manner for the positions of these states. Since the neutron number (50) for this nucleus is a magic number representing the filling of a closed shell, one would not expect the low excited states to be described by neutron excitations. Ford³¹ was the first to point out that the low states should be capable of being described as arising from two protons in almost pure configurations of the form $(p_{1/2})^2$, $(p_{1/2} g_{9/2})$, and $(g_{9/2})^2$. Subsequent theoretical work of a more detailed nature showed that the agreement between theory and experiment was quite good.

The experimental work up until recently was able to identify all of the states arising from the configurations just listed except for the 4^- state of the $(p_{1/2} g_{9/2})$ configuration. On the basis of somewhat indirect arguments, Wagner et al.³² concluded that the missing level was probably located at an excitation energy of 2.75 MeV. We have recently observed the $\text{Y}^{89}(\text{He}^3, \text{d})\text{Zr}^{90}$ reaction, in which we have definitely identified the 4^- level and have confirmed the surmise of Wagner et al.

The nucleus Y^{89} has a $p_{1/2}$ proton ground state, and can be considered the parent of the $(p_{1/2})^2$ and $(p_{1/2} g_{9/2})$ states in Zr^{90} , which will be excited in the reaction. A pulse-height spectrum is shown in Fig. 9. All four of the strong deuteron groups seen have the same width and

shape; thus they appear to represent the excitation of single, well-separated levels. In Fig. 10 the angular distributions of these levels are shown, along with the results of a DW calculation. Both the ground and first excited states have the same angular distribution, which agrees with the DW calculation for an $\ell = 1$ transition. Although in the zero-order shell-model theory the ground state would be pure $(p_{1/2})^2$, and the first excited state pure $(g_{9/2})^2$, they are known to be strongly mixed. Our results give a measure of this mixing. The angular distributions to the next two levels are also the same, and agree well with an $\ell = 4$ DW calculation. Since the first of these corresponds to the well-known 5^- state of the $(p_{1/2} g_{9/2})$ configuration at 2.32 MeV, the second, at 2.74 MeV, is clearly the missing 4^- state of this configuration. The spectroscopic factors for these two transitions are equal to each other to within 3%.

It is to be expected that over the next few years, advances both in experimental techniques and in theoretical treatment of the data will make studies of the reactions I have been discussing more popular among physicists.

FOOTNOTES

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FIGURE CAPTIONS

FIG. 1. Comparison of the $\text{Zn}^{68}(\text{d}, \text{He}^3)\text{Cu}^{67}$ excitation function with theoretical predictions: (1) experimental; (2) statistical model $\times 4100$; (3) pickup mechanism with transitions to all excited states up to 2 MeV allowed; (4) single-particle pickup model. All curves are normalized to the experimental at 15.4 MeV.

FIG. 2. Angular distributions for the $\text{Fe}^{56}(\text{He}^3, \alpha)$ reaction to several groups of states of Fe^{55} . The laboratory energy of the He^3 beam was 14.40 ± 0.15 MeV. The curves on this and following angular-distribution figures result from a DW calculation, and are normalized to the data in the forward-angle region. The error bars indicate typical standard deviations associated with the datum points.

FIG. 3. $\text{Ni}^{62}(\text{He}^3, \text{d})\text{Cu}^{63}$ spectrum at $\theta_{\text{lab}} = 27^\circ$. The laboratory energy of the He^3 beam was 22.05 ± 0.20 MeV. The curves through the datum points on this and following figures of spectra result from a digital computer program calculation, as described in the text.

FIG. 4. Angular distributions for the $\text{Ni}^{62}(\text{He}^3, \text{d})$ reaction to the ground and first few excited states of Cu^{63} . The error bars on this and following angular-distribution figures show the standard deviations associated with the respective datum points; in the present figure nearly all are smaller than the point size. The absolute cross-section scale has been determined to an accuracy of $\pm 15\%$.

FIG. 5. Angular distributions for the $\text{Ni}^{62}(\text{He}^3, \text{d})$ reaction to states or groups of states at 2.06, 2.36, and 2.51 MeV. The excitation energies have been determined to an accuracy of ± 0.03 MeV.

FIG. 6. Angular distributions for the $\text{Ni}^{62}(\text{He}^3, \text{d})$ reaction to states or groups of states at 2.79 and 3.48 MeV. The excitation energies have been determined to an accuracy of ± 0.04 MeV.

FIG. 7. $\text{Ni}^{58}(\text{He}^3, \text{d})\text{Cu}^{59}$ spectrum at $\theta_{\text{lab}} = 27^\circ$. The laboratory energy of the He^3 beam was 22.00 ± 0.20 MeV.

FIG. 8. Angular distribution for the $\text{Ni}^{58}(\text{He}^3, \text{d})$ reaction to the state or group of states at 3.87 ± 0.04 MeV.

FIG. 9. $\text{Y}^{89}(\text{He}^3, \text{d})\text{Zr}^{90}$ spectrum at $\theta_{\text{lab}} = 27^\circ$. The laboratory energy of the He^3 beam was 22.00 ± 0.20 MeV.

FIG. 10. Angular distributions for the $\text{Y}^{89}(\text{He}^3, \text{d})$ reaction to several states of Zr^{90} . The upper two curves result from $\ell = 1$ DW calculations; the lower two curves result from $\ell = 4$ DW calculations.

TABLE 1
The energy levels of O^{18} (in MeV)

Group number	(1)	(2)	(3)
1	1.980 ± 0.005	1.97	1.980
2	3.549 ± 0.005	3.55	3.552
3	3.627 ± 0.005	3.63	3.634
4	3.915 ± 0.005	3.92	3.916
5	4.449 ± 0.005	4.45	4.448
6	5.090 ± 0.005	5.10	5.067
7	5.247 ± 0.007	5.25	5.170
8	5.329 ± 0.007	5.33	5.311
9	5.368 ± 0.010	5.37	} 5.456
10	5.521 ± 0.010	5.51	
11	6.189 ± 0.010	6.18	6.190
12	6.341 ± 0.010	6.34	6.328
13	6.391 ± 0.010	6.39	
14		6.86 ± 0.02	
15		7.10 ± 0.02	7.115
16		7.60 ± 0.03	7.622
17		7.75 ± 0.02	
18		7.84 ± 0.02	
19		7.96 ± 0.02	
20		8.02 ± 0.02	8.041
21		8.11 ± 0.02	
22		8.19 ± 0.02	8.213
23		8.26 ± 0.02	8.286
24		8.39 ± 0.02	(8.403)
25		8.48 ± 0.02	
26		8.64 ± 0.02	

(1) Present energy levels from the $O^{16}(t, p)O^{18}$ reaction.

(2) Present energy levels from the $F^{19}(t, \alpha)O^{18}$ reaction.

(3) The energy levels of O^{18} as reviewed by Ajzenberg-Selove and Lauritsen

TABLE II. Transition strengths from the $\text{Al}^{27}(\text{d},\text{n})\text{Mg}^{26}$
and $\text{Al}^{27}(\text{He}^3,\text{d})\text{Mg}^{26}$ reactions.

Final state (MeV)	J^π	l	G_W^a	S/S_g P_W^b	C^c
0	0^+	2	1	1	1
1.83	2^+	2	2.2	1.53	1.87
2.97	2^+	2	-	0.32	0.64

^a R. N. Glover and E. Weigold, Nuclear Phys. 24, 630 (1961).

^b F. Pellegrini and S. Wiktor, Nuclear Phys. 40, 412 (1963).

^c B. Cujec, Phys. Rev. 128, 2303 (1962).

TABLE III. Transition strengths for
the $\text{Ni}^{62}(\text{He}^3, d)\text{Cu}^{63}$ reaction.

Assumed s.p. state	E_x (MeV)	$(C^2S)_{\text{exp}}$	$\Sigma(C^2S)_{\text{exp}}$	$\Sigma(C^2S)_{\text{pred}}$
$p_{3/2}$	g.s.	0.53	0.53	0.96 (0.60)
$p_{1/2}$	0.668	0.58	0.92	0.92
	1.547 (?)	0.01		
	2.06	0.18		
	2.79	0.12		
$f_{5/2}$	3.06	0.03	0.90 (0.80)	0.93
	0.961	0.40		
	1.412	0.40		
	2.36	0.10		
$f_{7/2}$	1.327	0.07		
$g_{9/2}$	2.51	0.64		0.86
$d_{5/2}$	3.48	0.21		0.86

FIG. 4. Comparison of the $\text{Zn}^{68}(d, \text{He}^3)\text{Cu}^{67}$ excitation function with theoretical predictions: (1) experimental; (2) statistical model $\times 4100$; (3) pickup mechanism with transitions to all excited states up to 2 MeV allowed; (4) single-particle pickup model. All curves are normalized to the experimental at 15.4 MeV.

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