Configuration Mixing and J Dependence in $l=3$ Stripping and Pickup Reactions*

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To study effects of configuration mixing on the forward angle J dependence in $l=3$ stripping and pickup reactions, angular distributions for the (d,p) reaction on ^{48}Ti, ^{50}Cr, ^{54}Fe, and ^{58}Ni have been measured for those final states which contain most of the $f_{7/2}$ or $f_{5/2}$ single-particle strength. At an incident energy of 19 MeV, these (d,p) reactions (with an average Q value of 6 MeV) correspond to the inverse (p,d) reaction measured at an incident energy of 25 MeV. The present data therefore can be directly compared with the ^{56}Fe and ^{58}Ni(p,d) data of Glashausser and Rickey. Significantly less J dependence is found for transitions to final states for which configuration mixing effects are unimportant. This observation thus strongly supports the explantion of the forward angle J dependence in terms of configuration mixing.

FORWARD angle J-dependent effects[1] in $l=3(p,d)$ reactions on nuclei in the mass region around $A\sim56$ were first observed by Sherr *et al.*[2]; and a more complete investigation of these effects has been published recently by Glashausser and Rickey.[3] Experimentally it has been found that the angular distributions for $f_{5/2}$ pickup fall off more steeply after the stripping maximum than those for $f_{7/2}$ pickup and that there is also a relative shift in the positions of the forward maxima. Sherr *et al.*[2] found that a distorted-wave Born-approximation (DWBA) calculation which used an "effective binding energy prescription" in the calculation of the wave function for the picked-up neutron was able to reproduce the (p,d) $l=3$ J dependence in the ^{56}Fe(p,d) reaction at 28 MeV. However, the effective binding energy prescription does not give the correct asymptotic tail for the bound-state wave function, and therefore this approach is somewhat questionable. Also, Glashausser and Rickey,[3] who studied the ^{56}Fe(p,d) reaction at energies from 18.5 to 27.5 MeV, found that the effective binding energy prescription was unable to reproduce the observed $l=3$ J dependence at the lower energies.

Following the experimental observation of Sherr *et al.*,[2] Huby and Hutton[4] suggested that the main differences between the $f_{5/2}$ and $f_{7/2}$ (p,d) angular distributions are not due to an intrinsic J dependence, but are rather a consequence of configuration mixing effects on the bound-state wave function of the picked-up neutron. In ^{58}Ni, for example, there are two neutrons in a mixed $p_{3/2}^2$, $f_{5/2}^2$, $p_{1/2}^2$ configuration outside the filled $f_{7/2}$ subshell. In an $f_{7/2}$ pickup transition on ^{58}Ni a hole is created in the filled $f_{7/2}$ subshell; and, therefore, because of the equivalence of particles and holes, it would be expected that the bound-state wave function for the picked-up neutron could be calculated reasonably well using a Woods-Saxon well and the usual separation energy prescription; B.E.$(n)=-Q(p,d)+2.225$ MeV. On the other hand, the ground state of ^{58}Ni has only an $\sim35\%$ admixture of the $f_{5/2}^2$ configuration[5]; and therefore the $f_{5/2}$ component of the ground-state wave function might be quite different from that calculated with a single-particle model.

The effects of configuration mixing in the (p,d) reaction on $N=30$ nuclei have been independently calculated by Huby and Hutton,[4] by Rost,[6] and by Prakash and Austern.[7] All three authors have obtained improved fits to the $f_{5/2}$ angular distributions if configuration mixing effects are taken into account. On the other hand, Johnson and Santos[8] have obtained similarly improved fits by an entirely different approach in which the D state of the deuteron was explicitly included in the DWBA calculation. However, neither the configuration mixing calculations nor the calculations which include the D state of the deuteron were able to reproduce the entire experimentally observed difference between the $f_{5/2}$ and $f_{7/2}$ transitions.

The present study was undertaken to investigate experimentally whether or not the observed J dependence in the $l=3$ (p,d) reaction is indeed a configuration mixing effect. If the configuration mixing argument is valid it would be expected that differences between the $f_{7/2}$ and $f_{5/2}$ angular distributions should disappear or at least become significantly less if the only transitions studied are those for which the bound-state wave function of the picked-up neutron can be well described by a single-particle wave function without the inclusion of configuration mixing effects. Since the $f_{5/2}$ admixtures in the ground states of nuclei in the mass region of Ni^{58} are only moderately large, the (p,d) reaction cannot be used to study the pickup from a relatively pure $f_{5/2}{}^n$ configuration. However, the (d,p) reaction [being the inverse of the (p,d)] can be used if the $f_{5/2}$ (d,p) transi-

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1 L. L. Lee, Jr., and J. P. Schiffer, Phys. Rev. Letters 12, 108 (1964).
2 R. Sherr, E. Rost, and M. E. Rickey, Phys. Rev. Letters 12, 420 (1964).
3 C. Glashausser and M. E. Rickey, Phys. Rev. 154, 1033 (1967).
4 R. Huby and J. L. Hutton, Phys. Letters 19, 660 (1966).
5 N. Auerbach, Phys. Rev. 163, 1203 (1967); and the experimental references cited therein.
6 E. Rost, Phys. Rev. 154, 994 (1967).
7 A. Prakash and N. Austern, Nucl. Phys. (to be published).
8 R. C. Johnson and F. D. Santos, Phys. Rev. Letters 19, 364 (1967).

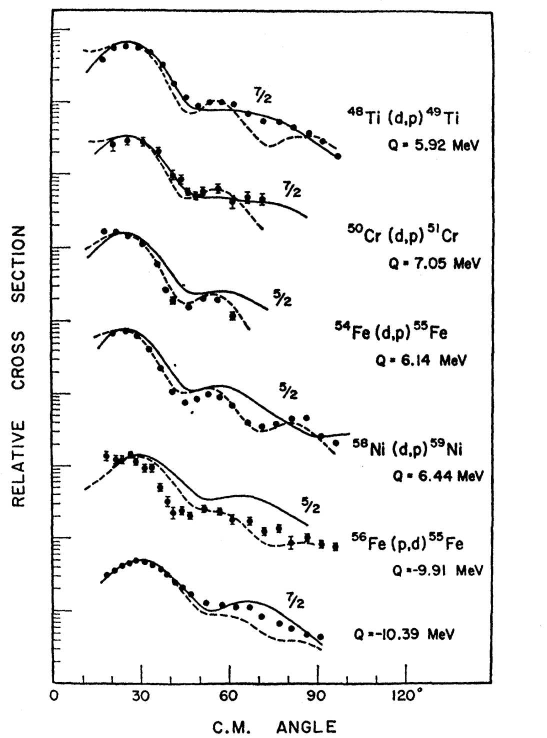

FIG. 1. Stripping angular distributions for various $l=3$ transitions at an incident deuteron energy of 19 MeV. With Q values of approximately 6 MeV these (d,p) data correspond to the inverse reaction measured at 25 MeV. For comparison the $^{56}Fe(p,d)^{55}Fe$ data measured by Glashausser and Rickey[3] at 25.4 MeV have been included. DWBA calculations performed without a cutoff radius (solid lines) and with a cutoff radius of 5 F (dashed lines) are also shown. The data have statistical errors less than the size of the data points except where noted by error bars.

tions which are studied reach final states containing most of the $f_{5/2}$ stripping strength.

In the present investigation the (d,p) reactions on ^{48}Ti, ^{50}Cr, ^{54}Fe, and ^{58}Ni were studied at a bombarding energy of 19 MeV; and angular distributions were obtained for the transitions to the $\frac{7}{2}^-$ ground states of ^{49}Ti and ^{51}Cr and to the lowest $\frac{5}{2}^-$ states in ^{55}Fe and ^{59}Ni at 930 and 340 keV, respectively. The (d,p) transitions to these final states all show large $l=3$ spectroscopic strengths.[9–12] The isotopically enriched ^{48}Ti, ^{54}Fe, and ^{58}Ni targets were rolled foils, approximately 1 mg/cm^2 thick, while the ^{50}Cr target was prepared by evaporating the isotope onto an aluminum backing. Protons from the (d,p) reactions were detected with a counter telescope consisting of two, 2-mm-thick, surface-barrier detectors. Coincidences between the detectors were required in order to discriminate against particles other

TABLE I. Optical-model parameters[a] used in the DWBA calculations.

	V (MeV)	r_0 (F)	a (F)	$4W_D$ (MeV)	r_0' (F)	a' (F)	V_{so} (MeV)	r_c (F)
d	93	1.15	0.81	78	1.34	0.68	···	1.3
p	45	1.25	0.65	45	1.25	0.47	8	1.25
n	b	1.25	0.58	···	···	···	$\lambda=25$	···

[a] The potentials are of the standard Woods-Saxon form with a surface derivative imaginary term.
[b] The well depth was adjusted by JULIE to make the neutron binding energy equal to its separation energy.

than protons. An over-all system resolution of 65 keV was sufficient to resolve the states of interest.

The measured angular distributions are shown in Fig. 1 together with the predictions of DWBA calculations. Also included for comparison are the $l=3$, $j=\frac{5}{2}$, and $j=\frac{7}{2}$ angular distributions from the $^{56}Fe(p,d)^{55}Fe$ reaction at 25.4 MeV obtained by Glashausser and Rickey.[3] Glashausser and Rickey also studied $l=3$ transitions in the $^{58}Ni(p,d)$ reaction at 25.4 MeV; and the angular distributions, while not as complete, are essentially identical to the $^{56}Fe(p,d)$ data. With an average Q value of 6 MeV, the (d,p) measurements at $E_d=19$ MeV correspond to a study of the inverse process [i.e. the (p,d) process] at 25 MeV, and therefore the (d,p) and the (p,d) data can be directly compared. The zero-range local calculations with, and without, a cutoff radius were performed with the spin-dependent code JULIE[13] using optical-model parameters closely related to the average deuteron and proton optical-model potentials obtained by Perey and Perey.[14,15] These parameters are listed in Table I. As is evident in Fig. 1, the DWBA calculations without a cutoff radius (solid curves) fit both the (d,p) and (p,d) $f_{7/2}$ angular

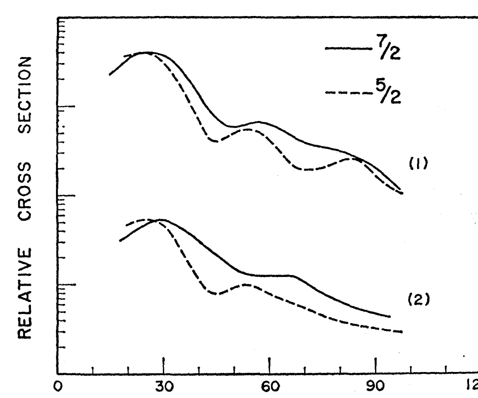

FIG. 2. Comparison of the $l=3$, $j=\frac{5}{2}$ and $j=\frac{7}{2}$ angular distributions from (1) the $^{48}Ti(d,p)^{49}Ti$ transition to $\frac{7}{2}^-$ ground state and the $^{58}Ni(d,p)^{59}Ni$ transition to the 0.34-MeV $\frac{5}{2}^-$ level; and (2) the $^{56}Fe(p,d)^{55}Fe$ transitions studied by Glashausser and Rickey (Ref. 3) at 25.4 MeV.

[9] P. D. Barnes, J. R. Comfort, C. K. Bockelman, O. Hansen, and A. Sperduto, Phys. Rev. 159, 920 (1967).
[10] J. E. Robertshaw, A. Sperduto, and W. W. Buechner, Bull. Am. Phys. Soc. 11, 318 (1966).
[11] J. R. Maxwell and W. C. Parkinson, Phys. Rev. 135, B82 (1964).
[12] R. H. Fulmer, A. L. McCarthy, B. L. Cohen, and R. Middleton, Phys. Rev. 133, B955 (1964).
[13] R. H. Bassel, R. M. Drisko, and G. R. Satchler, Oak Ridge National Laboratory Report No. ORNL-3240, 1962 (unpublished).
[14] F. G. Perey, Phys. Rev. 131, 745 (1963).
[15] C. M. Perey and F. G. Perey, Phys. Rev. 132, 755 (1963).

distributions rather well, whereas only the (d,p) $f_{5/2}$ angular distributions are fitted by the calculations, and these require a 5 F cutoff radius. In Fig. 2 the shapes of measured $f_{5/2}$ transitions from the (d,p) and (p,d) reactions are compared with those from $f_{7/2}$ transitions.

From Figs. 1 and 2 it is apparent that the forward angle J dependence is significantly less in the present data than in the ^{56}Fe$(p,d)^{55}$Fe reaction. This may simply reflect the difference in the Q values between the studied (d,p) and (p,d) reactions. However, if the Q dependence is predicted correctly by the DWBA calculations, these data strongly support the explanation of the forward angle J dependence in terms of configuration mixing effects since the DWBA predictions for the nonconfiguration mixed $f_{7/2}$ transitions closely agree with experiment while the $f_{5/2}$ data are only fitted where the transferred neutron should be well described by a single-particle wave function (though one should note that a 5 F cutoff radius is needed to fit the $f_{5/2}$ data, while the $f_{7/2}$ data is fitted without a cutoff). It is also apparent from the data that there is a residual J dependence which is possibly a consequence of the D state of the deuteron as has been suggested by Johnson and Santos.[8] Since the calculations by Johnson and Santos[8] were not able to reproduce the full J dependence observed in the $l=3$ (p,d) reactions, it will be of particular interest to see whether their method of calculation can reproduce the present data, in which configuration mixing effects are of lesser importance.

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Continuum Nuclear Structure of O^{16} in the Eigenchannel Reaction Theory*

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The total particle-particle S^J matrix of O^{16} for spin $J=1^-$ and excitation energies between 15 and 27 MeV has been calculated in the eigenchannel reaction theory for several parameters of the Saxon-Woods potential and the two-body force. The many-body problem has been treated in the 1-particle–1-hole approximation. The photon channels have been included by perturbation theory. Surprisingly, the most important structure of the experimental cross sections is reproduced quite well in this simple approximation.

1. INTRODUCTION

The proper theoretical treatment of the nuclear continuum has been one of the important challenges to nuclear theorists in recent years. Attempts have been made by various groups[1–11] to solve the problem at least for that case where only one nucleon is in the continuum, i.e., below the two-nucleon threshold. Since a nuclear reaction can be described only as a particular continuum state of the nuclear-system target plus projectile, it is clear that unambiguous statements about the target structure can be made only by a correct treatment of the continuum problem.

The calculations in the present paper are performed by applying the methods of the eigenchannel theory. The formal aspects of this theory have been presented earlier.[7,12] In this paper, first, we supplement the earlier treatment[7] by giving the details necessary for an actual calculation and, second, we discuss the results obtained in a computation of the 1^- compound system O^{16} in the 1-particle–1-hole approximation. Thus, our calculation encompasses the $N^{15}+p$ and the $O^{15}+n$ reactions as

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[1] R. H. Lemmer and C. M. Shakin, Ann. Phys. (N. Y.) **27**, 13 (1964).

[2] W. M. MacDonald, Nucl. Phys. **54**, 393 (1964); **56**, 636 (1964).

[3] C. Bloch and V. Gillet, Phys. Letters **16**, 62 (1965); **18**, 58 (1965).

[4] J. Raynal, M. A. Melkanoff, and T. Sawada, Saclay Report, 1967 (unpublished).

[5] H. A. Weidenmüller, Nucl. Phys. **75**, 189 (1966).

[6] B. Buck and A. D. Hill, Nucl. Phys. **A95**, 271 (1967).

[7] M. Danos and W. Greiner, Phys. Rev. **146**, 708 (1966).

[8] H. G. Wahsweiler, M. Danos, and W. Greiner, Phys. Rev. Letters **17**, 395 (1966).

[9] H. G. Wahsweiler, M. Danos, and W. Greiner, Phys. Letters **23**, 257 (1966).

[10] V. Gillet, M. A. Melkanoff, and J. Raynal, Nucl. Phys. **A97**, 631 (1967).

[11] M. Marangoni and A. M. Saruis, Phys. Letters **24B**, 218 (1967).

[12] M. Danos and W. Greiner, Z. Physik **202**, 125 (1967).