if we do not require that the phenomenological potential fit the α solution and β solution separately, but that it fit some linear combination of these. As with the deuteron problem when only the energy is specified, only one equation in $\delta\lambda_i$ is obtained at each value of the energy and we no longer need to solve for $\partial u/\partial\lambda_i$, $\partial w/\partial\lambda_i$. If the number of energy values at which we know the phase shifts is greater than the number of trial parameters in the potential, then we can obtain a solution for the latter. Moreover, it may well be asked whether, in view of the fact that we are treating a whole range of energy values, any essential information will be lost by proceeding in this way. This question is certainly an interesting one and is at present under investigation.

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(n,d) Reaction Studies on Ni^{58}, Cu^{63}, and Zn^{64} †

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Studies were made of (n,d) pickup reactions on Ni^{58}, Cu^{63}, and Zn^{64} initiated by 14-MeV neutrons. Deuteron spectra at a series of forward angles were measured using a counter telescope, and distorted-wave Born-approximation fits were made to the data. For Cu^{63}, the 1.17-MeV 2+ state in Ni^{62} is excited with a cross section of 0.5 that of the Ni^{62} ground state. For Zn^{64}, transitions to the ground and 0.67-MeV states of Cu^{63} involve p-particle pickup. Transitions to the 0.96-MeV $\frac{5}{2}$-state are not observed, indicating that the $f_{5/2}$ proton component in the Zn^{64} ground state is small. Strong transition strength to the 1.33-MeV $\frac{7}{2}-$level suggests that this state has a significant $(f_{7/2})^{-1}$ proton single-particle component, in addition to the core excitations included in recent calculations. In Ni^{58}, excitation of the 1.37-MeV level with $S=0.6$ implies a significant $2p$ proton admixture in the Ni^{58} ground state.

INTRODUCTION

In the last several years it has become possible to apply distorted-wave Born-approximation (DWBA) calculations with some confidence to the analysis of stripping and pickup reaction data, and such experiments have become of prime importance in studying the single-particle structure of nuclei. However, most of this work has been concerned with the neutron structure of nuclei, with relatively few experiments being done on single-proton transfer reactions. Proton-pickup-reaction studies via (n,d) and (d,He^3) reactions have been particularly sparse. With the exception of an experiment on V^{51},[1] virtually no (n,d) reaction studies on medium-mass nuclides have been done under sufficiently good experimental conditions to permit detailed conclusions to be extracted. Several (n,d) experiments[2–4] have provided some information on ground-state transitions in a few medium-mass nuclei, but they could not resolve excited-state transitions. In the present experiment (n,d) reactions on Cu^{63}, Zn^{64}, and Ni^{58} have been studied using 14-MeV neutrons.

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[1] K. Ilakovac, L. G. Kuo, M. Petravić, I. Šlaus, P. Tomaš, and G. R. Satchler, Phys. Rev. **128**, 2739 (1962).
[2] R. N. Glover and K. H. Purser, Nucl. Phys. 24, 431 (1961).
[3] L. Colli, I. Iori, S. Micheletti, and M. Pignanelli, Nuovo Cimento **20**, 94 (1961).
[4] G. Bassani, L. Colli, E. Gadioli, and I. Iori, Nucl. Phys. **36**, 471 (1962).

EXPERIMENT

Self-supporting metal foils of Ni^{58} and Cu^{63} (thickness 3.5 mg/cm^2) and of Zn^{64} (thickness 2.4 mg/cm^2) of isotopic purity greater than 99.8% were bombarded by 14.1-MeV D-T neutrons from the Rensselaer Cockcroft-Walton accelerator. Neutron flux was held at 5×10^8 n/sec during the experiment to minimize rate-dependent background, and was monitored by a plastic-scintillator proton-recoil counter. Deuterons emitted from the targets were detected by the ΔE-E counter telescope shown in Fig. 1. Detected deuterons pass through the two gas proportional counters A and B before stopping in the active region of the silicon surface-barrier detector C. The depletion depth (600 μ) of this detector was thick enough to stop 12-MeV deuterons. Acceptable events correspond to a triple coincidence from these three counters together with no pulse from the anticoincidence proportional counter D. The anticoincidence counter permits rejection of those background triple coincidences due to particles from the silicon proceeding backward through the spectrometer and those due to particles from the front wall of the telescope chamber.

Measurement of pulse heights from both the rear proportional counter (pulse height proportional to energy loss ΔE in the counter) and from the surface barrier detector (pulse height proportional to incident particle energy E) permitted separation of deuterons from protons as well as a determination of their energy.

The statistical spread in the ΔE pulse heights resulted in the deuteron events on a ΔE versus E plot lying in a broad swath with some overlap of the corresponding proton swath. To minimize the proton contamination in the data, this overlap region was rejected. The resultant efficiency for detection of deuterons was determined experimentally; it was slightly dependent on deuteron energy and its average was 87% over the energy region of interest.

The observed energy resolution for Cu^{63} and Ni^{58} at a deuteron energy of 8 MeV was about 250 keV and for Zn^{64} about 200 keV with most of this attributable to deuteron energy loss in the targets. The over-all ratio of true to background counts was about 3 to 1. The background, whose major source was chance coincidences, fell off with increasing deuteron energy, and was important only at energies below about 5 MeV.

The deuteron energy scale was calibrated using the observed location of deuteron groups from the $Al^{27}(n,d)$ reaction to the ground and first two excited states of Mg^{26}, and from the $Cu^{63}(n,d)$ reaction to the Ni^{62} ground state, for all of which the Q values are accurately known. The calibration curve is shown in Fig. 2. In terms of this calibration the Q values for the $Ni^{58}(n,d)$ and $Zn^{64}(n,d)$ ground-state reactions were measured as -5.97 and -5.52 MeV, respectively, in good agreement with values of -5.95 and -5.48 MeV, respectively, from published mass tables.[5] There is an uncertainty of about 50 keV in the experimentally determined energies in the present experiment.

Absolute (n,d) cross sections were obtained by replacing the targets in the spectrometer by a thin deuterated paraffin target in the same geometry and observing recoil deuterons in the forward direction from 14-MeV neutron scattering, for which the cross section is known.[6] As a cross check, the incident neutron flux determined in this manner was compared to the value obtained using a proton recoil neutron spectrometer of known efficiency; the two determinations agreed within 5%.

The very low counting rates in the present experiment (≈ 1 count/min) necessitated the use of a detector with modest angular resolution and limited data acquisition to a small number of angles in the forward hemisphere.

RESULTS

Energy spectra obtained by combining data for laboratory angles between 10° and 50° for each of the Cu^{63}, Zn^{64}, and Ni^{58} targets are shown in Figs. 3–5. Angular distributions for prominent peaks in the energy spectra are displayed in Figs. 6–8. Table I summarizes the experimental results. In addition to the experimental data, known states in the residual nuclei at energies corresponding to observed peaks in the present data are also tabulated together with their spins and parities.

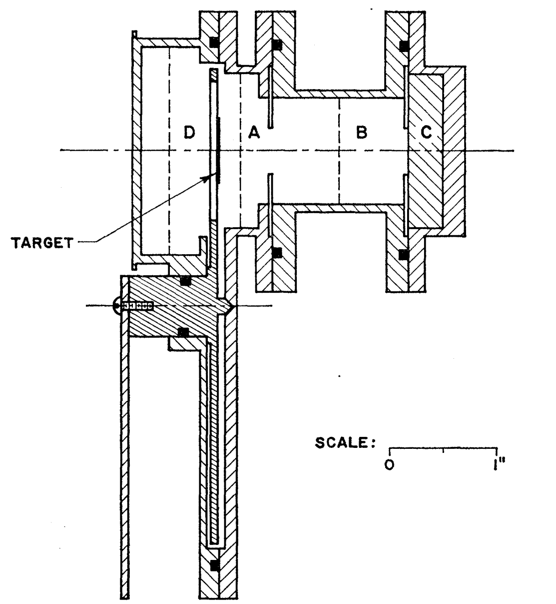

FIG. 1. The charged-particle spectrometer. A and B are proportional counters, C is a silicon surface-barrier detector, and D is an anticoincidence proportional counter. Targets are mounted in the spectrometer on the rotatable wheel.

The data were fitted by calculated DWBA curves. The calculations were performed using a computer program due to Smith and Ivash,[7] which assumes a Woods-Saxon shape for both real and imaginary deuteron and neutron potentials. Since detailed deu-

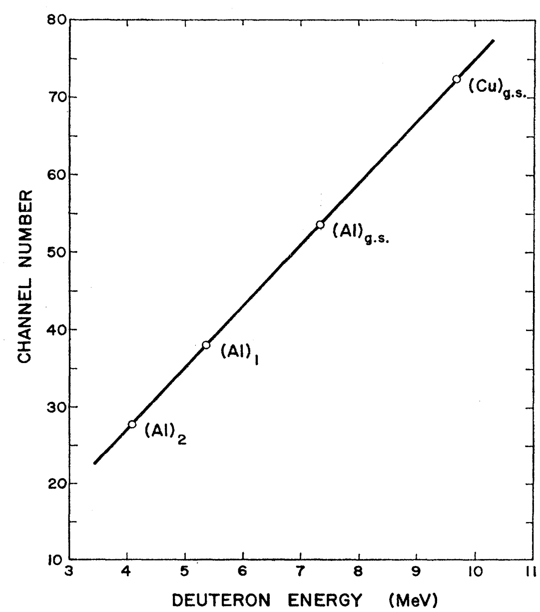

FIG. 2. Spectrometer energy calibration in terms of the $Cu^{63}(n,d)$ ground-state (g.s.) transition and the three highest energy $Al^{27}(n,d)$ groups. Deuteron energy plotted includes degradation in target and proportional-counter gas.

[5] L. A. König, J. H. E. Mattauch, and A. H. Wapstra, Nucl. Phys. **31**, 1 (1962).

[6] J. D. Seagrave, Phys. Rev. **97**, 757 (1955).

TABLE I. Data summary.

	Present data Q value, MeV ($\pm$0.05 MeV)	Excitation energy, MeV ($\pm$0.05 MeV)	l_p	Spectroscopic factor S	Corresponding known levels Excitation energy, MeV	J^π
$Cu^{63}(n,d)Ni^{62}$	-3.90	0	1	0.7 $\pm$0.1	0	0+
	-5.03	1.13	1	(0.55$\pm$0.1)[a]	1.17	2+
	-6.29	2.39			2.34	4+
	(-7.04)	(3.14)				
	-7.76	3.86	3	6.5 $\pm$2		
	-8.00	4.10				
$Zn^{64}(n,d)Cu^{63}$	-5.52	0	1	1.3 $\pm$0.2	0	$\frac{3}{2}-$
	-6.29	0.67	1	0.9 $\pm$0.2	0.668	$\frac{1}{2}-$
	-6.83	1.31	3	8$\pm$2	1.327	$\frac{7}{2}-$
	-7.47	1.95				
	-8.07	2.55				
	-8.53	3.01				
$Ni^{58}(n,d)Co^{57}$	-5.97	0	3	14$\pm$1.6	0	$\frac{7}{2}-$
	-7.34	1.37	1	1.6 $\pm$0.3	1.37	$\frac{3}{2}-$
	-7.85	1.88	3	9$\pm$2	1.90	($\frac{5}{2}-$)
	-8.48	2.51				
	-9.21	3.24				
	-9.71	3.74				

[a] Obtained by assuming a single-particle state.

teron and neutron elastic-scattering data at the relevant energies are not available for the present targets, a single set of average optical parameters was used and is listed in Table II. The deuteron potential was obtained by averaging the parameters obtained by Smith and Ivash[7] in this mass and energy region. The neutron potential is deduced from the elastic scattering parameters of Bjorklund and Fernbach[8] based on a surface imaginary potential, together with a comparison of surface and volume imaginary potential fits for proton scattering;[9] proton optical parameters appear to differ significantly from the corresponding neutron ones only in the depth of the real potential.

The computed angular distribution curves for the various transitions are shown in Figs. 6–8. Values for orbital angular momentum transfer l_p and spectroscopic factor S extracted from these fits are listed in Table I. For pickup, the spectroscopic factor is just equal to the ratio of the experimental cross section to that obtained from the DWBA calculation. The values so obtained for S have not been renormalized; other studies[10] suggest that they should be good to within a factor of two in absolute value; relative values may be somewhat better.

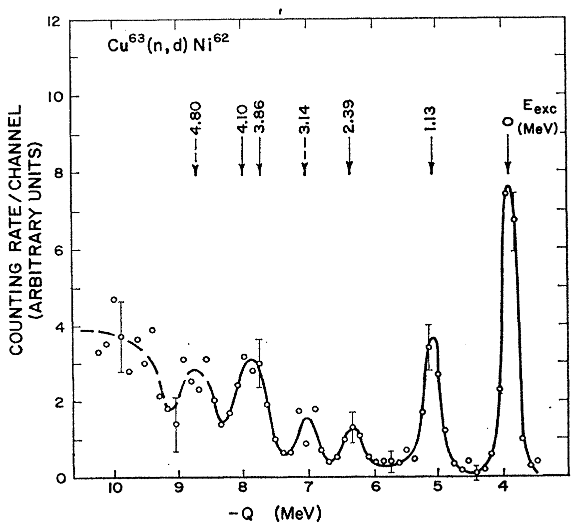

FIG. 3. $Cu^{63}(n,d)$ deuteron energy spectrum. Data at angles between 10° and 50° have been summed.

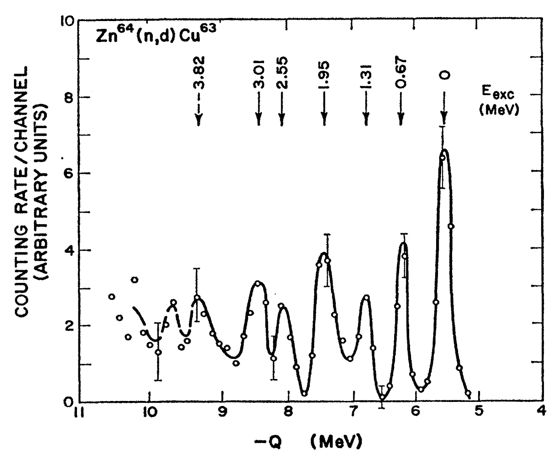

FIG. 4. $Zn^{64}(n,d)$ deuteron energy spectrum. Data at angles between 10° and 50° have been summed.

[7] W. R. Smith and E. V. Ivash, Phys. Rev. **128**, 1175 (1962).
[8] F. Bjorklund and S. Fernbach, Phys. Rev. **109**, 1295 (1958).
[9] F. G. Perey, Phys. Rev. **131**, 745 (1963).
[10] W. R. Smith, Phys. Rev. **137**, B913 (1965).

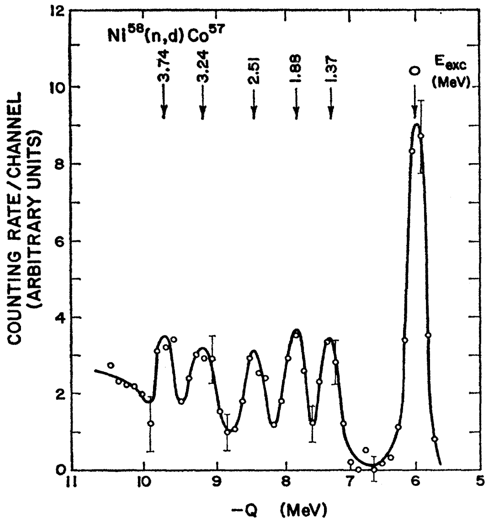

FIG. 5. $Ni^{58}(n,d)$ deuteron energy spectrum. Data at angles between 10° and 50° have been summed.

DISCUSSION

A. $Cu^{63}(n,d)Ni^{62}$

The spectrum in Fig. 3 is dominated by the $l=1$ transition to the Ni^{62} ground state. The observed spectroscopic factor for this transition is 0.7, which is a major fraction of the $l=1$ transition strength ($S=1$) expected for the $Cu^{63}(n,d)$ reaction, assuming that Cu^{63} is characterized by a single $p_{3/2}$ proton outside a closed $Z=28$ shell.

The 2+ first excited state at 1.17 MeV is also strongly excited, with a cross section of 0.5 that for the ground-state transition. The angular distribution is well fit by $l=1$. The cross section for this transition is strikingly large in view of the collective vibrational character of the 2+ state. A similar result has been recently reported[11] for the $Cu^{63}(d,He^3)$ reaction. There are at least three possible contributions to the excitation of this state, all of which may be important. First, the 2+ state will be directly excited by p proton pickup from Cu^{63} if the Cu^{63} ground state contains a component involving a p proton coupled to an excited 2+ Ni^{62} core. Unified model calculations[12,13] on Cu^{63} predict a 14% admixture of this component in the ground state. This would yield an (n,d) excitation of the 2+ state of 0.10 that of the ground state; this strength is significant, but much less than is observed. Second, the (d,He^3) data[11] for this transition deviates from an $l=1$ fit in the vicinity of the first minimum in the angular distribution, and this has been analyzed in terms of an $l=3$ admixture. This f strength is attributed to excitation, via $f_{7/2}$ single-particle pickup, of a sizeable $(f_{7/2})^{-1}(p_{3/2})^1$ single-particle component in the wave function of the 2+ state. A third contribution to the excitation of the 2+ state could arise from a pickup process which is accompanied by collective excitation of the core. The question as to whether such a process is important has been considered by Tanifuji[14] and by Penny and Satchler.[15] The latter authors point out that the effect of inelastic scattering in both incident and outgoing channels will be important in stripping and pickup reactions, and will give rise to significant excita-

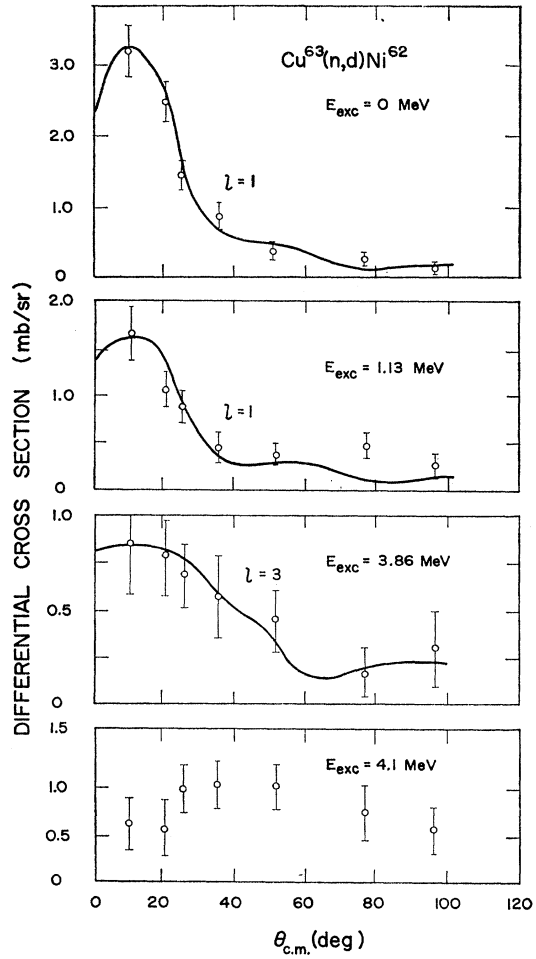

FIG. 6. Angular distributions of deuteron groups observed in $Cu^{63}(n,d)$. The solid curves are calculated distorted-wave predictions obtained as described in the text.

TABLE II. Optical-model parameters used in distorted-wave calculations.

Particle	V(MeV)	W(MeV)	r_0(F)	a(F)
Deuteron	60	20	1.40	0.65
Neutron	43	8	1.25	0.50
Proton	55		1.25	0.60

[11] J. C. Hiebert, E. Newman, and R. H. Bassel, Phys. Letters **15**, 160 (1965).
[12] M. Bouten and P. Van Leuven, Nucl. Phys. **32**, 499 (1962).
[13] V. K. Thankappan and W. W. True, Phys. Rev. **137**, B793 (1965).
[14] M. Tanifuji, Nucl. Phys. **58**, 81 (1964).
[15] S. K. Penny and G. R. Satchler, Nucl. Phys. **53**, 145 (1964).

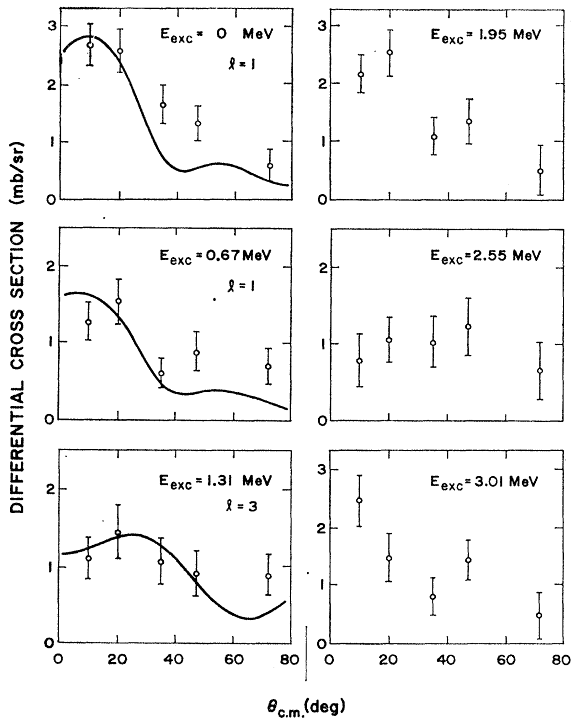

FIG. 7. Angular distributions of deuteron groups observed in $Zn^{64}(n,d)Cu^{63}$. The solid curves are distorted-wave predictions.

tion of core vibrations in such reactions. However, no detailed numerical calculations have been made.

The small peak observed at 2.39-MeV excitation energy with cross section 0.17 ± 0.03 that to the ground state corresponds to excitation of the 2+ and 4+ two-phonon states in Ni^{62} at 2.30 and 2.34 MeV. A broad peak at 4.0 MeV can be resolved into two levels at 3.86 and 4.10 MeV by virtue of the different angular distributions to these states. While the angular distribution data for the 3.86-MeV group has poor statistics, it is well fit only by $l=3$ and is probably due to $f_{7/2}$ pickup from the core. The large spectroscopic factor ($S=6.5\pm2$) suggests that a major part of the $f_{7/2}$ particle strength of 8 is in this level. The angular distribution for the 4.10-MeV group is not well fit by any single l value.

B. Zn^{64} (n,d) Cu^{63}

The three highest energy deuteron groups in the observed spectrum all correspond to states in Cu^{63} with known spins and parities; for each of these three transitions there is a unique l value allowed by conservation of angular momentum and parity. While the angular distribution data for $Zn^{64}(n,d)$ is of poorer quality than that for $Cu^{63}(n,d)$, the allowed l values indeed provide the best DWBA fits to the angular distribution data in each case. The calculated DWBA curves shown in Fig. 7 for these three cases correspond to these allowed l values.

The strongest transition is the $l=1$ transition to the Cu^{63} $\frac{3}{2}-$ ground state. The DWBA fit to the angular distribution data in Fig. 7 is indifferent. While the fit can be significantly improved by modest changes in the deuteron optical potential used in the calculation, no deuteron elastic-scattering data exists to justify such changes. The spectroscopic factor $S=1.3$ implies that a major part of the Zn^{64} ground-state wave function involves a $(2p_{3/2})^2$ outer proton configuration.

The five lowest states of Cu^{63} are listed in Table III. Of these, only the ground state and 0.67- and 1.33-MeV states are excited with observable strength in the present experiment. The calculations of Thankappan and True[13] yield wave functions for these levels in terms of admixtures of states involving a single proton in the $p_{3/2}$, $p_{1/2}$, or $f_{5/2}$ states coupled to a Ni^{62} core in either its ground state or in its one-phonon 2+ excited state; their results are summarized in Table III. Their calculated single particle admixtures for these states are in agreement with the recent (He^3,d) stripping results of Blair.[16]

The 0.96-MeV $\frac{5}{2}-$ state, according to these calculations, has comparable admixtures of an $f_{5/2}$ single-particle state and of a state involving a $p_{3/2}$ proton coupled to an excited Ni^{62} core, which we can denote as $(2,\frac{3}{2})$ (core spin 2, particle spin $\frac{3}{2}$). Hence our failure to excite this state implies that (1) the admixture of $(f_{5/2})^2$ proton configuration in the Zn^{64} ground-state wave function is small, and (2) the strength for exciting

TABLE III. Energy levels of Cu^{63} below 1.5 MeV.

Excitation energy MeV	J^π	$Zn^{64}(n,d)Cu^{63}$ (present experiment) l_p	S	Excitation energy, MeV	Corresponding calculated states[a] Percentage admixture[b] $(0,\frac{3}{2})$	$(0,\frac{1}{2})$	$(0,\frac{5}{2})$	$(2,\frac{3}{2})$	$(2,\frac{1}{2})$	$(2,\frac{5}{2})$
0	$\frac{3}{2}-$	1	1.3	0	85			11	3	1
0.668	$\frac{1}{2}-$	1	0.9	0.834		75		19		6
0.961	$\frac{5}{2}-$			1.069			38	58		4
1.327	$\frac{7}{2}-$	3	8	1.296				97		3
1.412	$(\frac{5}{2}-,\frac{7}{2}-)$			1.489			41	36	18	5

[a] From Thankappan and True (Ref. 13).
[b] The notation $(2,\frac{3}{2})$, for example, refers to a state in which a $p_{3/2}$ proton is coupled to a Ni^{62} core in its 2+ one-phonon state.

[16] A. G. Blair, Phys. Letters **9**, 37 (1964).

the $(2,\frac{3}{2})$ excited core component in the Cu^{63} $\frac{5}{2}-$ state by picking up a proton from Zn^{64} is negligibly small. This is in striking contrast to the strong excitation of the collective 2+ state at 1.17 MeV in Ni^{62} which we observed in $Cu^{63}(n,d)$.

The 0.67 MeV $\frac{1}{2}-$ first excited state in Cu^{63} is calculated to be 75% $(0,\frac{1}{2})$ and 19% $(2,\frac{3}{2})$. If we make the reasonable assumption that the (n,d) excitation of quadrupole core excitation is negligible for this state as it is for the $\frac{5}{2}-$ state, the state can only be reached by $2p_{1/2}$ single-particle pickup, and the observed $l=1$ strength $(S=0.9)$ provides a direct measure of the admixture of $(p_{1/2})^2$ in the Zn^{64} ground state.

The $l=3$ deuteron group corresponding to leaving Cu^{63} in its 1.33 MeV $\frac{7}{2}-$ state has a large spectroscopic factor, indicating that it arises from $f_{7/2}$ pickup from the core, and contains a major fraction of the expected $f_{7/2}$ strength $(S=8)$. The Cu^{63} calculations[13] predict that this state is mainly a $(2,\frac{3}{2})$ excited core configuration, in contrast to the present result. However, the $(0,\frac{7}{2})$ single-proton states which arise from the configurations $(f_{7/2})^{-1}(p_{3/2})^2$ and $(f_{7/2})^{-1}(p_{1/2})^2$ have not been included in these calculations; the present results indicate that these configurations are important components of the 1.33-MeV state and should be included. The weak excitation of this state in Ni^{62} (He^3,d)[16] is consistent with the presence of such admixtures, since this reaction should not excite f-hole configurations strongly.

The observed peaks corresponding to higher excited states of Cu^{63} probably are each made up of several unresolved levels, and their angular distributions are not well fit by any single l value.

C. $Ni^{58}(n,d)Co^{57}$

The deuteron energy spectrum is dominated by $f_{7/2}$ proton pickup leading to the $\frac{7}{2}-$ ground state of Co^{57}. The large spectroscopic factor obtained from the $l=3$ DWBA fit to the data implies that a major fraction of the expected $f_{7/2}$ strength $(S=8)$ is in this transition.

Relatively little is known about the excited states of Co^{57}. It has been suggested[17] that the low-lying states might be well described by an excited-core model in terms of a weak coupling between an $f_{7/2}$ hole and an excited Ni^{58} core. On this picture there should be a quintet of excited states whose center of gravity is at the energy of the 2+ first excited state of Ni^{58} (1.45 MeV). Indications are that the experimental situation is more complicated than this. In any case the observed (n,d) strength to the low-lying excited states is substantially greater than could be ascribed to excitation of the excited core quintet, even if the strength for this excitation is as great as that observed to the first excited state of Ni^{62} in the $Cu^{63}(n,d)$ experiment.

[17] G. Chilosi, S. Monaro, and R. A. Ricci, Nuovo Cimento **26**, 440 (1962).

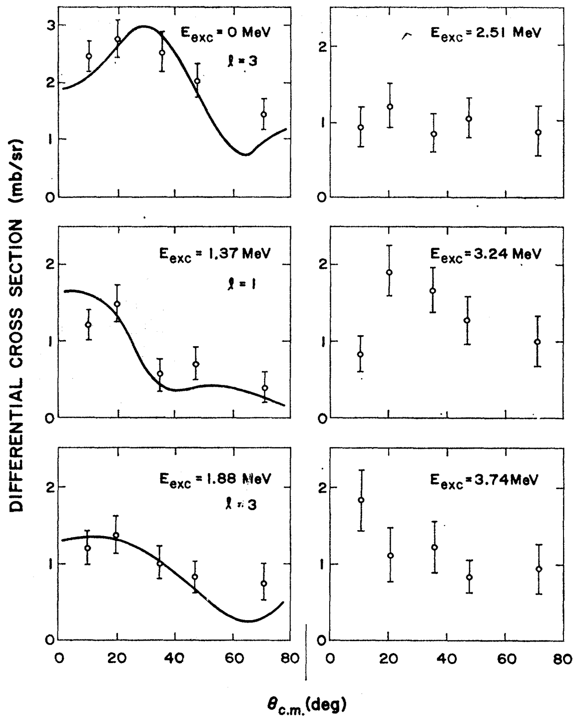

FIG. 8. Angular distributions of deuteron groups observed in $Ni^{58}(n,d)$. The solid curves are distorted-wave predictions.

A deuteron group is observed corresponding to transitions to the $\frac{3}{2}-$ first excited state of Co^{57} at 1.37 MeV; $l=1$ is required by angular momentum and parity conservation and the $l=1$ fit yields $S=1.6\pm0.3$. The excitation of this state implies that the Ni^{58} ground-state wave function is not well described in terms of a simple closed shell proton configuration but has a significant $2p$ proton impurity. A similar $2p$ admixture in the neutron configuration of Ti^{50}, which has 28 neutrons, has been observed in the $Ti^{50}(p,d)$ reaction.[18]

The peak at an excitation energy of 1.88 MeV is well fit only by $l=3$. It may correspond to the known $\frac{5}{2}-$ level in Co^{57} at 1.90 MeV, though the strength is much too great to be ascribed to an $f_{5/2}$ admixture in the Ni^{58} ground state. It appears more reasonable to ascribe this peak to excitation of a state with significant $(f_{7/2})^{-1}$ single-particle character.

[18] E. Kashy and T. W. Conlon, Phys. Rev. **135**, B389 (1964).