figurations of two $f_{7/2}$ proton holes and a single neutron in the $p_{3/2}$, $f_{5/2}$, and $p_{1/2}$ orbits. Figure 5 compares our results with these calculations. The left-hand sequence shows the positions of the experimentally determined energy levels, the l values of the captured neutron and, where possible, the spins and parities of the levels. The lengths of the horizontal lines are proportional to the stripping reduced widths as given in Ref. 2. The center sequence shows the results of the calculation by Ramavataram and the right-hand sequence the results of Maxwell and Parkinson. It is seen that both theories predict a low-lying $p_{1/2}$ state which one can relate to the 413-keV state. To the level at 2.49 MeV, Ramavataram relates a level at 2.43 MeV with spin $\frac{1}{2}$ (in contradiction to the experimental result) and Maxwell relates a level at 2.90 MeV with spin $\frac{3}{2}$. For excitation energies above 3 MeV, our results can be compared only with Maxwell's prediction. No level in Maxwell's prediction could be related to the 3.56-MeV state, and the spin predicted for the level at 4.5 MeV (which may be considered to correspond to the 3.80-MeV state) is $\frac{1}{2}^-$ contrary to our rather tentative result.

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$Ni^{60}(He^3,\alpha)Ni^{59}$ Reaction at 15 MeV*

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Measurements have been made of the angular distributions of alpha particles from the $Ni^{60}(He^3,\alpha)Ni^{59}$ reaction leading to the ground state and the 0.34-, 0.47-, 0.89-, 1.32-, 1.97-, 2.70-, 3.15-, 3.74-, and 7.33-MeV excited states of Ni^{59}. Distorted-wave Born-approximation analysis of the angular distributions has been carried out and spectroscopic factors extracted. The spectroscopic factors have been compared with the occupation-number predictions of pairing theory. The isobaric analog of the Co^{59} ground state has been observed at an excitation of 7.33 MeV in Ni^{59}.

I. INTRODUCTION

The experimental study of direct nuclear interactions together with theoretical analysis has been found in many cases to yield valuable nuclear structure and spectroscopic information. One of the most commonly studied direct interaction types is the pick-up reaction (and its stripping counterpart) involving a single-nucleon transfer. The (He^3,α) reaction, like the (p,d) and (d,t) reactions, is a single-neutron pick-up reaction which is very useful in studying single-hole states in neutron-deficient nuclei which are difficult to study by other reactions.

As a continuation of a study of the (He^3,α) reactions on the nickel isotopes,[1] the $Ni^{60}(He^3,\alpha)Ni^{59}$ reaction has been studied. The purpose of this investigation is to take advantage of the high positive Q value of the reaction to study higher excited states in Ni^{59}, which have not until recently[2–4] been studied by neutron pickup reactions. The applicability of the distorted-wave Born-approximation (DWBA) method in connection with the (He^3,α) reaction has been investigated as a tool for nuclear structure study. Comparison of the experimental results with the predictions of the shell-model pairing theory of Kisslinger and Sorensen has also been made concerning the occupation numbers in Ni^{60}.

II. EXPERIMENTAL PROCEDURES AND RESULTS

The details of the experimental procedures were similar to those described previously.[1] Briefly, a self-supporting 99.2% enriched Ni^{60} target of about 250 $\mu g/cm^2$ thickness was bombarded with a 15 MeV He^3 beam of ~60 nA average current from the University of Pennsylvania tandem accelerator. The experiment was performed using a 24-in.-diam scattering chamber,[5] in which the alpha particles were detected with 500-μ-thick surface-barrier solid-state detectors. Angular distributions were measured by detecting simultaneously the alpha particles at eight different angles relative to the incident beam direction. For beam monitoring purposes an additional detector was placed at a fixed

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* Work supported by the U. S. National Science Foundation.

[1] C. M. Fou and R. W. Zurmühle, Bull. Am. Phys. Soc. **10**, 496 (1965); Phys. Rev. **140**, B1283 (1965).

[2] R. Sherr, B. F. Bayman, E. Rost, M. E. Rickey, and C. G. Hoot, Phys. Rev. **139**, B1272 (1965).

[3] M. K. Brussel, D. E. Rundquist, and A. I. Yavin, Phys. Rev. **140**, B838 (1965).

[4] R. H. Fulmer and W. W. Daenick, Phys. Rev. **139**, B579 (1965).

[5] R. W. Zurmühle, Nucl. Instr. **36**, 168 (1956).

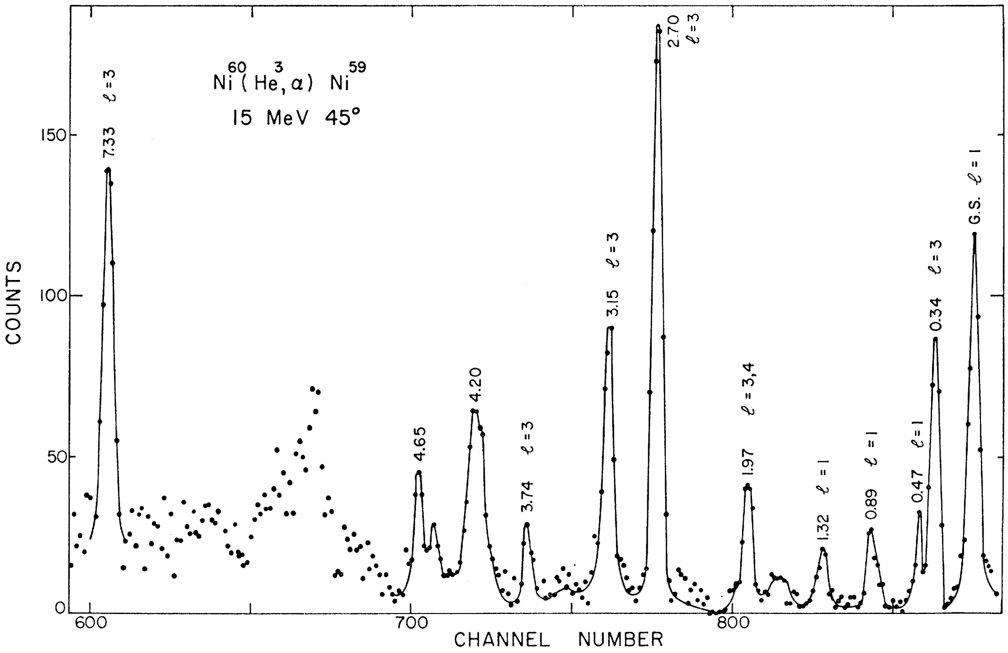

FIG. 1. Alpha-particle spectrum taken at the laboratory angle of 45°. The excitation energies and stripping-pattern l values are indicated.

angle of 45°. In the case of measurements made at angles less than or equal to 20°, pile-up rejection techniques were employed.

Twelve alpha-particle groups were observed corresponding to the ground state, and the 0.34-, 0.47-, 0.89-, 1.32-, 1.97-, 2.70-, 3.15-, 3.74-, and 7.33-MeV excited states of Ni^{59}. An alpha-particle spectrum at 45° is shown in Fig. 1. The excitation energies indicated there are estimated to be accurate to within ±50 keV. All these states have been previously observed in the high-resolution $Ni^{58}(d,p)Ni^{59}$ reaction study of Fulmer, McCarthy, Cohen and Middleton.[6] The presently reported excitation energies are in agreement with those from the (d,p) work within the reported experimental errors.

The experimental angular distributions are shown (by solid points) in Figs. 2–11. Error flags represent statistical uncertainties only. Absolute differential cross sections have been estimated by comparison with the elastic-scattering cross section of He^3. The uncertainties are estimated to be about ±30%.

III. DWBA ANALYSIS

A distorted-wave Born-approximation analysis of the angular distributions represented in Figs. 2–11 has been

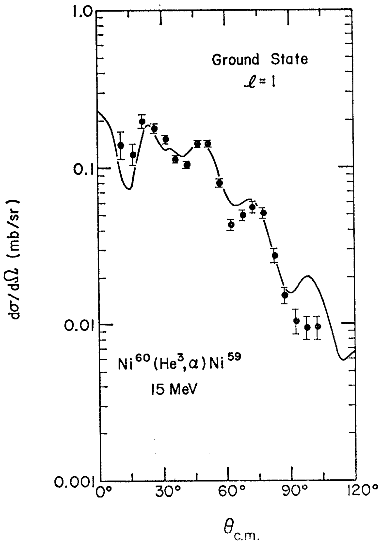

FIG. 2. Angular distribution for ground state. Solid points are experimental and the curve represents the predicted DWBA angular distribution for $l=1$.

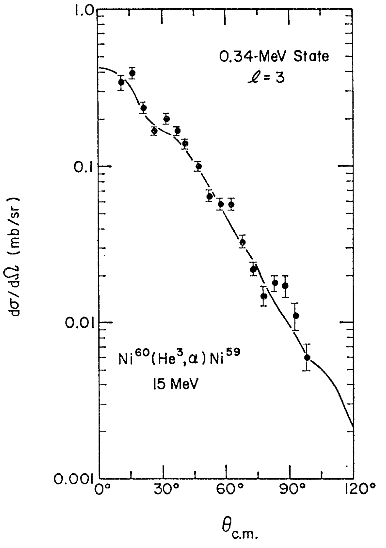

FIG. 3. Angular distribution for 0.34-MeV state. Solid points are experimental and the curve represents the predicted DWBA angular distribution for $l=3$.

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[6] R. H. Fulmer, A. L. McCarthy, B. L. Cohen, and R. Middleton, Phys. Rev. **133**, B955 (1964).

carried out using an optical-model potential of the form

$$U(r)=U_C(r)-\frac{V}{1+\exp x_V}-\frac{iW}{1+\exp x_W}$$

where $U_C(r)$ is the Coulomb potential for a uniform charge distribution of radius $r_CA^{1/3}$ and

$$x_V=(r-r_VA^{1/3})/a_V\,,$$
$$x_W=(r-r_WA^{1/3})/a_W\,.$$

The Oak Ridge National Laboratory JULIE code was used for the DWBA calculations. The numerical values of the optical-potential parameters used in the entrance and exit channels are listed in Table I. The parameters of the He^3 channel are the same as those used in the DWBA analysis of the $Ni^{58}(He^3,\alpha)Ni^{57}$ angular distributions.[1] They were obtained from the analysis of the angular distribution of 15-MeV He^3 elastically scattered from Ni^{58}. Within the limits of the experimental errors it was found that these parameters would also produce a fit to the angular distribution of elastically scattered 15-MeV He^3 from Ni^{60}. Parameters for the alpha-particle channels were obtained from the analysis of elastic alpha-particle scattering from Ni^{58} as described in Ref. 1. They were kept the same for all excited states of Ni^{59} contrary to the procedure used previously in the analysis of the $Ni^{58}(He^3,\alpha)Ni^{57}$ reaction, where the real well depths of the alpha-particle potential were adjusted depending on the energies of the outgoing alpha particles. It has been pointed out,[1] however, that the two procedures lead to the same choice of l values and the discrepancy between their predicted spectroscopic factors is less than 15%.

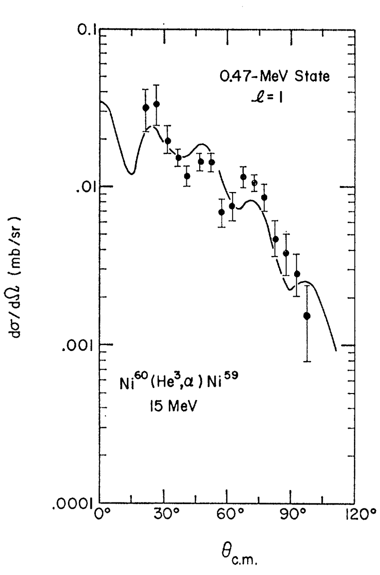

FIG. 4. Angular distribution for 0.47-MeV state. Solid points are experimental and the curve represents the predicted DWBA angular distribution for $l=1$.

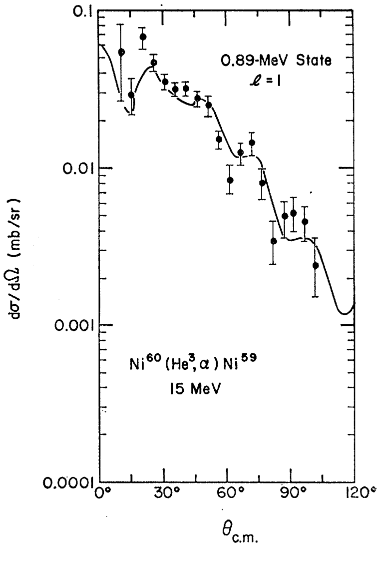

FIG. 5. Angular distribution for 0.89-MeV state. Solid points are experimental and the curve represents the predicted DWBA angular distribution for $l=1$.

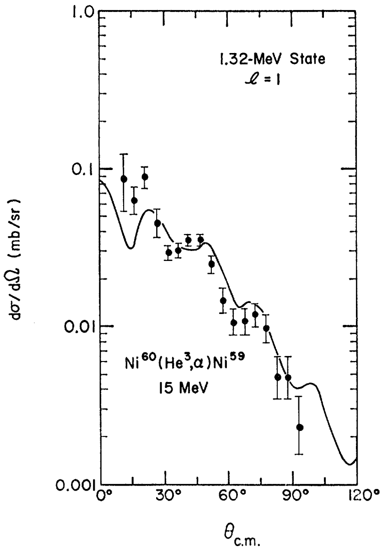

FIG. 6. Angular distribution for 1.32-MeV state. Solid points are experimental and the curve represents the predicted DWBA angular distiibution for $l=1$.

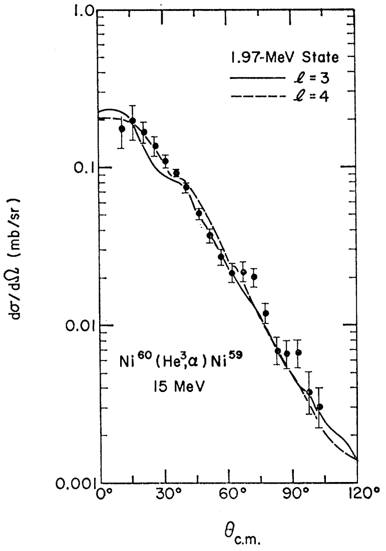

FIG. 7. Angular distribution for 1.97-MeV state. Solid points are experimental and the solid curve corresponds to the predicted DWBA angular distribution for the choice $l=3$ and the broken curve to the choice $l=4$.

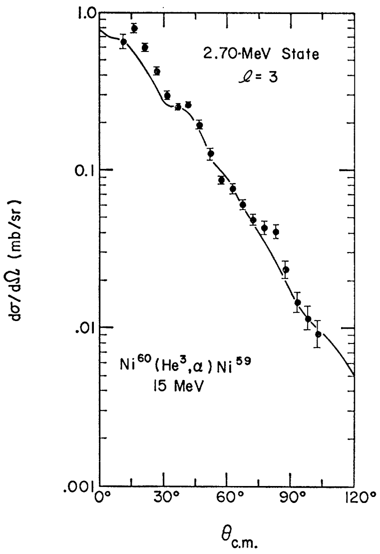

FIG. 8. Angular distribution for 2.70-MeV state. Solid points are experimental and the curve represents the predicted DWBA angular distribution for $l=3$.

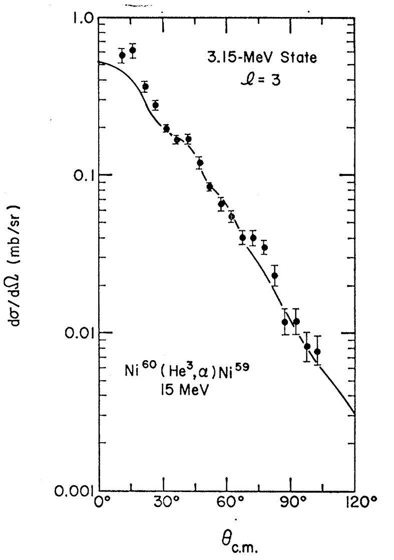

FIG. 9. Angular distribution for 3.15-MeV state. Solid points are experimental and the curve represents the predicted DWBA angular distribution for $l=3$.

The curves shown in Figs. 2–11 are "best-fit" angular distributions calculated by using the DWBA method, for the choice of l value indicated in the figures. The best-fit l values of the ground state and the 0.34-, 0.89-, 1.32-, 2.70-, 3.15-, and 7.33-MeV excited states are in agreement with values obtained from a Ni$^{60}(p,d)$Ni^{59} reaction study reported by Legg and Rost[7] and by Sherr *et al.*[2] Sherr *et al.* make an $l=3$ assignment for states observed at 1.96- and 4.17-MeV excitation. Either of the assumptions $l=3$ or $l=4$ for the state observed at 1.97-MeV in the present study leads to an acceptable fit of the calculated angular distribution to the experimental data of Fig. 7. Attempts to fit the angular distributions of alpha-particle groups corresponding to 4.20- and 4.65-MeV excitation did not lead to unique l-value assignments; these groups are presumed to arise from more than one (unresolved) level in Ni^{59}. Consequently, their angular distributions have not been reported. The assignments $l=1$ and $l=3$ are made for the angular distributions (not previously reported) of the 0.47- and 3.74-MeV states, respectively. At least for the low-lying states, the presently observed l values are the same as those observed by Fulmer *et al.*[6] in the Ni$^{58}(d,p)$Ni^{59} reaction.

To extract the spectroscopic factors the bound-state wave function of the transferred neutron was calculated using a Woods-Saxon real potential with radius $1.2A^{1/3}$ and diffuseness 0.65 F. The well depth has been determined by specifying the binding energy of the neutron and its shell-model orbital quantum number. Both the customary separation-energy (SE) and the effective-binding-energy (EB) prescriptions have been employed in the calculations. In the effective-binding-energy case the well depth was held fixed at 57.3-MeV. This is the well depth required to bind a $2p$ neutron with a binding

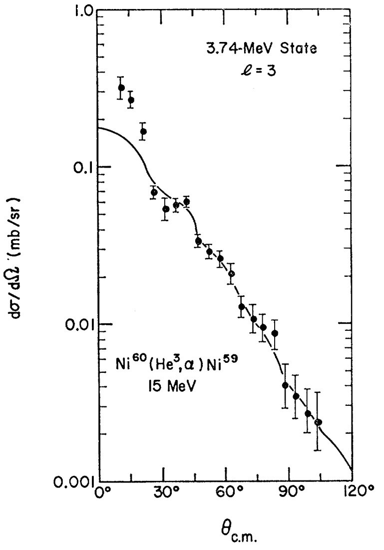

FIG. 10. Angular distribution for 3.80-MeV state. Solid points are experimental and the curve represents the predicted DWBA angular distribution for $l=3$.

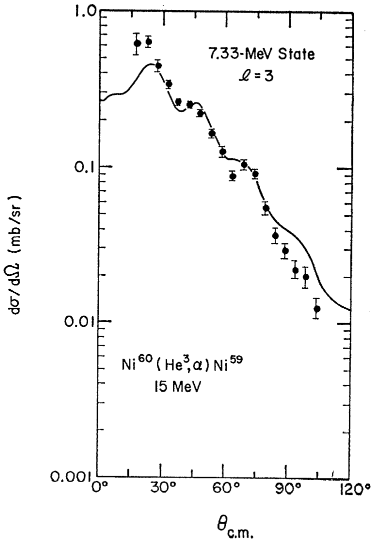

FIG. 11. Angular distribution for 7.33-MeV state. Solid points are experimental and the curve represents the predicted DWBA angular distribution for $l=3$.

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[7] J. C. Legg and E. Rost, Phys. Rev. **134**, B752 (1964).

energy equal to the single-neutron separation energy from Ni^{60} leaving the Ni^{59} nucleus in its ground state. The same well binds a $1f$ neutron with a binding energy equal to the separation energy of a neutron from Ni^{60} leaving Ni^{59} with an excitation energy of about 3 MeV. The angular distributions calculated on the basis of these two procedures differ only very slightly from one another at large angles. Thus, comparisons with the experimental angular distributions do not reveal any marked preference for one or the other. The extracted relative spectroscopic factors are listed in Table II. The spin assignments listed in Table II are those given in Ref. 2.

The discrepancies between the spectroscopic factors from these two procedures are small for the low-lying states with the exception of the $f_{5/2}$ state at 0.34-MeV excitation.

For the 7.33-MeV $\frac{7}{2}^-$ state they differ by a factor of 3. The results are in fairly good agreement with those obtained in the (p,d) work.[2]

IV. DISCUSSION AND CONCLUSIONS

The shell-model pairing theory[8] predictions of the occupation numbers for the $2p_{3/2}$, $1f_{5/2}$, $2p_{1/2}$, and $1g_{9/2}$ states in Ni^{60} are 2.28, 1.44, 0.20, and 0.08 respectively.

TABLE I. He^3 and alpha-particle optical-model parameters.

Channel	V (MeV)	W (MeV)	r_V (F)	r_W (F)	r_C (F)	a_V (F)	a_W (F)
He^3	34.3	12.9	1.67	1.67	1.4	0.58	0.58
α	77.0	12.0	1.52	1.52	1.4	0.60	0.60

TABLE II. Relative spectroscopic factors for individual levels from DWBA analysis. SE = separation energy; EB = effective binding energy.

Excitation energy (MeV)	l	Spin	Relative spectroscopic factor SE	EB
ground state	1	$\frac{3}{2}$	1.85	1.59
0.34	3	$\frac{5}{2}$	1.31	1.82
0.47	1	$\frac{1}{2}$	0.21	0.15
0.89	1	$\frac{3}{2}$	0.34	0.24
1.32	1	$\frac{1}{2}$	0.29	0.20
			4.00[a]	4.00[a]
1.97	3	$(\frac{5}{2}, \frac{7}{2})$	0.61	0.62
	4	$(\frac{9}{2})$	0.55	0.58
2.70	3	$\frac{7}{2}$	1.60	1.37
3.15	3	$\frac{7}{2}$	0.80	0.69
3.74	3	$\frac{7}{2}$	0.32	0.23
7.33	3	$\frac{7}{2}$	1.46	0.42
			4.79[b]	3.33[b]

[a] Subtotal for the $2p_{3/2}$, $f_{5/2}$ and $2p_{1/2}$ shell-model states.
[b] Subtotal for the $f_{7/2}$ shell-model state.

TABLE III. Total spectroscopic factors. SE = separation energy; EB = effective binding energy.

Shell	I SE	I EB	II SE	II EB	III SE	III EB
$p_{3/2}$	2.19	1.83	1.90	1.58	1.93	1.58
$f_{5/2}$	1.31	1.82	1.66	2.11	1.15	1.57
$p_{1/2}$	0.50	0.35	0.43	0.31	0.44	0.31
$g_{9/2}$					0.48	0.54
$f_{7/2}$	4.79	3.33	3.95	2.34	3.97	2.37
Normalization factor	28.4	33.0	32.5	38.2	32.3	37.8

The total spectroscopic factors of these shell-model states are listed in Table III after normalizing their sum to four, which is the total number of neutrons in Ni^{60} outside the doubly closed $f_{7/2}$ shell. The total spectroscopic factors for the $1f_{7/2}$ shell model state is also given in Table III together with the above mentioned normalization factor. The differential cross sections predicted by the DWBA calculations are smaller than the experimental cross sections by a factor of about 30. Similar factors were obtained in the analysis of the $Ni^{58}(He^3,\alpha)Ni^{57}$ reaction.[1] Column I of Table III represents the total spectroscopic factors for the spin assignments listed in Table II including the choice of $f_{7/2}$ for the 1.97-MeV state. This same choice has been used in normalizing the spectroscopic factors of individual states in Table II. Column II corresponds to the choice $f_{5/2}$ for the 1.97-MeV state and Column III to $g_{9/2}$. These results show that if the 1.97-MeV level is assumed to be a $g_{9/2}$ state ($l=4$), the occupation number for the $g_{9/2}$ shell is much larger than the theoretically predicted value on the basis of either the SE or the EB procedure. The EB prescription predicts a larger $f_{5/2}$ occupation number than the SE procedure. Therefore, according to the pairing theory the EB prescription would exclude the 1.97-MeV level as an $f_{5/2}$ state, while the SE procedure could include it as an $f_{5/2}$ state. It is also apparent that only about one half of the $f_{7/2}$ strength has been observed in the present study. Several more $\frac{7}{2}^-$ states may be expected to be observed above 3.74-MeV excitation.

The total spectroscopic factors for the hole states given in Table III may be compared directly to total spectroscopic factors for the particle states as obtained from the $Ni^{60}(d,p)Ni^{61}$ reaction. Ideally they are related through the expression

$$(2J+1)SJ(\text{particle})+SJ(\text{hole})=2J+1$$

for the J shell-model orbital. Such a comparison is made in Table IV with the (d,p) results reported in Ref. 1. In the work of Ref. 1 all states corresponding to $l_n=1$ were assumed by the authors to be $J=\frac{1}{2}$ when the spin of the state was not otherwise known. Perhaps this accounts to some degree for the fact that the sum of particle-plus-hole spectroscopic factors is too large for

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[8] L. S. Kisslinger and R. A. Sorensen, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. **32**, No. 9 (1960).

TABLE IV. Comparison of particle and hole total spectroscopic factors.

Shell	$2p_{3/2}$	$1f_{5/2}$	$2p_{1/2}$	$1g_{9/2}$	$1f_{7/2}$
$(2J+1)$ S(particle)[a]	1.24	4.74	2.24	9.10	0.0
S(hole)[b]	2.19	1.31	0.50	0.0	4.79
Total	3.43	6.05	2.74	9.10	4.79
$2J+1$	4.0	6.0	2.0	10.0	8.0

[a] Values from column (3), Table III of Ref. 6.
[b] Values from column I-SE, Table III of present paper.

the $2p_{1/2}$ and too small for the $2p_{3/2}$ state. As remarked earlier not all of the $f_{7/2}$ strength has been observed experimentally and this may also be true to a lesser extent for the $g_{9/2}$ strength. The over-all agreement must be regarded as adequate.

The present work shows that the levels in Ni^{59} excited by the $Ni^{60}(He^3,\alpha)Ni^{59}$ reaction are similar to those in Ni^{57} excited by the $Ni^{58}(He^3,\alpha)Ni^{57}$ reaction. Low-lying levels ($\frac{3}{2}^-$, $\frac{5}{2}^-$, and $\frac{1}{2}^-$) arise from configuration mixing in the Ni^{60} ground state and the $\frac{7}{2}^-$ hole-states are split into several widely separated states. Most of the $1f_{7/2}$ strength goes into one low-lying $\frac{7}{2}^-$ state and one highly excited $\frac{7}{2}^-$ state which is the isobaric analog of the Co^{59} ground state. It may be noted here that the analog state is much more strongly excited in the $Ni^{58}(He^3,\alpha)$ and $Ni^{60}(He^3,\alpha)$ reactions than in their $Ni^{58}(p,d)$ and $Ni^{60}(p,d)$ counterparts. In general transitions involving $l=3$ angular-momentum transfers may be expected to be stronger, relative to $l=1$ transitions, in (He^3,α) reactions than in (p,d) reactions. This is possible since the Q-value, and hence the momentum transfer, is much greater for the (He^3,α) reaction than it is for the (p,d) reaction.

The excitation energy (7.33-MeV in Ni^{59}) of the analog state corresponds to a Coulomb-energy difference of $E_C=(9.18\pm0.05)$ MeV between the ground state of Co^{59} and its analog in Ni^{59}. The analog state has also been observed by Anderson, Wong, and McClure[9] whose measured Q value to this state is (9.04 ± 0.13) MeV for the $Co^{59}(p,n)Ni^{59}$ reaction. The two determinations of the Coulomb energy are in agreement within their experimental uncertainties.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of Dr. R. H. Bassel in making the DWBA calculations.

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[9] J. D. Anderson, C. Wong, and J. W. McClure, Phys. Rev. 129, 2718 (1963).

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Polarization of 45-MeV Protons by Complex Nuclei*†

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The asymmetry produced by a beam of 45-MeV protons incident upon targets of beryllium, carbon, aluminum, vanadium, and rhodium has been measured utilizing the polarized proton beam of the U.C.L.A. sector-focused cyclotron. The development of the polarized beam is discussed, with emphasis upon the provision for an independent calibration of the polarization of the beam. The techniques used in the polarization measurements are given in detail, and the data are compared with previous results at similar energies.

I. INTRODUCTION

MEASUREMENTS of proton-nucleus polarization in the medium-energy region have become available in recent years for a limited range of energies, angles, and nuclides.[1–4] It has been shown that in this energy region, data on the differential cross section are not sufficient to constrain the parameters of the optical model,[3] and measurements of polarization must be correlated with the cross-section data. The purpose of the work described in this paper was to make measurements of polarization in proton-nucleus scattering which could be analyzed together with differential-cross-section[5] and total-reaction-cross-section data taken at this laboratory in an optical-model study of selected nuclides.

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