Characteristics of the Differential Cross Sections for the Low-Energy (p, n) Reaction on the Spin-$\frac{1}{2}$ Medium-Mass Nuclei*

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The differential cross sections of neutron groups resulting from the bombardment of isotopically enriched ^{111}Cd, ^{113}Cd, ^{117}Sn, and ^{119}Sn targets with a 5.35-MeV pulsed proton beam have been measured with a time-of-flight system. The observed angular distributions $\sigma(\theta)$ of the neutron groups feeding the low-lying residual states are all consistent with symmetry about $\theta=90°$. They show the following distinct features which characterize the spin change $\Delta I=I_f-I_i$, where I_i and I_f are the spin values of the target and residual states: $\Delta I=0$ transitions exhibit pronounced forward angle peaking; $\Delta I=1$ transitions are isotropic; $\Delta I=2$ transitions show mild peaking around 90°; the integrated differential cross section for $\Delta I=1$ is greater than that for $\Delta I=0$ for transitions from a given target nucleus leading to residual states with similar energies. A simplified consideration of the conservation of angular momentum and parity in the framework of the statistical theory of compound-nuclear reactions reveals that the characteristic shape of $\sigma(\theta)$ associated with the ΔI of a transition is a manifestation of the conservation laws. The experimental results also compare reasonably well with the theoretical predictions of the generalized Hauser-Feshbach theory of nuclear reactions.

INTRODUCTION

ALTHOUGH the statistical theory of compound nuclear reactions can be used as a spectroscopic tool for assigning the spins of the final states of a reaction,[1] this aspect of the theory has been exploited only in a few cases. Examples are the (p, n) work of Kim *et al.*[2,3] and the (n, n') work of Cranberg *et al.*[4] One reason for this limited usage is that often the statistical process does not dominate a nuclear reaction. For example, at moderate energies, direct reactions compete with the compound process. Also in light nuclei the level densities are too small for the theory to apply. Yet the theory is applicable to many reactions[5] in which the energy of the incident particle is not too high and the target is not too light. The (p, n) reactions on medium to heavy nuclei are particularly suitable. If the proton energy is chosen only a few MeV above threshold and also well below the top of the Coulomb barrier, then the compound states decay mostly by neutron emission to low-lying states. This neutron yield is expected to dominate over the direct process. (In contrast, inelastic proton groups, for example, will be strongly inhibited by the Coulomb barrier and may be about the same intensity as those from the direct process. At higher incident energies, this unfavorable competition with the direct process will hold also for the neutron groups because the compound states decay mostly in a boil-off spectrum rather than to low-lying states.)

We have been studying systematically the (p, n) reactions for targets ranging from As ($Z=33$) to Sn ($Z=50$) utilizing the neutron time-of-flight system associated with the 5.5-MV Van de Graaff accelerator. These choices of projectile, projectile energies, and targets are appropriate to the theory. The target nuclei are large enough so that the compound states are expected to be densely populated even at moderate excitation energies, and this expectation is supported by the available data[6,7] which show that the cross-sections vary smoothly with energy. Proton energies near 5 MeV are far enough up on the Coulomb barrier to assure an adequate cross section, about 10 mb for Sn, but not so far up as to cause much direct (p, n) reaction.

Our purpose in the present study was to see if the angular distributions of neutron groups from the (p, n) reaction reveal any information about the spin parities of the residual states. This study has been limited to four nuclei in the same mass region which share the common property of the same ground state spin-parity ($\frac{1}{2}^+$). Furthermore, we have divorced the analysis as much as possible from the detailed model-dependent parts of the theory. We find from a simple empirical examination for final states of known spin that the distributions are characteristic of the spin change ΔI be it 0, 1, or 2 units. Beginning with the general theory for statistical compound-nuclear reactions, we demonstrate that these properties are expected from the simple kinematics of the angular momenta involved in the reaction. On this basis we conclude that the observed

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[6] C. H. Johnson, A. Galonsky, and C. N. Inskeep, Bull. Am. Phys. Soc. **3**, 305 (1958); Oak Ridge National Laboratory Report, ORNL-2910, 1960 (unpublished); J. Wing and J. R. Huizenga, Phys. Rev. **128**, 280 (1960).
[7] C. H. Johnson and R. L. Kernell, Bull. Am. Phys. Soc. **10**, 53 (1965).

TABLE I. Excitation energy (ex) and spin parity (I^π) of states observed.

^{117}Sn$(p,n)^{117}$Sb ex (keV)	I^π	^{119}Sn$(p,n)^{119}$Sb ex (keV)	I^π	^{113}Cd$(p,n)^{113}$In ex (keV)	I^π	^{111}Cd$(p,n)^{111}$In ex (keV)	I^π
g.s.	$\frac{5}{2}+$ [a,b,c]	g.s.	$\frac{5}{2}+$ [a,c,d]	g.s.	$\frac{9}{2}+$ [e,f]	g.s.	$\frac{9}{2}+$ [f,g]
529	$\frac{7}{2}+$ [a,b,c]	270	$\frac{7}{2}+$ [a,c,h,i]	393	$\frac{1}{2}-$ [f,j,k]	535	$\frac{1}{2}-$ [g,l]
720	$\frac{1}{2}+$ [a,b,c,m]	645	$\frac{1}{2}+$ [a,c,h,i]	648	$\frac{3}{2}-$ [f,k]	801	unknown
924	$\frac{3}{2}+$ [a,b,c,m]	702	$\frac{3}{2}+$ [a,c,h,i]				

[a] T. Ishimatsu *et al.*, see Ref. 14.
[b] H. Fuchs *et al.*, Phys. Letters **25B**, 204 (1967).
[c] G. Bassani *et al.*, Phys. Letters **22**, 189 (1966).
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[h] G. Graeffe *et al.*, Phys. Rev. **158**, 118 (1967).
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[k] H. E. Bosch *et al.*, Phys. Rev. **159**, 1029 (1967).
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[m] G. Berzins *et al.*, Nucl. Phys. **A104**, 241 (1967).

distributions could be used to assign the spin changes. Finally we find that the predictions of the detailed theory with usual optical-model parameters agree fairly well with the experimental results.

EXPERIMENTAL PROCEDURE

Since our experimental technique has been described previously,[3] we need to mention only a few details here. Targets of about 0.4 mg/cm^2 each were prepared by evaporating isotopically-enriched elemental form of ^{111,113}Cd and ^{117,119}Sn onto Pt backings. The incident 5.35-MeV proton beam was pulsed with a 2-MHz repetition rate, and the neutrons were detected after a 3-m flight path by a detector which was movable from 0° to 120°. This particular value of the incident energy was chosen because no anomalies in the (p,n) yield are expected near $E_p = 5.35$ MeV (sufficiently away from the isobaric analogue resonances) for all the targets except ^{111}Cd. Although this energy is near the expected isobaric analogue resonance of the 1.31-MeV state of ^{112}Cd, the neutron yield studied around $E_p = 5.3$ MeV did not show any anomaly. A combined time resolution of about 2.5 nsec was achieved for the detection system and pulsed beam; hence the neutron energy resolutions for the 3-m flight path were about 42, 67, and 127 keV for 1, 2, and 3-MeV neutrons, respectively. The detected neutrons at each angle were normalized by use of a second detector which monitored the source strength from a fixed angle. γ rays were observed by means of a 30-cc Ge(Li) detector.

RESULTS AND DISCUSSION

Experimental Results

We found from auxiliary high-resolution studies of the neutron spectra and also from the spectra of the deexcitation γ rays that the residual nuclei ^{111,113}In and ^{117,119}Sb have many closely spaced levels above 1-MeV excitation. In this work, we have restricted our studies to states below 1 MeV. A representative neutron time-of-flight spectrum is shown in Fig. 1.

Table I lists the energies and the spin parities I^π of the low-lying states which we studied in the four residual nuclei, and Figs. 2(a)–2(d) show the observed angular distributions for the neutrons feeding these states. No angular distribution was obtained for the very weak group to the first-excited state of ^{119}Sb and the distribution to the second and third states is shown as a single sum because our effective resolution 130 keV

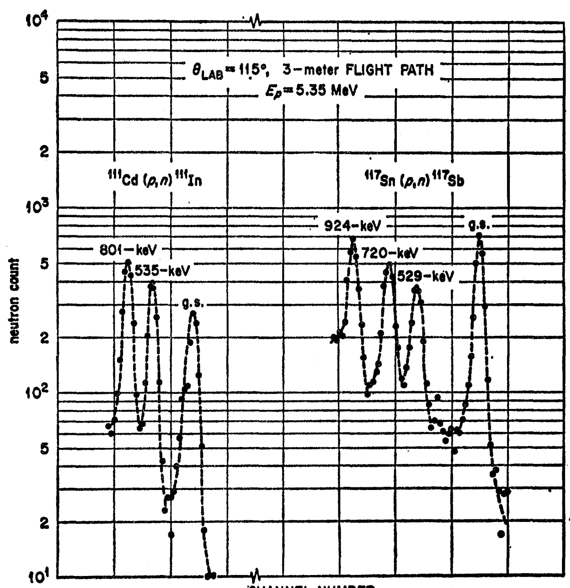
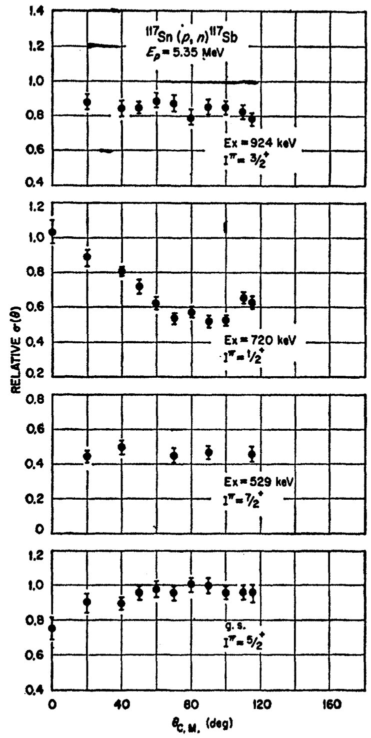
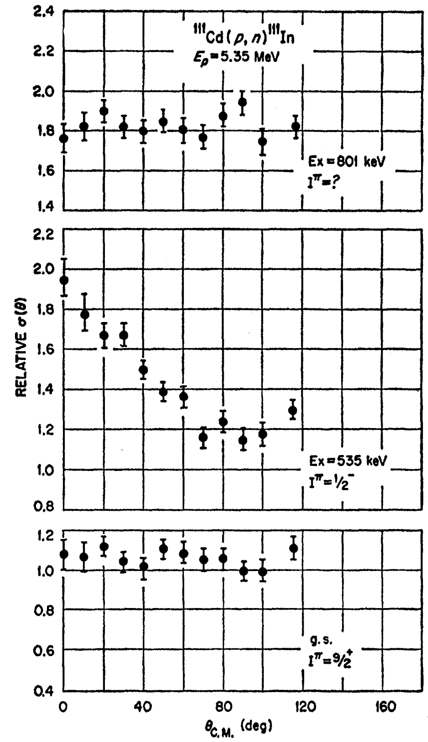


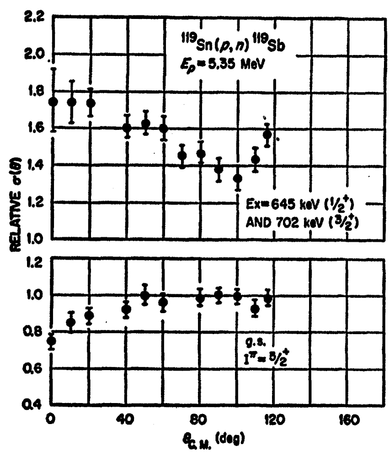
FIG. 1. Neutron time-of-flight spectra. The channel number corresponds to neutron flight time.



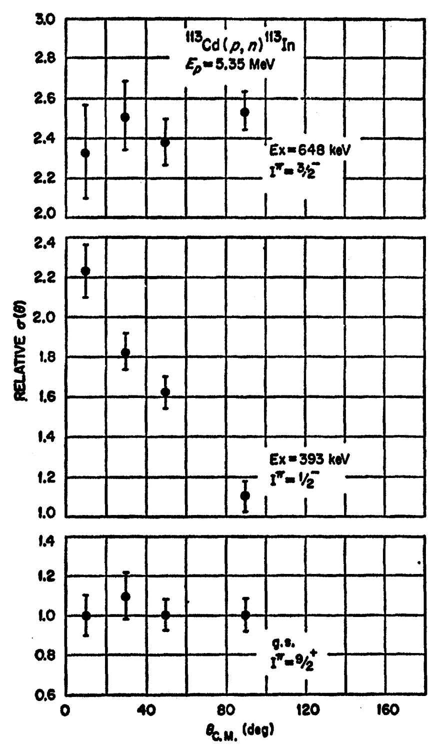
(a)



(b)



(c)



(d)

FIG. 2(a)–2(d) Relative differential cross section for the (p, n) transitions summarized in Table I.

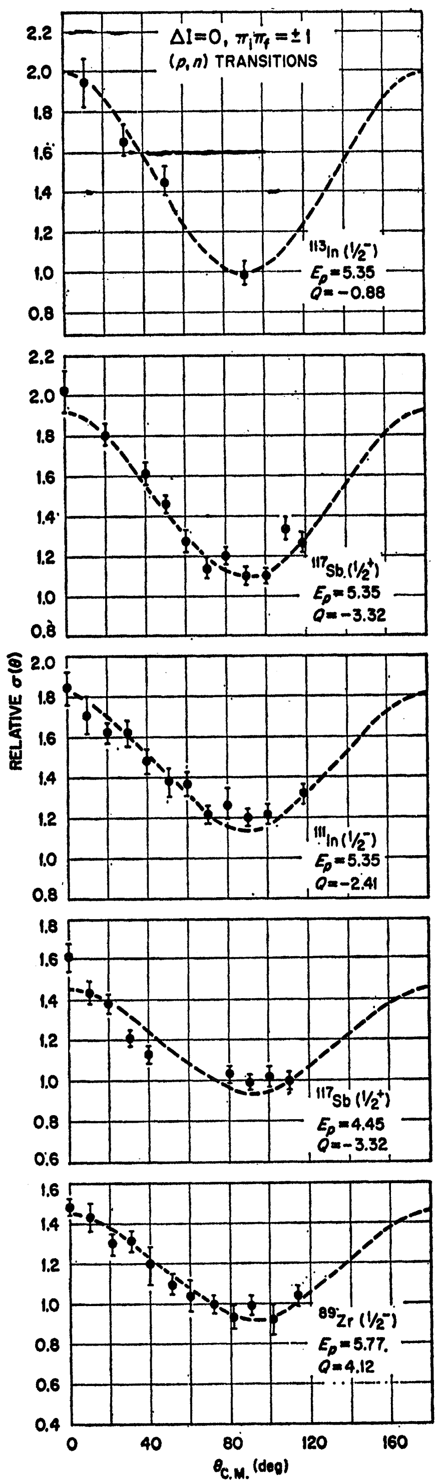


FIG. 3. Angular distributions of the neutrons resulting from $\Delta I=0$ transitions. Dashed curves shown are explained in the text.

was not adequate to separate these groups. In each figure the cross sections for all groups are given in a common unit which is unity for the ground-state neutron group at 90°. The indicated errors arise primarily from the uncertainty of the background subtraction.

The experimental data for ^{113}Cd and ^{119}Sn are less complete than for the other targets because the count rates were relatively low. The (p, n) reaction cross sections for all four targets for a given incident energy near 5 MeV are nearly the same[2,7]; therefore, the lower yield implies that the reaction cross sections for ^{113}Cd and ^{119}Sn are shared by more competing neutron channels than for ^{111}Cd and ^{117}Sn. This deduction is consistent with less negative (p, n) reaction Q values (hence more excitation energy available for the residual states) for ^{113}Cd ($Q=-0.49$ MeV) and ^{119}Sn($Q=-1.36$ MeV) as compared to -2.60 and -1.87 MeV for ^{117}Sn and ^{111}Cd.

According to the statistical theory, the differential cross sections $\sigma(\theta)$ are expected to be symmetric about 90°. Since the experimental $\sigma(\theta)$'s do not extend beyond 117°, checking the validity of this prediction is not an easy matter. However, as in the past,[3] a least-squares analysis of the data in terms of the Legendre polynomial indicates that the experimental $\sigma(\theta)$'s are consistent with this prediction. Also, as illustrated in Figs. 3–6 (dashed curves), all angular distributions can be

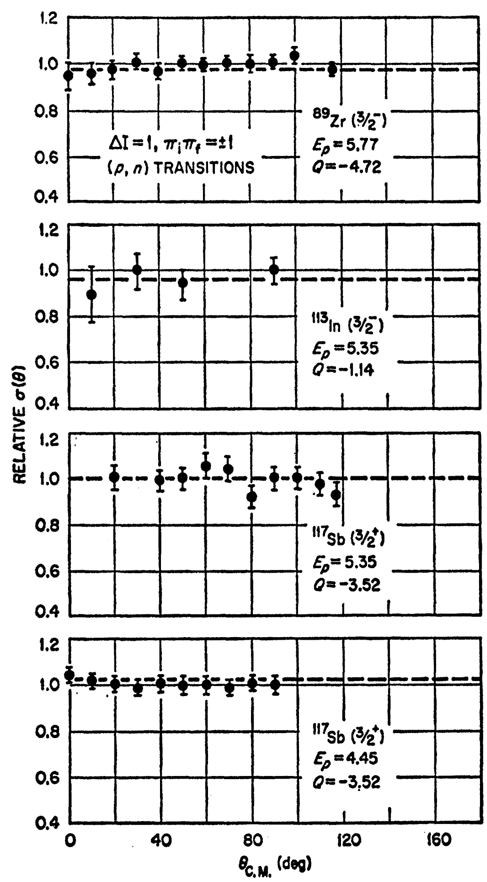


FIG. 4. Angular distributions of the neutrons resulting from $\Delta I=1$ transitions. Dashed curves shown are explained in the text.

adequately represented by an expression $\sigma(\theta)=\sigma_0+\sigma_2P_2(\cos\theta)$, where $P_2(\cos\theta)$ is the second-order term of the Legendre polynomial and $4\pi\sigma_0$ is the angle integrated cross section.

The data displayed in Figs. 2(a)–2(d) reveal that the anisotropies of $\sigma(\theta)$'s are of three general characters; isotropic, forward peaked, and peaked at 90°. It is also seen that each of the above characteristics is associated with the spin change ΔI encountered in a particular transition, where ΔI is the difference I_f-I_i between the target spin I_i and residual spin I_f. This correlation is best illustrated by regrouping the angular distributions according to ΔI for all targets as is done in Figs. 3–6. These figures also include the results of the ^{89}Y(p, n)^{89}Zr reaction[3] and the ^{117}Sn(p, n)^{117}Sb reaction for 4.5-MeV bombarding energy.[8] We note that the $\sigma(\theta)$'s dip at 90° for $\Delta I=0$, are isotropic for $\Delta I=1$, and rise at 90° for $\Delta I=2$. The curves shown, which are of the form $\sigma_0+\sigma_2P_2(\cos\theta)$, are visual fits. The above correlation can be stated more precisely in terms of σ_0 and σ_2 in the

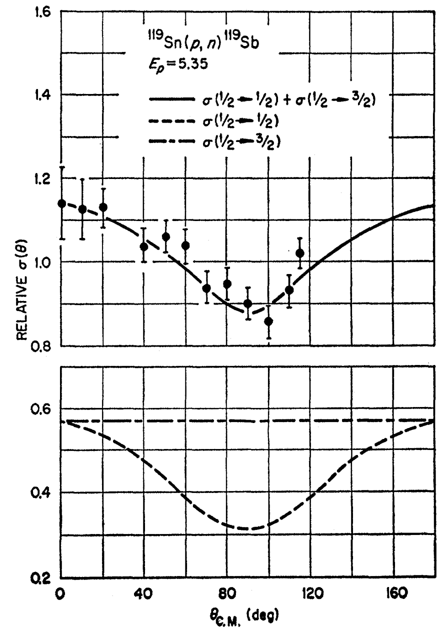


FIG. 6. Comparison of the neutron angular distribution leading to the 645-keV ($\frac{1}{2}^+$) and 702-keV ($\frac{3}{2}^+$) unresolved pair of states of ^{119}Sb to those leading to the analogous states of ^{117}Sb. See the text for detail.

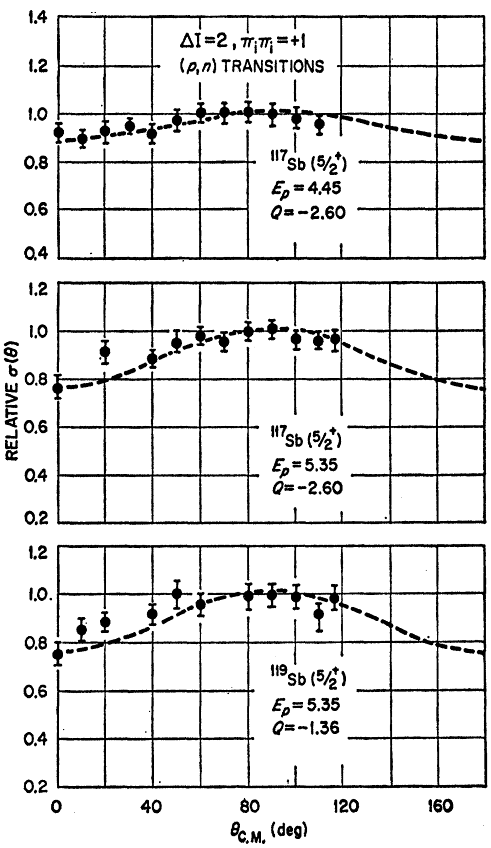


FIG. 5. Angular distributions of the neutrons resulting from $\Delta I=2$ transitions. Dashed curves shown are explained in the text.

following manner: σ_2/σ_0 has value ranging from $+0.3$ to $+0.5$ for $\Delta I=0$, $\sigma_2/\sigma_0=0$ for $\Delta I=1$, and σ_2/σ_0 has negative values ranging from -0.1 to -0.15 for $\Delta I=2$.

Because of the inadequate resolution used for the present work, we cannot examine the validity of the above correlation for the transitions to the 645-keV ($I^\pi=\frac{1}{2}^+$) and 702-keV ($I^\pi=\frac{3}{2}^+$) states of ^{119}Sb directly; however, the high-resolution work[2] at $E_p=4.6$ MeV shows the correlation to be valid for this pair of states involving $\Delta I=0$ and $\Delta I=1$. We can also check the validity for this unresolved pair of transitions indirectly since, from a general consideration of the statistical theory and from the above phenomenologica results, the differential cross sections for the (p, n) transitions at a given bombarding energy to the low-lying pair of states of ^{119}Sb should be similar to those of the analogous states of ^{117}Sb. For this purpose the pair of curves which represents the $\sigma(\theta)$'s for $\Delta I=0$ and $\Delta I=1$ transitons leading, respectively, to the 720-keV ($I^\pi=\frac{1}{2}^+$) and 924-keV ($I^\pi=\frac{3}{2}^+$) states of ^{117}Sb are summed together and compared with the experimental data. The comparison is shown in Fig. 7.

The experimental results also show that the forward angle ($\theta<20°$) differential cross sections $\sigma(\theta)$ for $\Delta I=1$ and $\Delta I=0$ transitions (from a given target nucleus) leading to residual states with similar excitation energies (whose respective spins are $\frac{3}{2}$ and $\frac{1}{2}$) are nearly the same for all cases studied. This observation

[8] H. J. Kim, R. L. Kernell, R. L. Robinson, and C. H. Johnson, Bull. Am. Phys. Soc. **13**, 657 (1958).

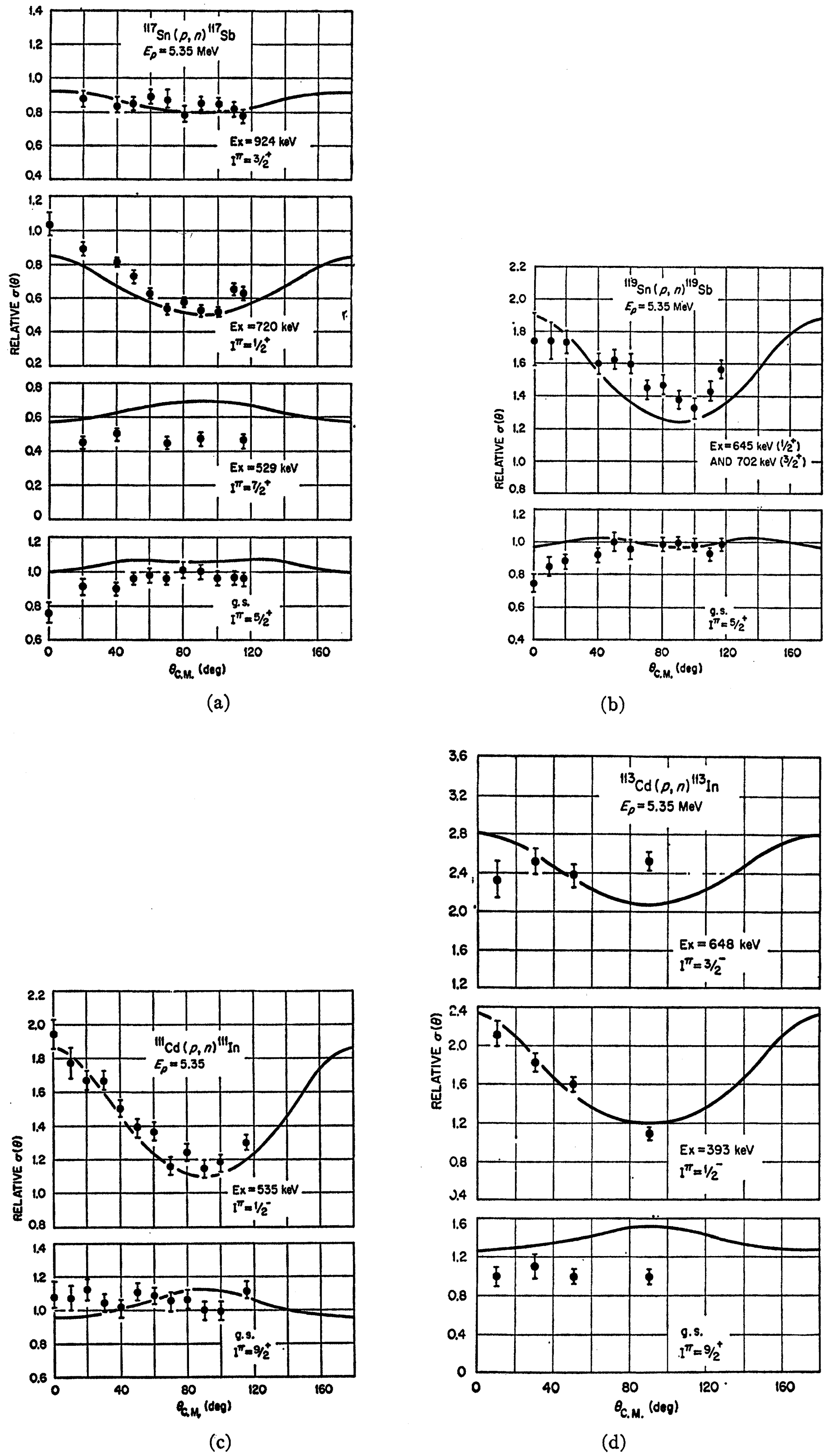


FIG. 7(a)–7(b) Comparison of the theoretical predictions (solid curves) with the experimental results.

is also valid for the (p, n) reaction results on ^{89}Y. Therefore, the partial reaction cross sections $4\pi\sigma_0$, for $\Delta I=1$ transitions are greater than those for the corresponding $\Delta I=0$ transitions [recall $\sigma(\theta)$'s for $\Delta I=0$ peak at forward angles whereas they are isotropic for $\Delta I=1$].

Theoretical Considerations

Although the degree of anisotropy, as shown in Figs. 3 and 5, depends on such factors as E_p, Q value, and size and energy of the compound nucleus, which affect the dynamics of the reaction, it is quite evident that the nature (sign) of anisotropy does not. The intimate relation observed between the spin change ΔI and the nature of anisotropy indicates that this correation may arise from the kinematics of the angular momenta involved in the transition. The following illustrates this to be the situation.

The differential cross section $\sigma(\theta)$ for a (p, n) transition $i\rightarrow f$ via the statistical compound-nuclear reaction[9] process is

$$\sigma(\theta)=\sum\sigma(Jl_pj_pl_nj_n)\eta_\nu(j_pj_pI_iJ)\eta_\nu(j_nj_nI_fJ)P_\nu(\cos\theta), \quad (1)$$

where

$$\sigma(Jl_pj_pl_nj_n)=\tfrac{1}{8}\lambda\!\!\!^{-2}\left(\frac{2J+1}{2I_i+1}\right)\frac{T(l_pj_p)T(l_nj_n)}{\sigma_{\mathrm{C.N.}}(Jl_pj_p)}.$$

The symbols and notations used in the above expressions are the same as those used by Sheldon[9] except the spins of the target and residual states are designated by I's rather than J's, and the partial compound-nucleus formation cross-section is denoted by $\sigma_{\mathrm{C.N.}}(Jl_pj_p)$. In general, the differential cross section, as given in Eq. (1), is quite complicated involving many terms. However, for the purpose of relating the observed dependence of $\sigma(\theta)$ on ΔI to the pertinent features of the statistical theory, $\sigma(\theta)$ can be simplified considerably. Since the experimental angular distributions are of the form $\sigma_0+\sigma_2P_2(\cos\theta)$, as illustrated in Figs. 3–6, the terms contributing to the fourth and higher order of this expansion may be neglected. Thus,

$$\sigma(\theta)\cong\sum\sigma(Jl_pj_pl_nj_n)\{1+\eta_2(j_pj_pI_iJ)\times\eta_2(j_nj_nI_fJ)P_2(\cos\theta)\}.$$

With a simplifying assumption that the nucleon transmission factors $T(lj)$ do not depend on j [i.e., neglect the spin-orbit interaction insofar as the $T(lj)$ are concerned]

$$\sigma(\theta)\cong(\sigma/4\pi)+\sum\sigma(J,l_p,l_n)A(J,l_p,l_n)P_2(\cos\theta), \quad (2)$$

where σ is the reaction cross section for $i\rightarrow f$,

$$A(J,l_p,l_n)=\sum_{j_p,j_n}\eta_2(j_pj_pI_iJ)\eta_2(j_nj_nI_fJ),$$

and j's are to be summed over $l\pm\frac{1}{2}$. We note that the coefficient for P_2 is a sum of products of two factors. Of these factors $\sigma(J,l_p,l_n)$, which is the partial (p, n) cross section for incident protons with angular momentum l_p forming compound states with spin J which then decay via neutrons with l_n leaving residual nucleus in state I_f, is positive and depends on the specific knowledge of the nuclear interaction; its value can only be calculated within a framework of a model theory. However, the second of these factors $A(J,l_p,l_n)$ is entirely made up of the probability amplitudes $\eta_\nu(jjIJ)$ that a given angular momentum j will combine with I to form compound states with spin J (η_ν's have been formulated and tabulated by Satchler[10]). Therefore $A(J,l_p,l_n)$'s are exactly calculable. The angular momentum conservation law is explicitly accounted for in the structure of η_ν's while the parity conservation restricts the terms to be included in $A(J,l_p,l_n)$ by requiring that l's be of correct parity. It follows that the characteristic anisotropy for various ΔI should reflect the conservation laws as applied through the kinematical factors, $A(J,l_p,l_n)$'s. To see this more clearly, the relevant values of $A(J,l_p,l_n)$ are tabulated in Table II for various spin changes ΔI for $I_i=\frac{1}{2}$ and both parities. Because of the simple nature of the observed results [recall $\sigma(\theta)=\sigma_0+\sigma_2P_2(\cos\theta)$] and in view of the low energies involved, entries in this table are limited to those associated with l_p, l_n, and J not exceeding 2. The entries in this table clearly explain the observed nature of the anisotropy; i.e., it is positive for $\Delta I=0$, it is much smaller for $\Delta I=1$ than for $\Delta I=0$ and $\Delta I=2$, and it is negative[11] for $\Delta I=2$. Also note that the anisotropy is independent of parity if the initial and final states are of the same parity, e.g., $\frac{1}{2}^-\rightarrow\frac{1}{2}^-$ is identical to $\frac{1}{2}^+\rightarrow\frac{1}{2}^+$. Recently Sheldon and Van Patter[12] investigated the relation between the anisotropy and ΔI for inelastic nucleon scattering reactions for various target spin I. Their theoretical results are consistent with the present work.

Thus, having been encouraged by the qualitative agreement between the theory and experiment, we calculated $\sigma(\theta)$ exactly as given by Eq. (1). These calculations were exact to the extent that the maximum value of the nucleon (proton and neutron) angular

[9] E. Sheldon, Rev. Mod. Phys. **35**, 795 (1963).

[10] G. R. Satchler, Proc. Phys. Soc. (London) **A56**, 1081 (1953).

[11] That it is negative even though one of the coefficients is positive is based on the following argument: If only the $A(1,1,1)$ coefficient played an important role, which would be required for a positive anisotropy for the $\Delta I=2$ case, then the $\Delta I=1$ case, where $A(1,1,1)=-0.40$, would have a strongly negative anisotropy. This is contrary to our experimental results where the angular distributions are isotropic for $\Delta I=1$.

[12] E. Sheldon and D. M. Van Patter, Rev. Mod. Phys. **38**, 143 (1966).

TABLE II. Tabulation of $A(J, l_p, l_n)$. Entries denoted by PV are parity forbidden cases.

J	l_p	l_n	$\Delta I = 0_{(1/2^- \to 1/2^-)}{}^{(1/2^+ \to 1/2^+)}$	$\Delta I = 1_{(1/2^- \to 3/2^-)}{}^{(1/2^+ \to 3/2^+)}$	$\Delta I = 2\,(\frac{1}{2}^+ \longrightarrow \frac{5}{2}^+)$	$\Delta I = 0\,(\frac{1}{2}^+ \longrightarrow \frac{1}{2}^-)$	$\Delta I = 1\,(\frac{1}{2}^+ \longrightarrow \frac{3}{2}^-)$
1	1	1	+0.50	−0.40	+0.10	PV	PV
1	2	2	+0.50	−0.00	−0.36	PV	PV
2	1	1	+0.70	0.00	−0.50	PV	PV
2	2	2	+1.50	+0.29	−0.57	PV	PV
1	1	2	PV	PV	PV	+0.50	0.00
1	2	1	PV	PV	PV	+0.50	−0.40
2	2	1	PV	PV	PV	+0.70	0.00
2	1	2	PV	PV	PV	+1.50	+0.26

momentum was extended to $j_{\max} = \frac{13}{2}$, and the partial cross sections were constructed with the nucleon transmission factors generated in the framework of the optical model. The potentials adopted for the calculation are those of Perey[13] for protons and of Wilmore and Hodgson[14] for neutrons. We found as in the past,[3] that the shape and relative strength (branching ratio) of $\sigma(\theta)$ for a particular residual state does not require a precise knowledge of the properties (spin parity and energy) of all competing reaction channels. Therefore, we simulated the effects of unknown neutron channels by including ten final states of both parities with spins $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, $\frac{7}{2}$, and $\frac{9}{2}$ uniformly spaced from 1.2- to 2.1-MeV excitation energy. The results are compared with the experimental $\sigma(\theta)$'s in Fig. 7. For each target, the theoretical curves have been normalized by a single factor which gives a good over-all visual fit to the data; therefore, comparisons can be made for the relative strengths of the transitions as well as the shapes. The agreement between the data and the predictions is reasonable in view of the fact that the curves are those predicted straight away rather than by a fitting procedure. In particular we note that the observed transition strengths as well as the magnitudes of anisotropy for $\Delta I = 0$ relative to $\Delta I = 1$ agree well with the theory. For $\Delta I = 1$ and $\Delta I = 2$, the theory does not clearly predict the observed distributions, even though the agreement is reasonably good.

CONCLUSION

We have shown phenomenologically that the low-energy (p, n) reactions from $I = \frac{1}{2}$ targets involving $\Delta I = 0$, 1, and 2 exhibit simple characteristic angular distributions which are the manifestations of the conservation of angular momentum and parity in the compound-nuclear reaction. A (p, n) reaction is, therefore, a useful tool for assigning spins. Although this tool does not yield a unique spin-parity assignment by itself, it can often give a unique result when used to supplement results from studies of radioactive decay or from nucleon transfer reactions, which usually are not unique either. For example, the ^{114}Sn$(d, {}^3$He$)^{113}$In reaction to the second and third excited states might show similar $l = 1$ angular distributions indicating the spins of these states are either $\frac{1}{2}$ or $\frac{3}{2}$ while the parity of both states is negative. The ^{113}Cd$(p, n)^{113}$In reaction would supplement this result by the use of phenomenological rules for the shape of the angular distributions as well as the relative strength of $\Delta I = 0$ and $\Delta I = 1$ transitions. Likewise the rules concerning $\Delta I = 1$ and $\Delta I = 2$ could supplement such result as the ^{116}Sn$(^3$He, d$)^{117}$Sb reaction leading to a $I = \frac{3}{2}^+$ or $\frac{5}{2}^+$ state via $l = 2$ transfer.[15]

[13] F. G. Perey, Phys. Rev. **131**, 745 (1963).

[14] D. Wilmore and P. E. Hodgson, Nucl. Phys. **55**, 673 (1964).

[15] T. Ishimatsu, K. Yagi, H. Ohmura, Y. Nakajima, T. Nakagawa, and H. Orihara, Nucl. Phys. **A104**, 481 (1968).