Structure of Odd-A Indium Isotopes Determined by the $(d, {}^3He)$ Reaction*

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The nuclear structure of the odd-A indium isotopes with masses 115, 117, 119, 121, and 123 has been studied using the proton pickup reaction $Sn(d, {}^3He)In$ with a deuteron bombarding energy of 28.9 MeV. Seven or more levels have been observed in each isotope. Excitation energies have been measured and l values and spectroscopic factors have been extracted from the measured angular distributions. Ground-state Q values have been measured relative to that for ${}^{116}Sn$. The five $(d, {}^3He)$ spectra are quite similar. The ground state and levels at approximately 0.3 and 0.6 MeV in each nucleus are excited by pickup of a proton from the $1g_{9/2}$, $2p_{1/2}$, and $2p_{3/2}$ orbitals, respectively. These three levels contain approximately 70% of the $g_{9/2}$ sum-rule strength, 75% of the $p_{1/2}$ strength, and 50% of the $p_{3/2}$ strength. There is evidence for additional $g_{9/2}$ strength in $l=4$ transitions near 1.4 MeV in each isotope. The existence of these transitions can be explained by an admixture of the $g_{9/2}$ hole configuration with the $\frac{9}{2}^+$ member of the multiplet formed by coupling a $g_{9/2}$ hole to the collective 2^+ state near 1.2 MeV in the tin core. Transitions to levels weakly excited near 1.0 MeV in ${}^{115}In$, ${}^{117}In$, and ${}^{119}In$ are best reproduced with $l=2$ distorted-wave-approximation curves. If these levels are populated by a one-step $l=2$ direct reaction, it indicates a nonclosure of the $Z=50$ proton shell in the tin ground state. Surprisingly, no $l=3$ transitions corresponding to pickup of protons from the $1f_{5/2}$ orbital were observed, even though most of the isotopes were studied up to 3.5-MeV excitation.

I. INTRODUCTION

The tin region of the periodic table is of particular interest in nuclear spectroscopy because of the major shell closure at $Z = 50$. Because tin has an unusually large number of stable isotopes, it is possible to observe in systematic fashion the effects of a changing neutron number on nuclear properties.

The proton configurations of the low-lying levels in the $Z = 49$ indium isotopes are expected to be relatively simple: To a first approximation they should be describable as single-hole states in the $Z = 28-50$ shell. It is of interest to determine the distribution of the proton-hole strength among the low-lying levels in indium experimentally and to observe the changes in this distribution as the number of neutron changes.

In the following sections we report the results of a systematic study of the level structure of the odd-A indium isotopes with masses 115, 117, 119, 121, and 123. These nuclei were studied using the $Sn(d, {}^3He)In$ proton pickup reaction with a bombarding energy of 28.9 MeV. Assuming the $Z = 50$ shell is completely closed in the even-A tin target nuclei, the $(d, {}^3He)$ reaction will excite levels in indium by picking up protons from the $1g_{9/2}$, $2p_{1/2}$, $2p_{3/2}$, and $1f_{5/2}$ single-particle orbitals.

Some results from a study of the $(d, {}^3He)$ reaction at 22 MeV on even tin isotopes have been published previously by Conjeaud, Harar, and Thuriere (CHT).[1] Their study of six indium nuclei was restricted, however, to the lowest three levels.

In each of the isotopes studied, we have observed seven or more levels, have measured their excitation energies, and have extracted l values and spectroscopic factors from their measured angular distributions. The ground-state Q values have been measured relative to that for ${}^{116}Sn$. The experimental results will be discussed in the context of possible models for these nuclei.

II. EXPERIMENTAL PROCEDURE

A 28.9-MeV deuteron beam from the University of Michigan 83-in. isochronous cyclotron was used to bombard thin targets of the tin isotopes. The beam was transported from the cyclotron to the scattering chamber by two double-focusing beam-preparation magnets. When recording the $(d, {}^3He)$ spectra with the best resolution, the incident beam was defined spatially in the scattering chamber by a 1.5-cm × 1-mm slit which limited the deuteron energy spread on the target to about 5 keV. The ${}^3He$ reaction products were analyzed in momentum using one of the three available magnets in the high-resolution magnetic-analysis system. The magnet subtended a solid angle of about 1.6×10^{-3} sr and 4° of scattering angle. Spectra recorded at each magnetic-field setting of the spectrograph covered approximately 2.5 MeV in excitation. The ${}^3He$ ions were detected in 100-μ Ilford K0 nuclear emulsion plates placed at the image surface of the spectrograph. After development, the plates were scanned by microscope to count the ${}^3He$ tracks. At scattering an-

TABLE I. The isotopic analysis, in at.%, of the enriched tin used in the fabrication of targets. The amounts of tin 112, 114, and 115 were each less than 0.06% in all targets.

	Tin isotope						
Target	116	117	118	119	120	122	124
^{116}Sn	95.7	1.02	1.49	0.32	1.06	0.13	0.15
^{118}Sn	0.37	0.42	96.6	0.82	1.58	0.13	0.06
^{120}Sn	0.2	0.12	0.5	0.39	98.4	0.15	0.26
^{122}Sn	0.34	0.17	0.91	0.49	4.72	92.3	1.12
^{124}Sn	0.43	0.30	1.17	0.40	1.75	1.21	94.7

gles less than 15°, a solid-state position-sensitive detector was used at the image surface of the spectrograph instead of plates, because of an intense deuteron background in the emulsions. With this arrangement, the unwanted deuteron signals could be electronically separated from those of the ^{3}He ions.

The enriched tin isotopes used in the target fabrication were obtained in metallic form from the Oak Ridge National Laboratory. The isotopic analysis of the enriched tin is listed in Table I.

Target thicknesses were determined by comparing measurements of the elastic scattering of 28.9-MeV deuterons from several natural tin targets and from the isotopically enriched targets, and then cutting and weighing the natural tin targets.

The absolute cross sections reported in the following are estimated to be correct to within 15%. The largest sources of uncertainty are due to inaccuracies in the track counting, in the determinations of target thicknesses, and in the spectograph solid angle.

III. RESULTS AND ANALYSIS

A. Spectra

The spectra obtained for the five odd-A indium isotopes are shown in Figs. 1–5. The energy resolution for the spectra of ^{115}In, ^{117}In, and ^{119}In is 12 keV near the point labeled 300 mm on the focal plane, and gradually worsens to 20 or 22 keV near 0 mm. The best resolution for the ^{121}In and ^{123}In spectra is 40 keV because thicker targets were used. Peaks due to an oxygen impurity in the targets obscure a level at 1.02 MeV in ^{121}In, and a level at 0.66 MeV in ^{123}In. These levels were observed at other scattering angles where the reaction kinematics shifted the oxygen peaks relative to the indium peaks.

In Figs. 1–5, the spectra cover slightly more than 2 MeV of excitation. No peaks, other than those due to the oxygen impurity, were observed to have cross sections greater than 5 μb/sr in the ^{115}In spectrum from 2 to 3.5 MeV, in the ^{117}In spectrum from 2 to 5 MeV, and in the ^{119}In and ^{121}In spectra from 2 to 3.5 MeV. The $(d, {}^3\text{He})$ spectrum for ^{123}In was not recorded beyond 2-MeV excitation. Peaks having cross sections of less than 5 μb/sr were too weak to be analyzed.

Excitation energies were assigned using the known energy-dispersion properties of the spectrograph and are believed accurate to within 2%. In addition, the energy difference between any two levels is accurate to within 2%.

A feature of the five spectra is their similarity. There are four prominent peaks in each spectrum corresponding to excitation of the ground state and levels near 0.3, 0.6, and 1.4 MeV. Differences in the spectra lie principally in the distri-

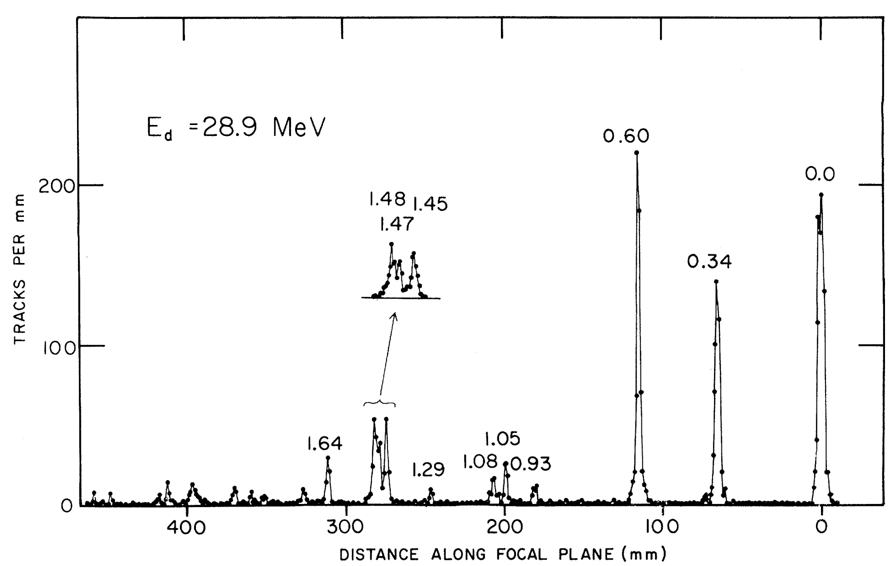

FIG. 1. Spectrum from the ^{116}Sn$(d, {}^3\text{He})^{115}$In reaction recorded at 25°.

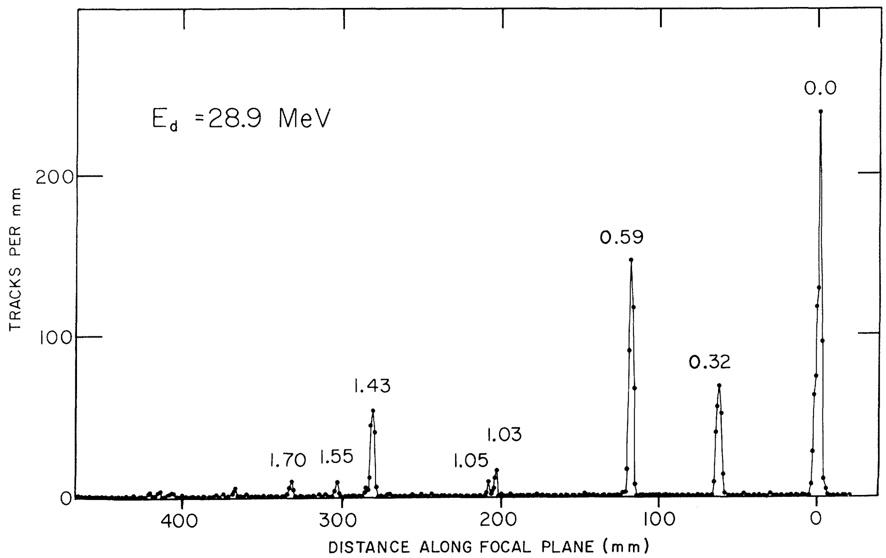

FIG. 2. Spectrum from the ^{118}Sn(d, ^{3}He)^{117}In reaction recorded at 22.5°.

bution of the weaker states above 1-MeV excitation.

B. Q Values

The ground-state (d, ^{3}He) reaction Q values were determined relative to the Q value for the ^{116}Sn(d, ^{3}He)^{115}In reaction. Spectra for two indium isotopes could be recorded simultaneously by placing the appropriate tin targets back to back in the scattering chamber. Because the (d, ^{3}He) Q values become more negative by roughly 800 keV in going from one even tin isotope to the next heavier, the ground-state peak of one indium isotope could be made to appear near the 600-keV level of another in the overlapped spectra. Using the known energy dispersion of the spectrograph and the previously determined excitation energy of the $p_{3/2}$ level near 0.6 MeV in each isotope, Q values could be determined relative to the Q value for the ^{116}Sn(d, ^{3}He) reaction.

The relative Q values determined in this manner and normalized to the Q value listed by Mattauch, Thiele, and Wapstra (MTW)[2] for the ^{116}Sn(d, ^{3}He) reaction are given with their uncertainties in Table II. The uncertainties include the 9-keV uncertainty quoted by MTW.[2] The Q values are compared with those measured in the Sn(d, ^{3}He) experiments by CHT[1] and with those listed in the tabulation by MTW.[2] The Q values measured in the two (d, ^{3}He) experiments agree to within their uncertainties and in some cases have considerably smaller uncertainties than the Q values from the mass data tabulation of MTW.

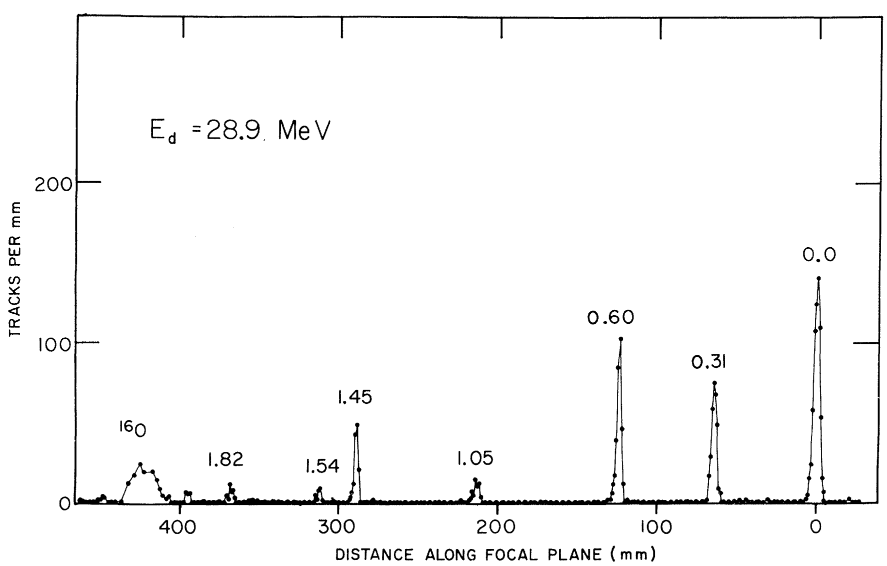

FIG. 3. Spectrum from the ^{120}Sn(d, ^{3}He)^{119}In reaction recorded at 25°.

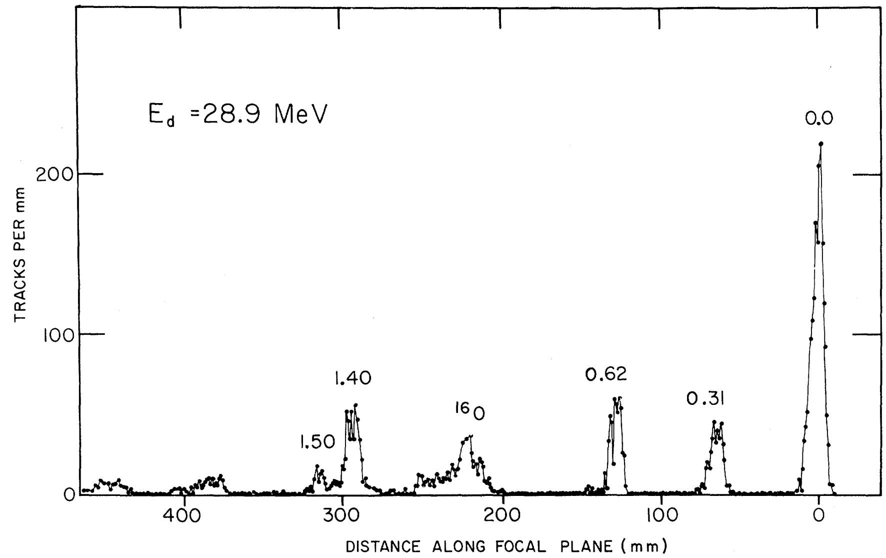

FIG. 4. Spectrum from the ^{122}Sn(d, ^{3}He)^{121}In reaction recorded at 20°.

C. Angular Distributions

The angular distributions for levels excited in ^{115}In, ^{117}In, ^{119}In, ^{121}In, and ^{123}In are shown in Figs. 6–10. The curves drawn through the experimental points are the results of the distorted-wave calculations discussed in the next section. The placement of the theoretical curves has been adjusted on the vertical axis to give the best visual fit to the data. The error bars on the data points represent one standard deviation plus an additional 10% due to uncertainties in the counting of tracks in the nuclear emulsions.

D. Distorted-Wave Analysis

For the (d, ^{3}He) reaction, the differential cross section can be written[3] as

$$d\sigma/d\Omega = 2.95\, S_{lj}\sigma_{lj}(\theta)\,.$$

The spectroscopic factors S_{lj} contain the nuclear-structure information and, for a particular transition, the corresponding S_{lj} can be interpreted as a measure of to what extent the wave function of the level in indium is equivalent to the ground state of the tin target plus a proton hole.

The reduced cross sections $\sigma_{lj}(\theta)$ were obtained from the distorted-wave-approximation (DWA) computer codes JULIE[4] and DWUCK.[5] The parameters used in the calculations are listed in Table III. The optical-model parameters for the incoming deuteron channel were obtained by an extrapolation to higher A and Z of the trends found by Newman *et al.*[6] to describe the elastic scattering

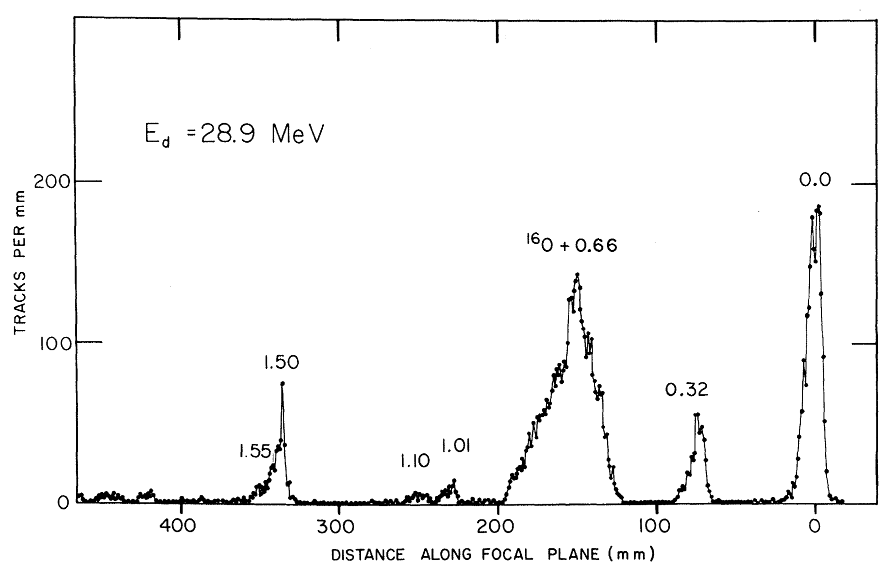

FIG. 5. Spectrum from the ^{124}Sn(d, ^{3}He)^{123}In reaction recorded at 25°.

TABLE II. Q values for the Sn(d, ^{3}He) reaction normalized to a value of −3.776 ± 0.009 MeV for the ^{116}Sn(d, ^{3}He) reaction.

Target	This work Q (MeV)	Ref. 1 Q (MeV)	Ref. 2 Q (MeV)
^{116}Sn		−3.74 ± 0.05	−3.776 ± 0.009
^{118}Sn	−4.481 ± 0.015	−4.44 ± 0.05	−4.522 ± 0.010
^{120}Sn	−5.169 ± 0.020	−5.16 ± 0.05	−5.326 ± 0.120
^{122}Sn	−5.861 ± 0.043	−5.91 ± 0.05	−6.126 ± 1.000
^{124}Sn	−6.572 ± 0.066	−6.61 ± 0.05	−6.300 ± 1.000

of 34.4-MeV deuterons on 18 nuclei in the mass range 12 to 96. The ^{3}He parameters are those reported by Rundquist, Brussel, and Yavin[7] in a study of ^{3}He elastic scattering on zirconium at 25 MeV.

In the DWA calculations, it was found that use of a lower cutoff radius (LCO) of 8 F was required to reproduce the shapes of the experimental angular distributions. Attempts with reasonable adjustments in other parameters in the calculation to bring the theoretical curves into agreement with experiment without the artifice of a LCO were without success. Different optical-model sets and local-energy-approximation corrections for finite-range and nonlocal effects were also of no avail. With a LCO of 8 F, the magnitude of the calculated cross section for each j transfer was within 5% of its value calculated with no LCO. However, as the LCO was increased beyond 8 F, as illustrated in Fig. 11, the cross sections began to decrease rapidly. All DWA calculations used to analyze the data were local, zero range, and included a LCO of 8 F.

Table IV summarizes the excitation energies, cross sections, l values, and spectroscopic factors assigned to the levels excited in the indium isotopes. Tentative assignments are in parentheses.

IV. DISCUSSION

A. Transitions to Low-Lying States

The ground states of the odd indium isotopes, which are known to have spin and parity $\frac{9}{2}^+$, are excited by $l = 4$ transitions corresponding to pickup of $g_{9/2}$ protons from tin targets. Spectroscopic factors for these transitions have values near 7, which is less than the sum-rule expectation of 10

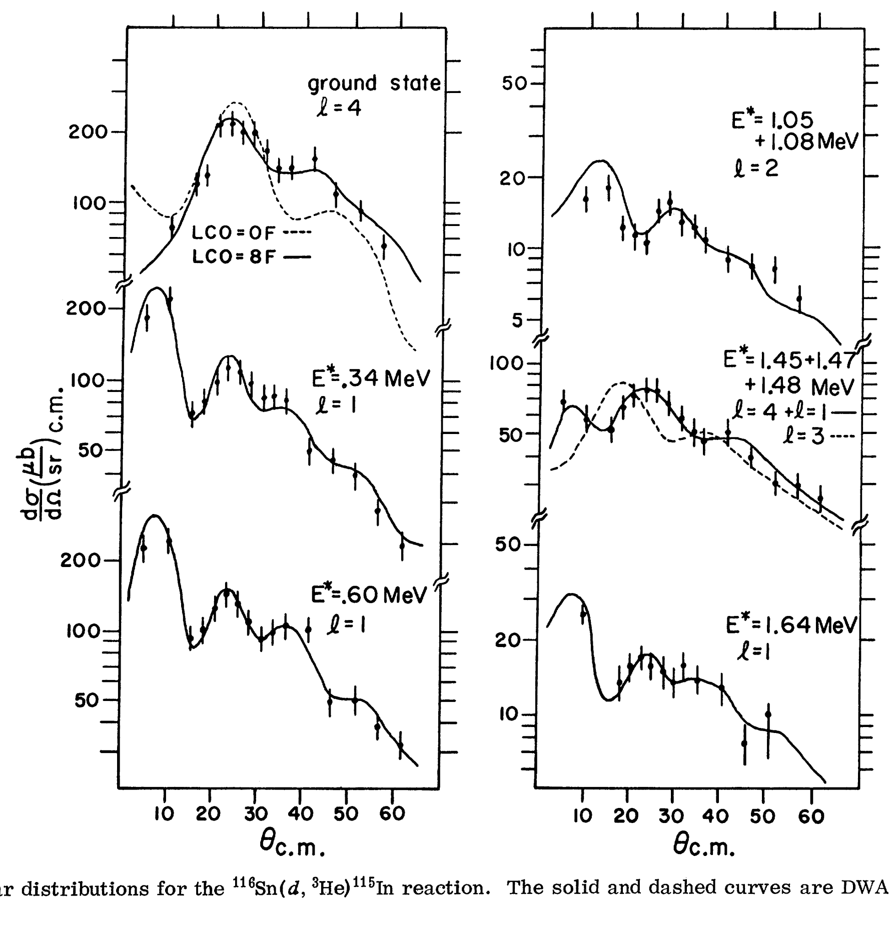

FIG. 6. Angular distributions for the ^{116}Sn(d, ^{3}He)^{115}In reaction. The solid and dashed curves are DWA predictions.

for pickup from a full $1g_{9/2}$ single-particle level.

States are excited with $l = 1$ transitions at approximately 0.3 and 0.6 MeV in each of the odd indium isotopes studied. Since the level at about 0.3 MeV has been assigned[8] a spin and parity of $\frac{1}{2}^-$ in γ-decay studies of ^{115}In and ^{117}In, it is believed to be excited by pickup of a $p_{1/2}$ proton. The spectroscopic factor for this level is about 1.5 in each isotope, while the sum-rule limit is 2.

The levels at 0.60 MeV in ^{115}In and at 0.59 MeV in ^{117}In have been previously assigned the conflicting spins $\frac{3}{2}^-$ and $\frac{5}{2}^-$ in different γ-decay studies.[9] Since these levels are excited by $l = 1$ transitions, the correct spin and parity must be $\frac{3}{2}^-$, indicating pickup from the $p_{3/2}$ orbital. The spectroscopic factors for these levels are about 2, and the sum-rule limit for pickup from a filled $p_{3/2}$ orbital is 4.

B. Transitions to Levels Above 1.0 MeV

1. l=4 and l=1 Transitions

Since the spectroscopic factors for the $l = 4$ and $l = 1$ transitions to the lowest three levels in each isotope fail to exhaust the sum-rule limits for pickup from the $g_{9/2}$, $p_{1/2}$, and $p_{3/2}$ orbitals, these levels are presumably not pure single-hole configurations, and the rest of the spectroscopic strength is expected to be admixed into other configurations having the same spin and parity.

There is evidence for $l = 4$ transitions at about 1.4 MeV in each isotope. In ^{115}In, the combined angular distribution for the triplet of states at 1.45, 1.47, and 1.48 MeV is best reproduced by a mixture of $l = 4$ and $l = 1$. From the results of Dietrich *et al.*,[10] the levels at 1.45 and 1.48 MeV are known to have positive parities, and they therefore must be excited by the $l = 4$ transitions and presumably have spin and parity of $\frac{9}{2}^+$. This assignment is in accord with the γ decay of these two levels.[10]

Unlike ^{115}In, in which two $l = 4$ transitions near 1.4 MeV are observed, only one $l = 4$ transition is observed near 1.4 MeV in each of the other four isotopes. Assuming these transitions proceed via pickup of a $g_{9/2}$ proton, the sum of the $g_{9/2}$ spectroscopic factors is near the sum-rule limit of 10 for each isotope.

The hole-core coupling model provides a possible explanation for the $l = 4$ transitions to levels near 1.4 MeV. According to this model, there may exist states in odd-*A* nuclei that can be described as a coupling of the odd particle or hole to

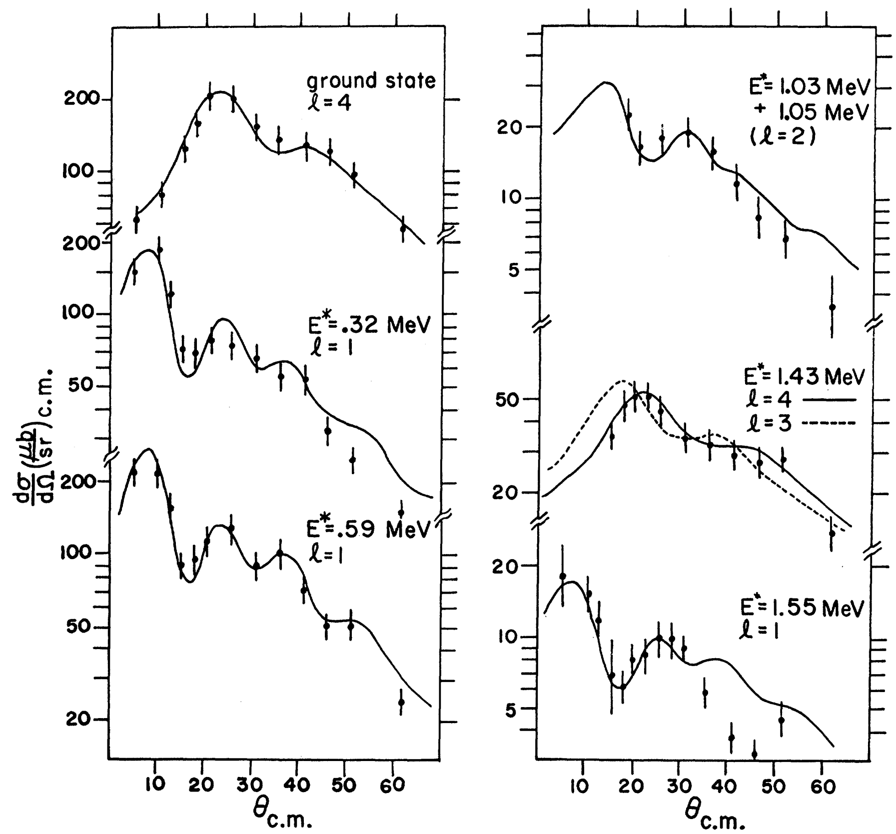

FIG. 7. Angular distributions for the ^{118}Sn$(d, {}^3\text{He})^{117}$In reaction. The solid and dashed curves are DWA predictions.

collective excitations of the even-even core. As a result of this coupling, one expects a multiplet of excited states which are collective in nature.

In each even-A tin isotope (the "core"), there are two strongly collective states; a 2^+ state near 1.2 MeV and a 3^- state near 2.3 MeV. If in indium the $g_{9/2}$ proton-hole state couples to the 2^+ state of the core, the result will be a quintet of positive-parity states near 1.2-MeV excitation. These $(g_{9/2}, 2^+)_J$ hole-core configurations could be excited by inelastic scattering or Coulomb excitation, but would not be directly excited in a one-step proton pickup reaction. An $l = 4$ transition may be observed to a level near 1.4 MeV if there is mixing between the $\frac{9}{2}^+$ member of the quintet and the $g_{9/2}$ proton-hole configuration.

There is additional experimental evidence which supports this hole-core coupling conjecture. In the inelastic scattering[11] of 42-MeV α particles from ^{115}In, strong $L = 2$ groups of unresolved levels have been observed near 1.2 MeV; namely, at 1.12, 1.29, and 1.46 MeV. Also strong $L = 3$ unresolved groups have been observed at 2.07 and 2.40 MeV, both of which energies are close to 2.27 MeV, the energy of the 3^- state in the ^{116}Sn core. Hence in (α, α') one excites collective states in ^{115}In near the excitation energies of the collective core states as predicted by the hole-core coupling model.

The collective states of ^{115}In have been studied by Dietrich *et al.*[10] using Coulomb excitation and deuteron inelastic scattering. They found a group of collectively enhanced levels in the region between 900 and 1500 keV. In addition, they calculated the ^{115}In spectrum and included the coupling of a $1g_{9/2}$ proton hole to the collective states of ^{116}Sn, and obtained good agreement with the experimentally determined level positions, with the $B(E2)$ values, and with the ground-state quadrupole moment. The calculated wave functions also gave good agreement with the $g_{9/2}$ $(d, {}^3\text{He})$ spectroscopic factors measured in the present work.

As noted previously, the levels near 0.3 and 0.6 MeV do not contain the full $p_{1/2}$ and $p_{3/2}$ strength. One might expect to observe additional $l = 1$ transitions above 1 MeV if there is sufficient mixing

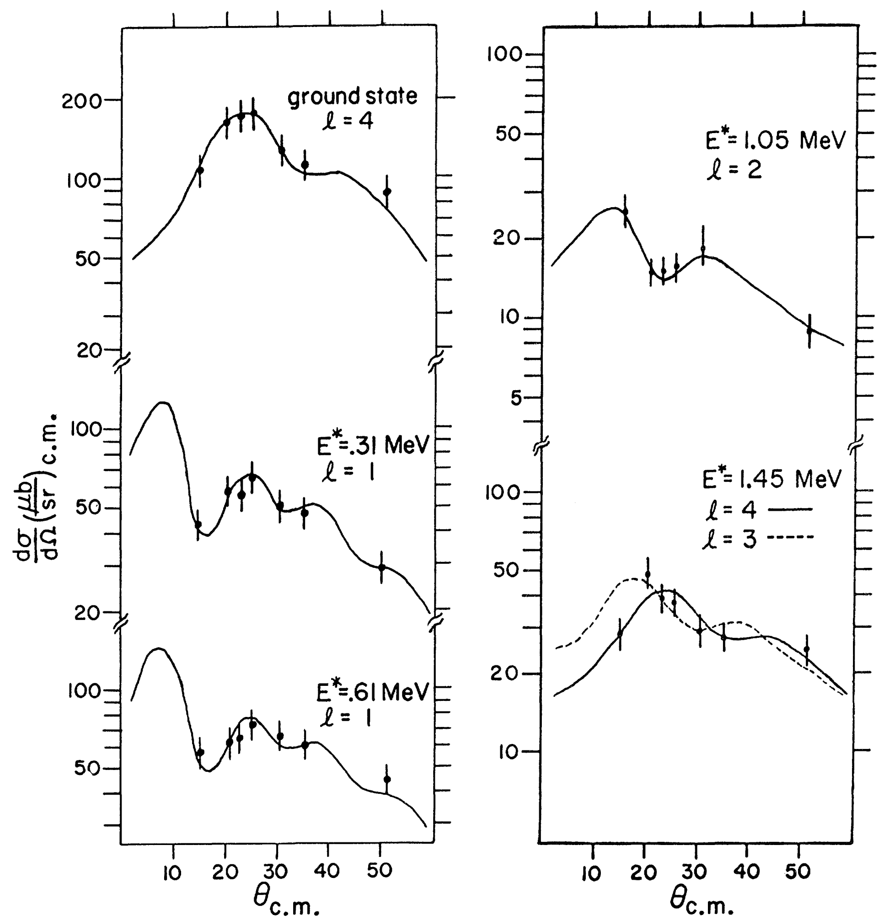

FIG. 8. Angular distributions for the ^{120}Sn$(d, {}^3\text{He})^{119}$In reaction. The solid and dashed curves are DWA predictions.

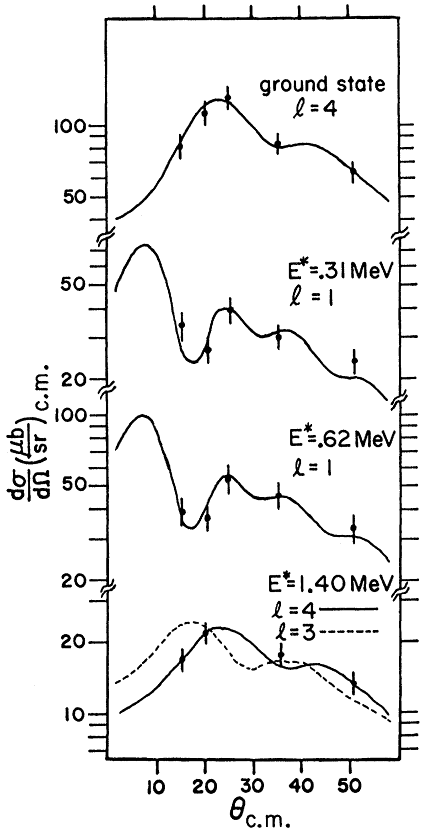

FIG. 9. Angular distributions for the $^{122}Sn(d, {}^{3}He)^{121}In$ reaction. The solid and dashed curves are DWA predictions.

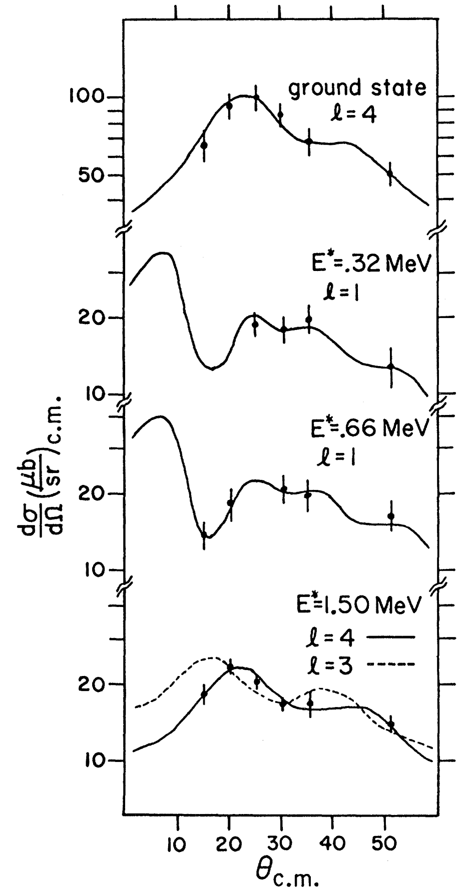

FIG. 10. Angular distributions for the $^{124}Sn(d, {}^{3}He)^{123}In$ reaction. The solid and dashed curves are DWA predictions.

between the $p_{1/2}$ and $p_{3/2}$ hole configurations and the negative-parity states in the $(g_{9/2}, 3^-)_J$, $(p_{1/2}, 2^+)_J$, and $(p_{3/2}, 2^+)_J$ hole-core multiplets. Such transitions have been tentatively identified in ^{115}In and ^{117}In.

2. $l = 2$ Transitions

Somewhat unexpectedly, the angular distributions for the levels weakly excited near 1.0 MeV in ^{115}In, ^{117}In, and ^{119}In are best reproduced with $l = 2$ DWA curves. If these levels are indeed populated by a one-step $l = 2$ direct reaction, it indicates that the protons in the ground states of the even-mass tin targets do not form completely closed $Z = 50$ shells, and that a "d" shell-model orbital, probably the $2d_{5/2}$ which is known to lie near the bottom of the $Z = 50$ to 82 shell, is partially occupied by proton pairs. A level at 1.078 MeV in ^{115}In, which is possibly the same as one of the levels observed in the present experiment, has been previously assigned[10,12] a spin and parity of $\frac{5}{2}^+$.

The sum of the $l = 2$ spectroscopic factors is about 0.5 in each of three isotopes; a value of 6.0 would be expected if the $2d_{5/2}$ orbital were full. This implies that the average occupation of the $2d_{5/2}$ level in the tin ground state is about $\frac{1}{2}$ proton or $\frac{1}{4}$ pair. As there is no other direct experimental evidence for nonclosure of the $Z = 50$ proton shell in the even-mass tin isotopes, this interpretation must be considered as tentative.

Because these levels have small $(d, {}^3He)$ cross sections, it is possible that they are excited by other than a single-step direct reaction. For example, the reaction might proceed by inelastic scattering to a 2^+ collective state along with pickup of a $g_{9/2}$ proton, resulting in the formation of a $\frac{5}{2}^+$ state in indium. Such second-order processes have been found to contribute[13] to $(d, {}^3He)$ spectra, and it is known that the angular distributions for these processes can be similar to those for a direct reaction.

C. Absence of $l = 3$ Transitions

It was anticipated that levels excited with $l = 3$ angular distributions, corresponding to pickup of

TABLE III. Parameters used in the DWA calculations for the Sn(d, ^{3}He)In reactions. The form of the optical potential was

$$U(r)=V_C(r)-V_0\frac{1}{1+e^x}-iW_0\frac{1}{1+e^{x'}}+iW'\left(\frac{d}{dx'}\right)\frac{1}{1+e^{x'}}+\frac{h^2}{(2\pi m_\pi c)^2}\frac{V_s}{r}\left(\frac{d}{dr}\right)\frac{1}{1+e^x}\vec{L}\cdot\vec{S},$$

where $x=(r-r_0A^{1/3})/a$, $x'=(r-r_0'A^{1/3})/a'$, and V_C is the Coulomb potential for a point charge incident on a uniformly charged sphere of radius $R_C=r_CA^{1/3}$. The potential used to obtain the wave function of the bound proton had the form

$$U(r)=V_C-V_0\left[\frac{1}{1+e^x}+\frac{a(l)\lambda}{ar}\left(\frac{h}{4\pi m_p c}\right)^2\frac{e^x}{(1+e^x)^2}\right],$$

where $\lambda=25$, $a(l)=l$ for $j=l+\frac{1}{2}$, and $a(l)=-(l+1)$ for $j=l-\frac{1}{2}$.

	Deuteron	^{3}He	Proton
V_0 (MeV)	99.3	179.45	Adjusted
W_0 (MeV)		14.95	
r_0 (F)	1.11	1.14	1.20
a (F)	0.814	0.71	0.625
r_c (F)	1.30	1.40	1.20
V_s (MeV)	7.00		
r_0' (F)	1.25	1.54	
a' (F)	0.85	0.78	
w' (MeV)	60.52		

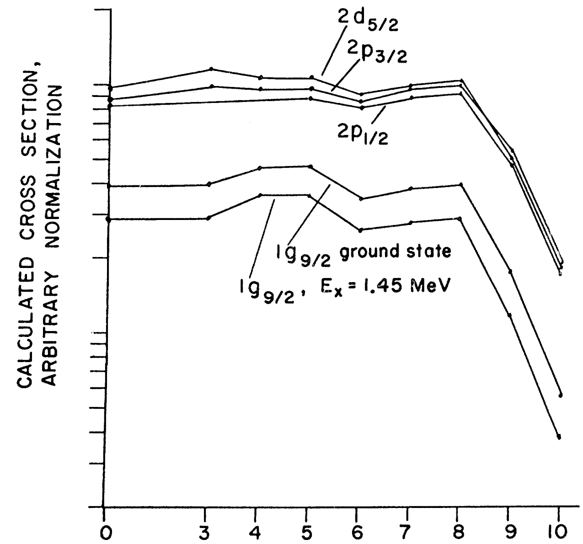

FIG. 11. Effects of using a lower cutoff radius on the calculated DWA cross sections for the ^{116}Sn(d, ^{3}He)^{115}In reaction. The cross sections decrease rapidly when the lower cutoff radius exceeds 8 F.

protons from the shell-model $1f_{5/2}$ single-particle level in the $Z=28$ to $Z=50$ shell, would be observed in the (d, ^{3}He) spectra. However, contrary to this expectation, no $l=3$ transitions were identified up to 5-MeV excitation in ^{117}In, up to 2 MeV in ^{123}In, and up to 3.5-MeV excitation in the other three isotopes. First indications of this result led early in the experiments to a careful reappraisal of the method for recording and analyzing the angular distributions. It was concluded that the l assignments were correct and, indeed, no $l=3$ transitions were being observed.

We are uncertain as to why no $l=3$ transitions are observed. One might conjecture that the $f_{5/2}$ protons are more tightly bound in the tin nuclei than one expects from systematics. Or it may be that the $l=3$ strength is fragmented and mixed into many levels, no single level carrying sufficient strength to be identified through its angular distribution. At excitations greater than 1.5 MeV, the (d, ^{3}He) spectra exhibit many levels with cross sections of less than 5 μb/sr; none of these levels, if assumed to be excited by $f_{5/2}$ pickup, would have a spectroscopic factor greater than 0.5. As yet, no $\frac{5}{2}^-$ states have been positively identified in the odd-A indium nuclei.

V. SUMMARY

We have presented the results of an experimental study of the level structure of five odd indium isotopes using the (d, ^{3}He) reaction at 28.9 MeV. The spectra are all quite similar, indicating that the proton configurations of the low-lying states are little affected by changes of up to eight in the neutron number.

The ground states and first two excited states in each isotope contain a large fraction of the $g_{9/2}$, $p_{1/2}$, and $p_{3/2}$ hole strength. Additional $l=4$ strength is observed at higher excitations and provides evidence for the mixing of single-hole configurations and the multiplets that result from the coupling of a hole to a collective state in the tin core.

There were two unexpected results from this work. First no $l=3$ transitions, corresponding to the pickup of an $f_{5/2}$ proton, were observed, although the range of excitation examined in most isotopes covered 3.5 MeV and, in one case, was as high as 5 MeV. The second unexpected result was the observation of $l=2$ transitions to levels near 1 MeV in ^{115}In, ^{117}In, and ^{119}In. These transitions suggest the possibility of a small nonclosure in the $Z=50$ shell of the even-A tin isotopes.

TABLE IV. Summary of results for levels in indium excited by the Sn(d,^{3}He) reaction.

Isotope	E_x (MeV)	$d\sigma/d\Omega$(lab) (μb/sr)	θ_{lab} (deg)	l	J^π	S
^{115}In	0.00	225	20	4	$\frac{9}{2}^+$	6.7
	0.34	125	20	1	$\frac{1}{2}^-$	1.5
	0.60	175	20	1	$\frac{3}{2}^-$	1.9
	0.93	5.4	20			
	1.05	12	20	(2)	($\frac{5}{2}^+$)	0.21
	1.08	12	20	(2)	($\frac{5}{2}^+$)	0.21
	1.29	2	20			
	1.45	28	20	(4)	($\frac{9}{2}^+$)	1.2
	1.47	18	20	(1)	($\frac{1}{2}^-$, $\frac{3}{2}^-$)	0.33 [a]
	1.48	38	20	(4)	($\frac{9}{2}^+$)	1.7
	1.64	16	20	(1)	($\frac{1}{2}^-$, $\frac{3}{2}^-$)	0.40 [a]
^{117}In	0.00	188	20	4	$\frac{9}{2}^+$	6.7
	0.32	79	20	1	$\frac{1}{2}^-$	1.5
	0.59	115	20	1	$\frac{3}{2}^-$	2.3
	1.03	8.5	20	(2)	($\frac{5}{2}^+$)	0.19
	1.05	8.5	20	(2)	($\frac{5}{2}^+$)	0.19
	1.43	54	20	4	($\frac{9}{2}^+$)	2.9
	1.55	7.4	20	(1)	($\frac{1}{2}^-$, $\frac{3}{2}^-$)	0.38 [a]
	1.70	7.0	20			
^{119}In	0.00	162	25	4	$\frac{9}{2}^+$	6.5
	0.31	68	25	1	$\frac{1}{2}^-$	1.6
	0.60	76	25	1	$\frac{3}{2}^-$	1.8
	1.05	15.3	25	2	($\frac{5}{2}^+$)	0.5
	1.45	38	25	4	($\frac{9}{2}^+$)	2.9
	1.54	7.3	25			
	1.82	6.8	25			
^{121}In	0.00	83	35	4	$\frac{9}{2}^+$	7.2
	0.31	30	35	1	$\frac{1}{2}^-$	1.4
	0.62	45	35	1	$\frac{3}{2}^-$	2.1
	1.02	10.2	35			
	1.40	16.9	35	(4)	($\frac{9}{2}^+$)	2.4
	1.50	3.2	35			
^{123}In	0.00	67	35	4	$\frac{9}{2}^+$	7.2
	0.32	19	35	1	$\frac{1}{2}^-$	1.4
	0.66	24	35	1	$\frac{3}{2}^-$	1.7
	1.01	2.0	20			
	1.10	3.7	20			
	1.50	18	20	4	($\frac{9}{2}^+$)	2.5
	1.55	2.5	20			

[a] Computed for $J^\pi = \frac{3}{2}^-$.

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Neutron-Capture Gamma Rays from the 14.1-eV Resonance in Xe^{131}(n, γ)Xe^{132}†

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The γ rays from neutron capture in the 14.1-eV resonance in Xe^{131} have been studied. A target of Na_4XeO_6 was irradiated in a thermal-neutron beam and in monoenergetic neutron beams of 5.16-, 9.47-, and 14.1-eV energy from a neutron diffraction monochromator. The resulting γ-ray singles spectra were studied with Ge(Li) detectors of ≈12-, 15-, 20-, and 30-cm^3 active volume. γ rays were assigned to the Xe^{131}(n, γ)Xe^{132} reaction by a comparison of these spectra. Ge(Li)-Ge(Li) coincidence measurements were carried out on resonance with the 20- and 30-cm^3 Ge(Li) detectors in combination. 14 Xe^{132} γ rays were assigned as primary capture γ rays from the 14.1-eV resonance. The energies (in keV) and relative intensities [I(667.5) = 100] of these primary γ rays are as follows: 8934.2 ±1.0 (0.02), 8268.5 ±0.9 (1.0), 6950.1 ±2.3 (0.14), 6750.1 ± 0.8 (0.13), 6466.8 ±0.5 (13.2), 6380.5 ±0.5 (2.8), 6346.8 ±2.5 (0.09), 6223.0 ±1.0 (0.23), 5755.0 ±1.0 (1.9), 5692.3 ±1.2 (0.4), 4981.1 ±1.7 (0.3), 4910.3 ±2.0 (0.7), 4842.3 ±1.0 (0.7), and 4745.6 ±2.5 (0.09). These data together with the information obtained from the coincidence measurements and earlier radioactive-decay studies indicate levels in Xe^{132} with energies 667.5 ±0.3, 1297.7 ±0.5, 1440.0 ±0.3, 1803.9 ±0.8, 1962.7 ±0.7, 1985.4 ±1.0, 2040.2 ±0.6, 2110.2 ±0.1, 2168.7 ±1.3, 2187.2 ±0.8, 2350.7 ±0.2, 2394.3 ±0.5, 2424.9 ±0.7, 2468.8 ±0.5, 2555.0 ±0.6, 2588.66 ±0.11, 2714.3 ±1.3, 2754.43 ±0.13, 3181.3 ±1.5, 3243.4 ±1.5, 3954.1 ±1.0, 4026.5 ±1.5, 4094.0 ±1.0, and 4189.5 ±1.5 keV. The neutron separation energy of Xe^{132} is 8936.3 ±1.0 keV. The most prominant feature of the Xe^{132} level scheme obtained is the strong feeding of the 2468.8-keV level by the intense 6466.8-keV γ ray from the capture state. The observed mode of decay of this level indicates spin and parity 3^- for this state although spin 2 cannot be ruled out. If the 3^- assignment is correct, then the 14.1-eV neutron resonance in Xe^{131} has spin 2. The properities of the energy levels of Xe^{132} are discussed.

I. INTRODUCTION

Ewan and Tavendale,[1] in an early paper on the application of Ge(Li) detectors to the study of γ rays, recognized that these detectors provided an important new tool for the study of neutron-capture γ rays. Since then Ge(Li) detectors have become readily available in many laboratories, and studies of the γ rays from both thermal- and resonance-neutron capture have been reported for almost all of the elements. The rapid increase in our knowledge of the neutron-capture γ rays, which has resulted from the application of these detectors, is clearly seen in a comparison of the neutron-capture γ-ray compilations of 1958–1959 (Bartholomew and Higgs[2] and Groshev, Demidov, Lutsenko, and Pelekhov[3]) and 1967–1969 (Bartholomew, Doveika, Eastwood, Monaro, Groshev,