large. Hence if we assume that the higher order meson exchanges are unimportant we can view our theory both as an independent conformation of the hard core as well as an indication that our method of going off the energy shell is qualitatively correct. Furthermore, our work shows the necessity of using qualitatively accurate wave functions. Thus we believe that the major unknown effect is the higher order exchanges, recoil being completely overshadowed by the hard core. An extension into two meson exchange effects should determine whether the above conclusions are meaningful.

Finally we remark that at the lower energies our work indicates that the entire effect is essentially a classical one; there are no mesonic contributions of importance. Thus we may conclude that the various classical calculations[1] account for the low-energy phenomenon in a manner which is consistent with first principles.

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Spin States Associated with Neutron Resonances in In^{115}

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By polarizing both the neutron beam and the nuclear sample, the spin states of the first three slow neutron resonances in the target nucleus In^{115} have been measured. These were obtained by observing the direction of change in the transmitted intensity upon reversing the polarization of the neutrons with respect to the target nuclei. The spin states associated with the resonances at 1.46 ev, 3.86 ev, and 9.10 ev were found to be $J=5$, 4, and 5, respectively. These spin assignments are consistent with measurements of other parameters of these resonances.

INTRODUCTION

THERE has been much recent interest in the spin states of levels in compound nuclei formed by interaction with slow neutrons. In particular, the information desired is the relationship of the spin state to the other resonance parameters such as the radiation width, neutron scattering width, level spacing, capture gamma-ray spectrum, and the distribution of the two possible spin states among the resonances in an isotope. We are considering only cases where the neutron orbital angular momentum is zero. Sailor[1] has made a survey of the measured spin states and concludes that the often made assumption that the two possible spins are equally distributed among the levels may not be valid, since there are many more levels with measured spin states $J=I+\frac{1}{2}$ than with $J=I-\frac{1}{2}$, where I is the spin of the target nucleus ground state.

Generally speaking, the spin states of these compound nucleus levels have eluded measurement because the methods commonly used to obtain the resonance parameters are rather insensitive to the spin state. In principle, the combination of good measurements of total and scattering or capture cross sections would yield all the resonance parameters, including J. Several laboratories [2–5] are presently using this method to obtain J values, although partial cross-section measurements to the necessary degree of accuracy are difficult to make and results obtained in different laboratories have not always been in agreement. In some cases, spin assignments could be made on the basis of total or scattering cross-section measurements alone[6–8] (see also cases cited in reference 1). In the kilovolt region, Hibdon[9] has reported J values for several resonances in aluminum from analysis of total cross-section curves. Other investigators[10,11] have measured spin states by looking for the presence of a ground-state transition. This technique is applicable only when $I=\frac{1}{2}$.

The technique adopted in this investigation is to polarize both the neutron beam and the target. The spin state of the compound nucleus can then be obtained directly by observing the direction of change in the transmitted intensity upon reversing the relative orientation of the neutrons and the nuclei. The transmission of a polarized neutron beam through a polarized

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target is given by[12]

$$t=e^{-N\sigma_0}[\cosh f_I f_N N\sigma_0 - f_n \sinh f_I f_N N\sigma_0], \quad (1)$$

where N is the target thickness in atoms/cm^2, σ_0 is the cross section in the absence of polarizations, f_N is the polarization of the nuclear target, f_n is the polarization of the neutron beam, and f_I is a spin dependent factor given by

$$f_I=I/(I+1) \quad \text{for} \quad J=I+\tfrac{1}{2}$$
$$=-1 \quad \text{for} \quad J=I-\tfrac{1}{2}.$$

Upon reversing the relative spin directions of the neutrons and the nuclei, the fractional change in transmission is then

$$\Delta t/t_0=2\phi f_n \tanh f_I f_N N\sigma_0 \approx 2\phi f_n f_I f_N N\sigma_0, \quad (2)$$

where ϕ is the efficiency for flipping the neutron polarization direction, and t_0 is the transmission when $f_n=0$. The direction of the change then gives the spin state of the compound nucleus directly. The approximation is true since f_N is quite small with presently available experimental techniques. Experiments of this kind have been pioneered by workers at the Oak Ridge National Laboratory who have measured spin states in the thermal neutron region in manganese,[13] samarium,[14] and indium.[15] The principle difficulty, of course, is in producing a target polarization large enough to yield a significant effect. Our work is based largely on the experiment of Dabbs, Roberts, and Bernstein,[15] here after referred to as DRB, which first demonstrated the "brute force" method for polarizing a target. In this technique, the sample is polarized to a few percent by direct coupling of the nuclear magnetic moments with an external magnetic field when the sample temperature is reduced to a few hundredths of a degree Kelvin. The polarization produced is given by[16]

$$f_N=\frac{1}{3}\frac{I+1}{I}\frac{\mu H}{kT}, \quad (3)$$

when $\mu H/kT \ll 1$. In this formula, μ is the nuclear magnetic moment, k is Boltzmann's constant, and T is the absolute temperature. Although the "brute force" method doesn't produce as large a polarization as some of the more subtle methods,[17] it is more appropriate for the present application since it produces a polarized target free of all nuclei except those under investigation. In addition, it requires no special chemical techniques and is applicable to a wide range of nuclei.

The main improvement we have made over the experiment of DRB is to provide a means for changing the neutron energy so that several resonances in the same isotope can be investigated. The measurement of spin states by this technique then requires three basic components in addition to the usual detection equipment: (a) A method for polarizing and monochromatizing the neutron beam, (b) A method for controlling the neutron beam polarization in flight, and (c) A method for producing a polarized target. These will be discussed in the following sections.

POLARIZED NEUTRON SPECTROMETER

A schematic top view of the spectrometer is shown in Fig. 1. The neutron beam is both polarized and monochromatized by reflection from the (111) planes of a cobalt-iron crystal.[18] This crystal is located between the poles of a small water-cooled electromagnet which produces a field in air of about 6 kilogauss. The magnet can be rotated about a vertical axis by an external control connected to a rotary table. A fine adjustment to the tilt of the crystal planes can also be made by an external control which couples to the crystal via a rod which goes through the top pole piece. The middle section of the cylindrical shield is made of masonite and is cut as shown in Fig. 1. It is surrounded above and below by cylindrical tanks filled with water and boric acid. The inside hole is lined with 3 inches of lead, and the top is covered with a masonite lid. This entire assembly rests on a bearing so that it can be rotated. The shield is 3.5 feet high and 6.5 feet in diameter. This large size is necessary to reduce the fast neutron flux from a reactor of the NRL type (swimming pool with MTR type fuel elements) to a biologically safe

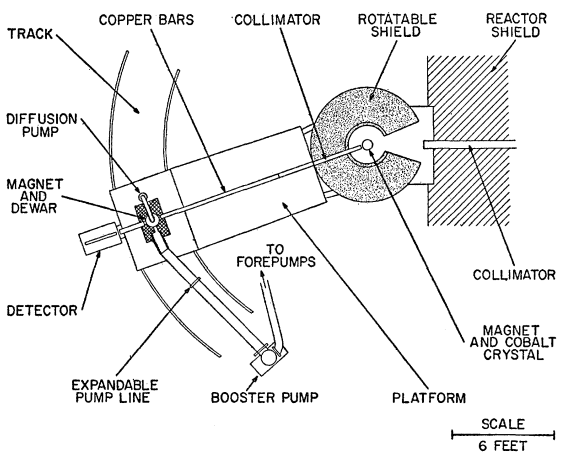

FIG. 1. Schematic top view of polarized neutron spectrometer.

[12] A. W. Saenz (private communication).
[13] S. Bernstein, L. D. Roberts, C. P. Stanford, J. W. T. Dabbs, and T. E. Stephenson, Phys. Rev. **94**, 1243 (1954).
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[17] M. J. Steenland and H. A. Tolhoek, *Progress in Low-Temperature Physics*, edited by J. C. Gorter (North-Holland Publishing Company, Amsterdam, 1957), Vol. 2, Chap. 10. This reference gives a good summary of all methods and applications of nuclear orientation.
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level, since the beam ports look directly at the fuel. Two collimators are used. One is inserted in the beam hole before the crystal; it is of the Soller slit type, employing steel shims and it produces an angular divergence of 15 minutes of arc. Another collimator is placed at the exit hole of the cylindrical shield and employs removable brass shims so that the beam polarization will not be affected. With all the shims in, the angular divergence from this collimator is 13.5 minutes of arc. This second collimator serves mainly to reduce the background from neutrons scattered inside the shield, and is important only when operating at small angles to the direct beam.

The cryogenic equipment, including a heavy water-cooled magnet with a Dewar between its poles, is mounted on a car which is mechanically coupled to the rotatable shield, and rolls on a track. The coupling is covered with a platform which is a convenient place for putting vacuum pumps and other equipment. The entire assembly is easily moved manually by means of winches. The position is obtained from a scale attached to the outside rail. The instrument was calibrated by observing the positions of the resonances in In^{115}, and these agreed well with calculated positions. The total distance between the polarizing crystal and the sample is 160 inches. This distance was made large to satisfy the adiabatic rotation condition for higher energy neutrons, as explained below. All of the runs were performed with the spectrometer set at the center of the resonance under investigation.

The orientation of the neutron spins after leaving the polarizing crystal is controlled by current-carrying copper bars. These bars are powered by a 4.5-kilowatt motor-generator set, and draw about 300 amperes. The field between the bars is about 25 gauss. The bars have a 90° twist in them over a length of 8 feet so that the neutron spins are adiabatically rotated from the vertical direction at the polarizing magnet to the horizontal direction at the cryogenic magnet. By throwing a set of switches, this condition can be changed to one in which the neutrons are "flipped" relative to the field by sending the beam through a region of rapid field reversal.[19] We have incorporated a suggestion of DRB here by sending the beam through a current-carrying aluminum foil 0.08 inches thick, which improves the flipping condition considerably. To change from one neutron spin orientation to the other requires a change in the field direction of the polarizing magnet and also in the section of copper bars between the polarizing magnet and the aluminum foil. These changes are made by ganged switches, and require only a few seconds. Measurements have been made of the shim effect and the double reflection effect[20] by using another cobalt crystal as an analyzer in the gap of a 2300 gauss permanent magnet. These measurements indicated that the beam polarization was about 0.95 and that the flipping efficiency was about 0.90. These values were considered adequate for these experiments.

Data were taken by reversing the orientation of the neutron beam every five minutes. This procedure completely removes any errors due to fluctuations in reactor flux or counter stability when enough counts are accumulated, so that a monitor channel was not necessary. Background data were taken by setting the crystal off the Bragg angle. This was done while liquid helium was being transferred and pumped down, and after the liquid was gone. Counting rates varied between the three resonances investigated because of the differences in cross section and reactor spectrum. For the 1.46-, 3.86-, and 9.10-ev resonances, the count rates were approximately 50, 100, and 120 counts per minute, respectively. The backgrounds were about 20, 21, and 30 counts per minute, respectively. The reactor was operated at 100 kilowatts. The detector is a one inch diameter, 22-inch long $B^{10}F_3$ counter filled to a pressure of 120 cm Hg, and surrounded by a shield of paraffin, boron, and cadmium.

NUCLEAR POLARIZATION

The apparatus used to polarize the nuclear target is shown schematically in Fig. 2. It is basically the same arrangement used by DRB in their "brute force" polarization experiment. The polarization is achieved by reducing the temperature of the sample to a few hundredths of a degree Kelvin by the adiabatic demagnetization technique,[21] simultaneously keeping it in a strong magnetic field. The magnet is of the *H*-type and is made of Armco iron; the total weight is about 2.5 tons. It is powered by a 15-kilowatt motor-generator set. The generator field current is electronically regulated by an error signal from the load. We have usually used a field strength of 19 kilogauss with a 2-inch gap. The magnet is used both to magnetize the paramagnetic cooling salts and to provide the polarizing field for the indium sample, as will be explained below. The salt-sample assembly is contained in a tube which is inserted into the liquid helium bath. A radiation shield of the ring and disk type with felt washers prevents radiation from reaching the sample from the warm end of the tube. The upper part of this sample tube is made of *K*-monel and the lower part is made of brass. It can be smoothly raised or lowered through an *O*-ring seal by means of a hydraulic lift. By throttling the flow rate of oil operating the hydraulic cylinder, the rate of rise is easily controlled. The sample tube is pumped via a bellows connected to an MCF-300 oil diffusion pump

[19] E. Majorana, Nuovo cimento **9**, 43 (1932) [English translation available from Armour Research Foundation, ADI Document 2229].

[20] C. P. Stanford, T. E. Stephenson, L. W. Cochran, and S. Bernstein, Phys. Rev. **94**, 374 (1954).

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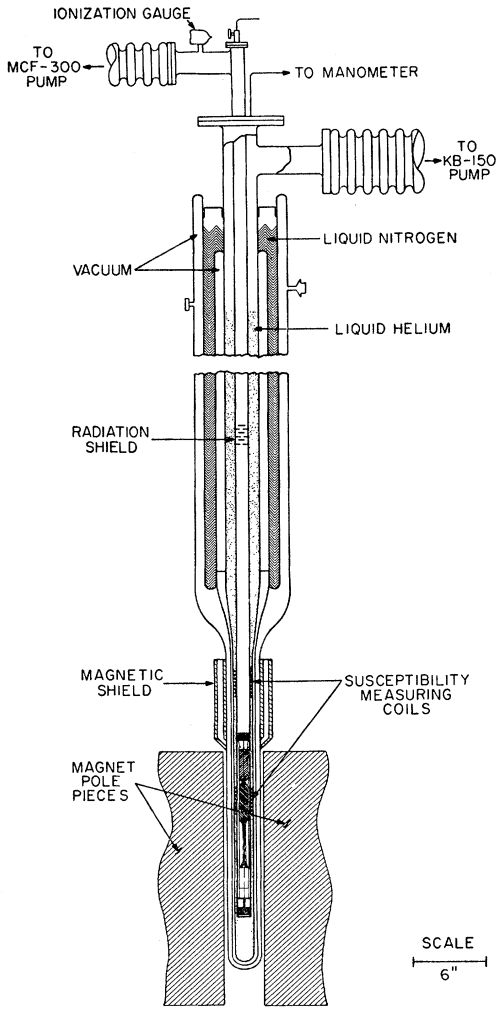

FIG. 2. Nuclear polarization apparatus.

and backing forepump. In this way, the sample tube can be pumped while in motion. The liquid helium bath is pumped by three Cenco Hypervac 100 mechanical pumps backing a KB-150 oil booster pump. This system can bring the temperature of the liquid helium to about 1°K. Since the cryogenic equipment is movable, a variable length pump line is used between the booster pump and the Dewar. This contains sliding sections with *O*-ring seals, and bellows. The temperature of the liquid helium bath is obtained from the vapor pressure using the compilation of Clement.[22] The vapor pressure is read on a mercury manometer for pressures above 4 cm, and a dicapryl phthalate manometer for pressures below this.

A pair of mutual inductance coils are wound on the brass portion of the sample tube; the lower set surrounds one of the paramagnetic salts. These coils are connected so that the primaries are aiding and the secondaries are bucking. Magnetic susceptibility measurements are made on the paramagnetic salt while the liquid helium is being pumped down. The susceptibility is obtained from the deflection of a galvanometer when a current of 100 milliamperes is reversed in the primary coils. These deflections are calibrated against the bath temperature in the usual way.[21,23] After demagnetizing the salt, its temperature can thus be obtained and monitored during a run. These "magnetic temperature" readings are converted to thermodynamic temperatures by using the data of Bleaney[24] and Daniels and Kurti[25] for chromium potassium alum, after making the appropriate demagnetizing factor correction,[26] since the salt is not spherical.

A drawing of the two-stage salt-sample assembly is shown in Fig. 3. The upper salt is a cylinder of iron ammonium alum grown around flattened gold wires. The lower salt is a cylinder of chromium potassium alum grown around flattened silver wires. They are connected by a thin lead wire. Each salt is about 2 inches long and $\frac{5}{8}$ inch in diameter. The flattened portions of the wires were crimped in a zig-zag manner to increase the contact surface with the salts. Forty annealed, 0.020 inch in diameter, high purity silver wires form the thermal link between the lower salt and the indium sample. The contact area between the salt and the wires is about 100 cm^2. A pair of wires is soldered to each of twenty indium foils, ten of which are 0.010

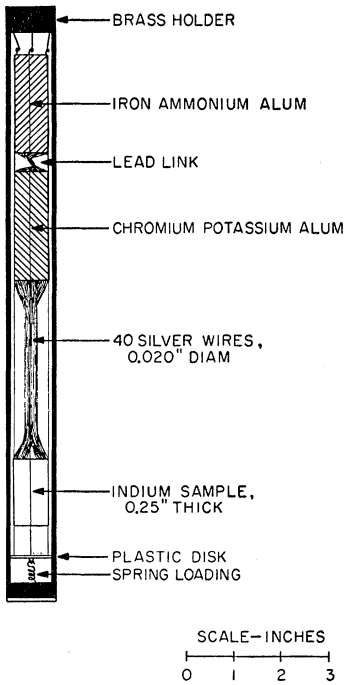

FIG. 3. Two-stage salt-sample assembly.

[22] J. R. Clement, Report of NRL Progress, June, 1958, Naval Research Laboratory, Washington ,D. C.

[23] R. A. Hull, *Report of Cambridge Conference on Low Temperatures* (Physical Society, London, 1947).

[24] B. Bleaney, Proc. Roy. Soc. (London) **A204**, 216 (1950).

[25] J. M. Daniels and N. Kurti, Proc. Roy. Soc. (London) **A221**, 243 (1954).

[26] N. Kurti and F. Simon, Phil. Mag. **26**, 849 (1938).

inch thick and ten 0.015 inch thick. The foils are insulated from each other by very thin sheets of Mylar to reduce eddy current heating. The entire assembly is suspended by nylon fibers from a brass frame, with spring loading to provide tension.

The demagnetization cycle is performed as follows: With the magnetic field on, the temperature of the entire assembly is brought to about 1°K by several microns of helium exchange gas, which establishes thermal contact with the pumped liquid helium bath. The gas is then pumped out until the pressure at the top of the sample tube is about 7×10^{-6} mm, as read with an ionization gauge. The sample tube is then slowly and smoothly raised by the hydraulic lift until the first salt leaves the field and enters a magnetic shield (see Fig. 2). As it cools, it lowers the temperature of the second salt via the lead wire linking the two. Further raising of the sample tube brings the lead wire into the shield, where it becomes superconductive, and thus thermally isolates the upper salt from the rest of the assembly. The cycle is completed by raising the second salt into the shield, where it cools the indium sample via the silver wires. The time required to raise the sample tube through the traverse of 5.5 inches is about one half hour. This process must be done slowly to reduce eddy current heating in the silver wires and sample, to keep the system in temperature equilibrium, and to allow the gas evolved when the tube is pulled out of the liquid helium to be pumped off. Vibrational heating was considered to be negligible. The average temperature for a run lasting one and one half hours was about 0.04°K, although initial temperatures of the order of 0.01°K were reached. A typical warm up rate was 0.015°K/hr at about 0.04°K, corresponding to about 200 ergs/min. We believe the main source of heat input to be eddy current heating due to fluctuations in the generator output supplying the magnet, in spite of the electronic feedback regulator. It would be impractical to run the magnet with batteries. Residual gas in the sample tube probably constituted the second largest source of heat input. A complete discussion of transient and steady-state heat inputs is given by DRB, and most of their remarks are applicable to our experiment. It should be mentioned that the average temperatures we have obtained with the setup of Fig. 3 are not very much lower than we have obtained with single-stage demagnetizations. However, the upper salt serves as a good getter for residual gas and also as a trap for radiation that managed to get through the radiation shield.

RESULTS

The results of our measurements on the first three resonances in In^{115} are listed in Table I. After the J values, we have listed the observed changes in the fractional transmitted intensity when the neutron spin direction was reversed with respect to the target polarization. The errors quoted are the fractional standard deviations, i.e., $(2N)^{\frac{1}{2}}/N$, where N is the number of counts accumulated in either of the two sets of numbers corresponding to the two relative spin orientations. The minus sign used for the 3.86-ev resonance simply indicates that the direction of the effect here was opposite to that for the other two resonances. For a resonance with $J=I+\frac{1}{2}$, the transmitted intensity is lower when the neutron spin and nuclear spin directions are parallel. In assigning spins we must remember that the neutron spin direction produced by the magnetized cobalt crystal is parallel to the field (since the neutron magnetic moment is negative), and that the magnetic moment of indium is positive. Our result for the 1.46-ev resonance agrees with that found by DRB, and also with a previous measurement[27] we have made using a block of magnetized steel for a neutron polarizer. The observed transmission changes were corrected for the presence of potential scattering, which is spin independent. In addition, a large correction was necessary in the case of the 3.86-ev resonance because of the presence of the 1.46-ev resonance which has opposite spin. These corrected transmission changes are listed in the fourth column of the table. We can then use these results to compute the average nuclear polarization using Eq. (2), and the average temperature of the indium sample using Eq. (3). These numbers are also listed in the table. The last column lists the average temperature of the chromium potassium alum salt obtained from susceptibility measurements. Since these temperatures are always considerably lower than the temperature of the indium sample, we suspect that the thermal contact between the salt and sample could be improved. However, eddy current heating of the metallic parts of the suspension may be the principle problem, since this would tend to warm up the sample faster than the salt.

TABLE I. Measured spin states associated with neutron resonances in In^{115}. Also listed are the observed and corrected percent changes in the transmitted intensity upon reversing the neutron beam polarization, and the corresponding values of the average nuclear polarization and temperature. The last column gives the measured average temperature of the cooling salt.

E_0 (ev)	J	$(\Delta t/t_0)$ in % observed	$(\Delta t/t_0)$ in % corrected	$\bar{f}_N$ %	$\bar{T}$ (°K) computed	$\bar{T}$ (°K) measured
1.46	5	10.5±2.2	10.9	2.4	0.064	0.039
3.86	4	−6.7±1.0	−9.1	3.0	0.052	0.033
9.10	5	2.9±0.9	3.3	2.5	0.062	0.043

To be certain that the effects shown in the table are real, we ran a series of warm runs on the 1.46-ev resonance. These were performed in exactly the same manner as a normal run, except that the sample was at room temperature. The resulting effect was $\Delta t/t_0$

[27] A. Stolovy and M. E. Bishop, Bull. Am. Phys. Soc. **3**, 177 (1958).

$=(0.60\pm1.15)\%$. This clearly demonstrates that the effects obtained are due to the polarization of the sample.

DISCUSSION

The 1.46-ev and 3.86-ev resonances are known to have radiation widths which are significantly different.[28] The low-energy capture gamma-ray spectra associated with these resonances have been studied by Draper et al.[29] who found significant differences in the intensity ratios of two pairs of gamma-ray lines between the 1.46-ev and the 3.86-ev resonances. However, they also found a significant difference in the ratio of one pair of lines between the 9.10-ev and the 1.46-ev resonances, which we have found to have the same J value. Recent measurements on the resonance capture gamma-ray spectra in indium have been made by Vogt,[30] in which he observed low-energy gamma rays in coincidence with high-energy gamma rays. These measurements show that the spectra associated with the 1.46-ev and 9.10-ev resonances are almost identical, while the spectrum associated with the 3.86-ev resonance is significantly different. It appears then that there is a correlation between the level spins and both the total and partial radiation widths for this isotope. However, Rae et al.[2] found no correlation between level spins and radiation widths in their work on the silver isotopes. Similarly, the work on manganese by Kennett et al.[31] showed no clear correlation between spin states and capture gamma-ray spectra, although the largest differences in the spectra were between resonances with different J. It is clear that many more spin states need to be measured for resonances in the same isotope, especially if the other resonance parameters are well known.[32]

In conclusion, we would like to point out that the method of measuring resonance spin states used here has the advantage of yielding an unambiguous result with a minimum of interpretation since it attacks the problem directly. It has two serious drawbacks, however: It would be difficult to observe resonances much above 20 ev, and it would be difficult to polarize nuclei with magnetic moments much below 2 nuclear magnetons. With increased reactor power these limitations could be reduced, but many resonances still would not be observable with this technique. It follows that all methods that will yield resonance spin states are to be encouraged, so that a coherent picture of the role of the spin state can be obtained. It should be mentioned that the technique used here is the only one that gives any promise of obtaining the spin assignments of resonances in the fissionable isotopes.

ACKNOWLEDGMENTS

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[28] H. H. Landon and V. L. Sailor, Phys. Rev. **98**, 1267 (1955).
[29] J. E. Draper, C. A. Fenstermacher, and H. L. Schultz, Phys. Rev. **111**, 906 (1958).
[30] R. H. Vogt (private communication).
[31] T. J. Kennett, L. M. Bollinger, and R. T. Carpenter, Phys. Rev. Letters **1**, 76 (1958).

[32] *Note added in proof.*—Recent measurements of the ratio of the 54-minute to 13-second activities of In^{116} by F. Domanic and V. L. Sailor show that this ratio differs for the 1.46-ev and 3.86-ev resonances by a factor of 3.5. Similarly, recent work by J. E. Draper and T. E. Springer show that the capture gamma-ray multiplicities for the 1.46-ev and 9.10-ev resonances are the same while that of the 3.86-ev resonance is significantly larger. These measurements coupled with ours indicate that the decay of these levels is strongly spin-dependent.