N$^{14}$ is 5 times larger than in C$^{12}$. If the results of the DWBA calculations are substituted for $d\sigma/d\Omega_{\text{theory}}$ in the above expression this ratio increases to 10. Though no real fit to the angular distribution has yet been obtained with these DWBA calculations the absolute magnitudes consistently give this ratio over a wide range of parameters.

### D. The ($\alpha$,Li) Reactions on Al$^{27}$ and Ni

As shown by the observed strong forward peaking a direct reaction mechanism still seems to dominate the ($\alpha$,Li) reactions on aluminum and nickel, though the cross section for the ground-state transition drops by a factor of 50 for aluminum and by three orders of magnitude for nickel as compared to the ($\alpha$,Li$^6$) cross section for light elements. This decrease in cross section with increasing $A$ could be due to the fact that shell-model levels are filling out of phase in this mass region and reducing the correlation needed to form deuteron clusters.

## V. CONCLUSIONS

The larger deuteron reduced width obtained for N$^{14}$ compared to that for C$^{12}$ and the rapid drop in cross section with increasing $A$ are consistent with an interpretation of the ($\alpha$,Li$^6$) reaction at medium energies as a deuteron-pickup reaction. DWBA calculations based on this model are unable to reproduce the experimental angular distributons. However, in view of the simplicity of the interaction chosen in such calculations, and the questionable validity of the optical model in this region, this lack of agreement is not necessarily meaningful.

## ACKNOWLEDGMENTS

The author wishes to thank Professor F. H. Schmidt for his guidance in this work. He also thanks Dr. William R. Gibbs of the Los Alamos Scientific Laboratory for assistance with the DWBA calculations. He is grateful to the entire operating staff of the University of Washington cyclotron for assistance with the experimental aspects of the work.

PHYSICAL REVIEW VOLUME 136, NUMBER 5B 7 DECEMBER 1964

# Spin Dependence of the Thermal Neutron Cross Section of Ho$^{165}$†

R. I. SCHERMER
*Brookhaven National Laboratory, Upton, New York*
(Received 17 July 1964)

Transmission experiments have been carried out with polarized, monochromatic neutrons and polarized Ho$^{165}$ nuclei using a single crystal sample of holmium metal. (61.0±2.8)% of the thermal capture is into $I-\frac{1}{2}=3$ states, which establishes the contribution of one or more bound levels to the thermal cross section. Additional measurements on a polycrystalline sample show that the scattering cross section has no appreciable spin dependence.

## I. INTRODUCTION

THE interaction of slow neutrons with Ho$^{165}$ can proceed via compound states of total angular momentum $J=I+\frac{1}{2}=4$ or $J=I-\frac{1}{2}=3$. The fraction of neutrons captured in each spin state is of interest in the analysis of capture gamma-ray measurements.[1] By studying the transmission of polarized neutrons through a target of Ho$^{165}$ nuclei polarized in a holmium metal single crystal, we have determined that (61.0±2.8)% of the thermal absorption cross section is into $I-\frac{1}{2}$ states. An additional study on a polycrystalline sample shows that the scattering has essentially no spin dependence—i.e., is almost entirely coherent. The experiment and its analysis are quite similar to that already performed on Co$^{59}$,[2] so that this report is a brief one.

† Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] H. T. Motz and E. T. Jurney, Bull. Am. Phys. Soc. **9**, 31 (1964).

[2] R. I. Schermer, Phys. Rev. **130**, 1907 (1963).

## II. GENERAL CONSIDERATIONS

Monochromatic, polarized slow neutrons from a crystal spectrometer are passed through a nuclear sample which is contained in a demagnetization cryostat mounted on the spectrometer arm. We measure the transmission of the sample for neutrons polarized parallel ($\tau_p$) and antiparallel ($\tau_a$) to the externally applied magnetic field which orients the nuclei. The transmission effect is defined by

$$\mathcal{E}=(\tau_p-\tau_a)/(\tau_p+\tau_a). \quad (1)$$

The theoretical expression for this quantity including the effects of magnetic scattering has been derived for a simple ferromagnet, e.g., cobalt.[2] Although holmium has a spiral structure in low fields, our field of 17.5 kOe applied along an easy direction of the single-crystal sample is sufficient to produce magnetic saturation.[3] We thus produce the equivalent of a simple ferromagnet

[3] D. L. Strandburg, S. Legvold, and F. H. Spedding, Phys. Rev. **127**, 2046 (1962).

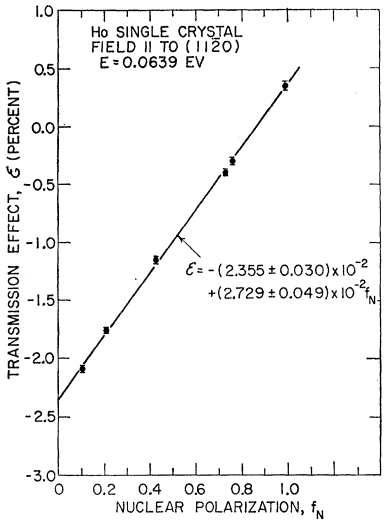


FIG. 1. Transmission effect at 0.0639 eV in a holmium metal single crystal as a function of nuclear polarization. An external magnetic field of 17.5 kOe was applied parallel to the direction of easy magnetization (11$\bar{2}$0). The solid line is the least-squares fit of the data.

and may use the previous results directly:

$$\mathcal{E}=-f_n^0((1+\phi)/2)h(1-Dt)Nt(\sigma_{ps,\mathrm{int}}+f_N\sigma_{pT}) = \mathcal{E}_{\mathrm{elect}}+f_N\mathcal{E}_{\mathrm{nuc}}. \quad (2)$$

The quantity of interest is $\sigma_{pT}$:

$$\sigma_{pT}=[I/(2I+1)](\sigma_{T+}-\sigma_{T-}). \quad (3)$$

For comparison, the nuclear cross section for unpolarized neutrons is

$$\sigma_{0T}=[(I+1)/(2I+1)]\sigma_{T+}+[I/(2I+1)]\sigma_{T-},$$

where $\sigma_{T+}$ and $\sigma_{T-}$ are the total (absorption plus scattering) cross sections for nuclear interactions in the two possible spin states. $\sigma_{ps,\mathrm{int}}$ is a quantity analogous to $\sigma_{pT}$ for the interference between nuclear and electronic magnetic scattering. The purely nuclear term contains the nuclear polarization $f_N$ as a factor and is thus temperature dependent. The interference term is temperature-independent at temperatures well below the magnetic ordering temperature. A series of measurements of $\mathcal{E}$ as a function of temperature therefore serves to distinguish between the nuclear and electronic contributions.

The auxiliary quantities appearing in (2) are discussed below.

(a) $f_n^0$ is the incident beam polarization and $\phi$ the beam flipping efficiency. Using an analyzing crystal of known high efficiency, we have recently remeasured these quantities with better precision than had been obtained in the past. We find that the values for $f_n((1+\phi)/2)$ used in previous work[2] were somewhat too large ($\sim 6\%$).

(b) $h$, the higher order correction, was calculated using previously measured values of the second-order fraction in the beam.

(c) Since we have a magnetically saturated single crystal we take the beam depolarization parameter $D\approx 0$.

(d) $Nt$ is the sample thickness in atoms/cm$^2$. The most accurate technique for measuring this is to measure the sample area and weight. Since our sample had an irregular shape, we could not do this and were thus forced to use the thickness ($0.035\pm 0.001$ in.) and the density (8.78)[4] to obtain $Nt=(2.83\pm 0.08)\times 10^{21}$ atoms/cm$^2$. The measured transmission of the crystal at the 3.92-eV resonance agreed within experimental error with that calculated using this value.

(e) In principle, the nuclear polarization can be derived from a knowledge of the hyperfine splitting and a measurement of the sample temperature. In practice, we do not usually measure the sample temperature directly. We measure instead a magnetic temperature $T^*$ for the refrigerating salt from which we deduce the thermodynamic temperature $T$ of the salt. The bulk of our previous data shows that, with favorable experimental conditions, this may be taken to be the sample temperature. However, there are some uncertainties involved in this procedure, notably in the $T-T^*$ correlation. This has been circumvented in this instance. Brunhart and Postma[5] have measured $\mathcal{E}$ as a function of temperature at the 3.92-eV resonance using the same single-crystal sample and experimental arrangement as the present work. In their experiment, $\sigma_{pT}$ was known and $f_N$ was the quantity of interest. We have used their measurements to provide a calibration curve of $f_N$ versus $T^*$, thus avoiding the usual thermometry problems.

## III. CAPTURE CROSS SECTION

Figure 1 shows the results obtained at 0.0639 eV for effect versus nuclear polarization. Similar plots were obtained at 0.1611 and 0.789 eV. From the slope of the best fitting straight lines at each energy, we have determined $\sigma_{pT}$, using Eq. (2). $\sigma_{pT}$ is negative in all cases, indicating that the $I-\frac{1}{2}$ state is favored. Some further discussion is required before we can separate the absorption and scattering components, however.

A single-crystal sample was required for this experiment because of the strong neutron beam depolarization in polycrystalline Ho metal.[6] In general, one does not measure the same cross sections in transmission on polycrystalline and single crystal samples. One expects that with a random placement of the single crystal in the beam, there will be no coherent Bragg scattering, so that the apparent scattering cross section will be lower for the single crystal than for the polycrystal. The two approach each other at neutron energies $E\gg k\theta_{\mathrm{Debye}}$, where inelastic scattering predominates. Such a behavior has been described, for instance, in quartz

[4] This is an average of the values given by K. A. Gschneider, *Rare Earth Alloys* (D. Van Nostrand Company, Inc., Princeton, New Jersey, 1961), p. 21.

[5] G. Brunhart and H. Postma (unpublished).

[6] Hans Postma, H. Marshak, V. L. Sailor, F. J. Shore, and C. A. Reynolds, Phys. Rev. **126**, 979 (1962).

crystals.[7] Thus, in the current measurement, the scattering contribution to the cross section at each energy is not well known. However, this does not cause any problem in analyzing the $\sigma_{pT}$ results unless the scattering is strongly spin-dependent. Fortunately, as will be discussed below, a further experiment on a polycrystalline sample shows that the scattering is in fact almost spin-independent.

To a sufficiently good approximation, then, we have taken the energy behavior of $\sigma_{pT}$ to be of the usual form of a constant scattering component $\sigma_{ps}$ plus an absorption component varying as $E^{-1/2}$.

$$\sigma_{pT}=\sigma_{ps}+\sigma_{pa}(0.0254/E)^{1/2}.$$

A plot of $\sigma_{pT}$ versus $E^{-1/2}$ is shown in Fig. 2. From the slope of this line, and taking the 0.0254-eV capture cross section to be 65 b with no error,[8] we deduce that $(39.0\pm2.8)\%$ of the thermal capture is into $I+\frac{1}{2}$ states. This is accounted for by the resonances at 3.92 and 12.8 eV, both of which are known to have $J=4$.[6] The remaining positive energy levels make no appreciable contribution to the thermal cross section, so that the $I-\frac{1}{2}$ component must be due to one or more bound $I-\frac{1}{2}$ levels.

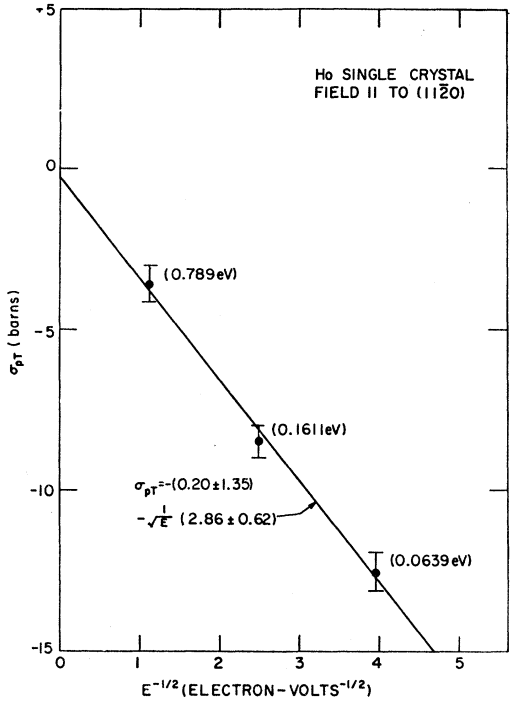


FIG. 2. $\sigma_{pT}$ versus $E^{-1/2}$, where $\sigma_{pT}$ is defined in Eq. (3). The solid line is the least-squares fit to the data.

[7] B. N. Brockhouse, Rev. Sci. Instr. **30**, 136 (1959).

[8] D. J. Hughes and R. B. Schwartz, Brookhaven National Laboratory Report BNL-325, Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C., 1958, 2nd ed. (unpublished).

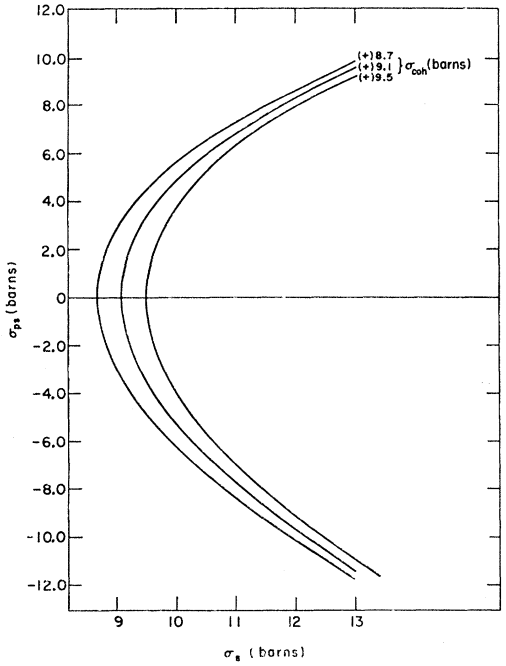


FIG. 3. Predicted values of $\sigma_{ps}$ as a function of the nuclear scattering cross section for unpolarized neutrons $\sigma_s$, for several values of the nuclear coherent scattering cross section $\sigma_{coh}$.

## IV. NUCLEAR SCATTERING CROSS SECTION

The spin dependence of the nuclear scattering was deduced from a measurement at 0.789 eV on a polycrystalline slab of Ho metal 0.096 in. in thickness. In using a polycrystal instead of a single crystal, we introduce two corrections. One is the beam depolarization $D$, appearing in Eq. (2), which we estimate from the correlation of Postma *et al.*[6] $D=1.67/E$ cm$^{-1}$, where $E$ is in electron volts. Second, the nuclear polarization does not lie along the applied magnetic field so that we only observe a fraction $K_m$ of the true polarization and hence of the true effect. We estimate $K_m\approx0.5$ from previous work.[6,9] The second-order correction is rather large at this energy. It has been calculated assuming that all the cross section at the second-order energy (3.16 eV) is due to the 3.92-eV resonance. Since this resonance has a spin opposite to the net spin at 0.789 eV, this leads to an overestimate of the magnitude of $\sigma_{pT}$ at 0.789 eV. Finally, we subtract the capture contribution, using the results obtained with the single crystal, and find $\sigma_{ps}\approx-1$ b. This is to be compared with the known nuclear coherent scattering cross section $\sigma_{coh}=(9.1\pm0.5)$b,[10] indicating only a small spin dependence for the scattering.

Let us see if this is reasonable in light of what is known about the low-energy cross sections for $Ho^{165}$. Koehler *et al.*[10] have measured the nuclear coherent

[9] V. L. Sailor, R. I. Schermer, F. J. Shore, C. A. Reynolds, H. Marshak, and Hans Postma, Phys. Rev. **127**, 1124 (1962).

[10] W. C. Koehler, E. O. Wollan and M. K. Wilkinson, Phys. Rev. **110**, 37 (1958).

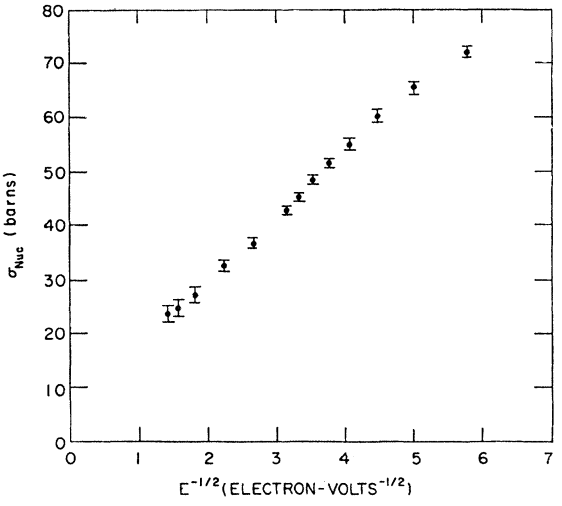


FIG. 4. Nuclear cross section $\sigma_{\text{nuc}}$, calculated from $\sigma_T-\sigma_{\text{para}}$, as a function of $E^{-1/2}$.

amplitude and the form factor for paramagnetic scattering, from which they have calculated the paramagnetic scattering cross section $\sigma_{\text{para}}$ as a function of energy. Bernstein *et al.*[11] have measured the total (transmission) cross section $\sigma_T$. Recent unpublished work by the author with better counting statistics agreed with this latter measurement except for slightly lower ($\sim$1 b) values in the region above 0.1 eV. The problem relevant to the present experiment arises because there is no direct measurement of the nuclear total (coherent plus incoherent) scattering cross section $\sigma_s$. If one knows both $\sigma_{\text{coh}}$ and $\sigma_s$, as was the case in $Co^{59}$,[2] there are only two possibilities for $\sigma_{ps}$ and the experiment must simply choose between them. Koehler *et al.* attempted to deduce a value of 13 b for $\sigma_s$ for $Ho^{165}$ by subtracting their data from that of Bernstein *et al.* at 0.5 eV. This would lead to expected values of $\sigma_{ps}$ of either +9.63 b or −11.33 b in contradiction with the present result, which requires $\sigma_s\approx\sigma_{\text{coh}}$. Figure 3 shows how the expected values of $\sigma_{ps}$ vary with $\sigma_s$, for several values of $\sigma_{\text{coh}}$.

However, there appears to be a discrepancy in the above calculation of $\sigma_s=13$ b. The published curve of Bernstein *et al.* appears to give $\sigma_T=26.5$ b at 0.5 eV. Assuming, as they did, $\sigma_a(2200)=64$ b with $1/v$ behavior gives a total scattering cross section of 12 b. Following Koehler, we take 1 b for paramagnetic scattering and thus find $\sigma_s=11$ b, which is still somewhat high.

We have attempted a more detailed analysis which has, however, not been any more successful. One may start with the $\sigma_T$ data, subtract $\sigma_{\text{para}}$ as given by Ref. 10 to extract the purely nuclear cross section $\sigma_{\text{nuc}}$, and then attempt to correct for any non-$1/v$ component of the capture cross section. This is possible for the positive energy resonances and is quite important, since the capture contribution at 0.5 eV due to the 2.93- and 12.8-eV levels is 1.3 b larger than a $1/v$ calculation predicts. However, the contribution of the negative level, whose existence was established by the current work, is probably less than a $1/v$ prediction by the same order of magnitude. A plot of the residual cross section versus $E^{-1/2}$ should then be a straight line with an intercept equal to $\sigma_s$. The result is shown in Fig. 4 using the author's $\sigma_T$ data and without any attempt at the above "non-$1/v$ correction" which does not help matters. It is seen that there is curvature at both ends of the plot. At least part of this curvature is due to small corrections to the paramagnetic scattering analysis of Koehler *et al.* Contained in their analysis is the assumption that the forward scattering amplitude of the $Ho^{3+}$ ion in $Ho_2O_3$ is 5.45 b/sr characteristic of the free $Ho^{3+}$ ion. As shown by Odiot and Saint James,[12] however, crystal-field effects lower this value by 0.10–0.15 b/sr, the exact value depending on the crystal-field model taken for $Ho_2O_3$. This makes $\sigma_{\text{para}}$, as calculated by Koehler *et al.*, 1 to $1\frac{1}{2}$ b too large at low energies, with the correction becoming smaller at higher energies. This would make $\sigma_{\text{nuc}}$ larger at low energies. In addition, Koehler *et al.* have used for $d\sigma/d\Omega$ only the terms due to the spherical part of the charge distribution. Including the higher order terms would make $\sigma_{\text{para}}$ very slightly larger at low energies, and $\sigma_{\text{nuc}}$ in Fig. 4 correspondingly smaller. Both these corrections would help straighten the plot in Fig. 4. The calculations are probably not worth performing because the energy behavior of the capture cross section is not known. However, it would appear from a reasonable extrapolation of the data in Fig. 4 that a value of $\sigma_s<10$ b is required, in support of the present result.

## ACKNOWLEDGMENTS

The author would like to thank Dr. G. Brunhart and Dr. H. Postma for the use of their $f_N$ versus $T^*$ data on the Ho single crystal prior to publication. He would also like to acknowledge several helpful discussions with Dr. M. Blume, and the expert technical assistance of R. D. Schmidt, E. Caruso, and W. K. Kristiansen.

[11] S. Bernstein, L. B. Borst, C. P. Stanford, T. E. Stephenson, and J. B. Dial, Phys. Rev. **87**, 487 (1952).

[12] S. Odiot and D. Saint-James, Phys. Chem. Solids **17**, 117 (1960).