uncertainties in the determination of the scattering angle and the background under the inelastic peak.

We conclude from the measurements presented herein that $Q_{2^+}(\mathrm{Cd}^{114})$ is significantly smaller than the rotational-model value. The larger negative moment previously associated with $\mathrm{Cd}^{114}$ was based principally on the results from Refs. 2 and 5. However, a recent investigation[8] of systematic errors associated with particle-$\gamma$ coincidence experiments has shown that the $Q_{2^+}$ value derived from Ref. 2 has to be decreased by about a factor of 2. If, in addition, the result from Ref. 5 is also modified for reasons already cited, the emphasis shifts from the larger moments. The remaining results in Table II are not inconsistent with a $Q_{2^+}(\mathrm{min})$ of about half the rotational-model value. The scatter in these values, however, is large and probably not completely statistical, so that an error-weighted average of all the data cannot be taken appropriately. We point out that the most recent results, from this measurement and from Ref. 8, are consistent with each other; their mean is $(-0.32\pm0.08)e$ b, which, as noted above, is significantly different from the larger moments on which past theoretical comparisons were based.

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# Reaction $\mathrm{D}(d,n)^3\mathrm{He}$ at 0° with Polarized Beam: A New Source of Polarized Neutrons from 7 to 18 MeV*

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Experimental results are reported for the neutron polarization from the reaction $\mathrm{D}(d,n)^3\mathrm{He}$ at 0° with the incoming beam polarized to the extent $p_3=p_{33}\approx0.82$ perpendicular to the direction of motion, where $p_3$ and $p_{33}$ are components of vector and tensor polarizations, respectively. The measured neutron polarization varies in the range 0.65 to 0.72 for $E_d$ in the range 4.1 to 15.1 MeV. The measurements are consistent with a process in which the neutron spin suffers little interaction. The influence of the deuteron $D$ state is noted. Comparison is made to several other sources of polarized neutrons, with the conclusion that near $E_n=10$ MeV this process is outstanding.

The reaction $\mathrm{D}(d,n)^3\mathrm{He}$ is a very high-yield source[1,2] of monoenergetic neutrons with energies in the neighborhood of $E_n=10$ MeV. It is also very sharply peaked forward in the laboratory system, such that by $\theta=30°$ (lab) the cross section is down by a factor of 10 compared to 0°. The forward peaking becomes more pronounced as energy increases. With an unpolarized deuteron beam incident, it is necessary to work near the cross-section minimum to obtain polarized neutrons. The highest neutron polarization for this reaction was reported by Spalek *et al.*[3] to be about 0.43 at $E_d=12$ MeV and 31.1° (lab). Under these conditions the cross section is 20 times smaller than that at 0°.

Polarizing the incident beam changes the situation completely. The purpose of this note is to present measurements of the neutron polarization from the $d$-$d$ reaction at 0°, where a polarized deuteron beam is used. The resulting values of neutron polarization are large and remarkably constant for $E_d$ in the range 4 to 15

MeV. This work is a continuation of similar polarization transfer measurements[4] on the reaction T$(d,n)^4$He, and we assume much of the background and description of the method presented there. To our knowledge there have been only two comparable measurements on the *d-d* reaction; one by Blyth *et al.*[5] at 12 MeV, with which comparison will be made below, and the other at 460 keV by Janett, Huber, von Möllendorff, and Striebel,[6] where apparently only small effects were observed.

The polarized beam was obtained from a Lamb-shift ion source[7] at the Los Alamos tandem Van de Graaff accelerator. Beam currents on target varied in the range 10 to 50 nA, with poorest performance generally coming at the lower energies. The beam polarization on target was close to $p_3 = p_{33} = 0.82$, where $p_3$ and $p_{33}$ are the vector and tensor polarizations in Goldfarb's notation.[8] Stated otherwise, the beam was 82% in the $m=+1$ spin state, with the remainder unpolarized, relative to a quantization axis $\hat{s}$ which was perpendicular to the incident momentum direction $\vec{k}_{\text{in}}$.

We consider only the case where the reaction plane is taken normal to $\hat{s}$; the $y$ axis is parallel to $\vec{k}_{\text{in}} \times \vec{k}_{\text{out}}$, with the $z$ axis along $\vec{k}_{\text{in}}$. The outgoing $y$ component of neutron polarization, $p_y'(n)$, is described by the following equations of Gammel, Keaton, and Ohlsen[9]:

$$I(\theta)p_y'(n) = I_0(\theta)[P(\theta) \pm \tfrac{3}{2}p_3 K_y^{\,y}(\theta) + \tfrac{1}{2}p_{33}K_{yy}^{\,y}(\theta)], \quad (1)$$

$$I(\theta) = I_0(\theta)[1 \pm \tfrac{3}{2}p_3 A_y(\theta) + \tfrac{1}{2}p_{33}A_{yy}(\theta)]. \quad (2)$$

Here $I(\theta)$ and $I_0(\theta)$ are the polarized and unpolarized differential cross sections, respectively, $P(\theta)$ is the polarization function, $K_y^{\,y}(\theta)$ and $K_{yy}^{\,y}(\theta)$ are the vector and tensor polarization-transfer functions, and $A_y(\theta)$ and $A_{yy}(\theta)$ are the vector and tensor analyzing powers.[10] For $\hat{s}$ parallel (antiparallel) to the $y$ axis the plus (minus) signs apply in Eqs. (1) and (2).

At 0° we define the $y$ axis to be parallel to $\hat{s}$ since $\vec{k}_{\text{in}} \times \vec{k}_{\text{out}}$ is undefined. Three of the parameters become zero, and the expression for $p_y'(n)$ simplifies to

$$p_y'(n) = \tfrac{3}{2}p_3 K_y^{\,y}(0)[1 + \tfrac{1}{2}p_{33}A_{yy}(0)]^{-1}. \quad (3)$$

In general, the function $K_y^{\,y}(\theta)$ may vary between +1 and −1, while $A_{yy}(\theta)$ has limits +1 and −2. At 0° $A_{yy}(0)$ is further constrained to be between +1 and $-\frac{1}{2}$.

Various experimental details are the same as in Ref. 4. A liquid-helium polarimeter (4.8 moles $^4$He) was positioned at a distance $R_1 = 99$ cm from the 3-cm-long gas target cell. Deuterium gas was used at a pressure of 4.8 atm, absolute. The distance from the liquid-He cell to the final detectors was $R_2 = 35.6$ cm. The analyzing angle was held constant at 115° (lab) for all runs. Neutron polarizations were deduced from the relation $e = p_y'(n)P(n, {}^4\text{He})$, were $e$ is the observed left-right asymmetry and $P(n, {}^4\text{He})$ is the $n$-$^4$He analyzing power as given by Satchler *et al.*[11] Corrections were made for geometry and multiple scattering in the helium cell. For most of the runs, detector efficiency effects were removed by reversing the neutron spins with a spin-precession solenoid. At $E_d = 12$, 13.5, and 15 MeV the neutron spin was reversed by ion-source control, that is, the $m = +1$ and $m = -1$ deuteron spin states were alternately selected in the ion source. This method requires a small correction to the asymmetries (≈0.7%) because the polarizations of the +1 and −1 states are not exactly the same, and is only applicable to 0° experiments. The two methods overlapped at $E_d = 12.0$ and 13.5 MeV, with agreement to within the statistical accuracy.

The results of the experiment are given in Table I. For a beam polarization $p_3 = p_{33} \approx 0.82$, it is seen that the measured neutron polarization $p_y'(n)$ varies between 0.67 and 0.72 for $E_d$ in the range 4 to 15 MeV. If the incident beam were completely in the $m = +1$ spin state, the resulting polarization is given in the right-hand column as $p_y'(n)_{\max}$; these values vary from 0.77 to 0.86. To a great extent the outgoing neutron retains the polarization it had in the incident deuteron. The fifth column of the table gives $A_{yy}(0)$, which was determined from intensity ratios of the "singles" neutron rate in the $^4$He scintillator when the spin state was cycled between $m = +1$ and $m = 0$. The values of $A_{yy}(0)$ are rather constant at values near $\frac{1}{4}$ and imply an ~10% increase in the forward differential cross section when the beam is polarized. Values of $K_y^{\,y}(0)$ are given in the sixth column; those values may be interpreted as the neutron polarization which would result if a 100% vector-polarized deuteron beam were used (i.e., if $p_3 = \frac{2}{3}$, $p_{33} = 0$).

We have one point of comparison to the measurement of Blyth *et al.*[5] at Birmingham. They reported a preliminary result of $p_y'(n) = 0.34 \pm 0.06$ at $E_d = 12$ MeV and an angle of 0°. The vector polarization of their beam was $p_3 = 0.45$.

TABLE I. Summary of the measurements of neutron polarization $p_y'(n)$ in the reaction $D(d,n)^3He$ at 0°.

| $E_d \pm \Delta E/2$ (MeV) | $E_n$ (MeV) | $p_3$ | $p_y'(n)$ [a] | $A_{yy}(0)$ | $K_y^y(0)$ | $p_y'(n)_{\max}$ [b] |
|---|---|---|---|---|---|---|
| 4.06 ± 0.25 | 7.3 | 0.817 | 0.717 ± 0.021 | 0.184 ± 0.007 | 0.629 ± 0.018 | 0.864 |
| 6.04 ± 0.17 | 9.2 | 0.814 | 0.719 ± 0.018 | 0.256 ± 0.004 | 0.650 ± 0.016 | 0.864 |
| 8.04 ± 0.14 | 11.2 | 0.831 | 0.699 ± 0.012 | 0.238 ± 0.002 | 0.616 ± 0.011 | 0.826 |
| 10.02 ± 0.12 | 13.0 | 0.806 | 0.718 ± 0.015 | 0.237 ± 0.002 | 0.651 ± 0.014 | 0.873 |
| 11.97 ± 0.10 | 14.9 | 0.815 | 0.695 ± 0.012 | 0.238 ± 0.002 | 0.624 ± 0.011 | 0.836 |
| 13.50 ± 0.09 | 16.3 | 0.824 | 0.649 ± 0.014 | 0.246 ± 0.002 | 0.578 ± 0.013 | 0.772 |
| 15.08 ± 0.08 | 17.8 | 0.825 | 0.680 ± 0.024 | 0.259 ± 0.007 | 0.608 ± 0.022 | 0.807 |

[a] Errors are standard deviations.

[b] $p_y'(n)_{\max}$ corresponds to $p_3 = p_{33} = 1.0$.

We understand[12] that the tensor polarization of their beam was zero. On this basis a value of $K_y^y(0) = 0.50 \pm 0.09$ can be calculated from their results by use of Eq. (1), which is about 1 standard deviation low compared with our results of Table I. This is satisfactory agreement.

Breakup neutron polarizations were measured in this experiment at incident energies of 11.97, 13.50, and 15.08 MeV, to which we allude briefly here. At these energies measurements were made by ion-source selection of $m = \pm 1$ states, as mentioned earlier. In these measurements the time requirements on the signal were relaxed in such a way as to accept the high-energy neutron group and the broad distribution of breakup neutrons as well. The pulse-height resolution of the He scintillator was quite adequate to separate the two groups and varied from 17.5 to 10% (full width at half-maximum) for neutron energies of 7.3 to 17.8 MeV, respectively, which represents improved performance relative to our previous work. At $E_d = 13.5$ MeV the measured asymmetry of neutrons near the peak of the breakup spectrum ($E_n \approx 6.9$ MeV) was 0.47 ± 0.015. Estimating the necessary corrections, a value is implied for the neutron polarization of 0.58 ± 0.02, which is only 12% less than the polarization of the main group. Values of the breakup polarization at deuteron energies of 12 and 15 MeV are comparable to that at 13.5 MeV.

The large values of $p_y'(n)$ measured in the $D(d,n)^3He$ polarization transfer process are consistent with a picture in which the neutron of the incoming deuteron suffers little spin perturbation. This idea is not inconsistent with the view that the reaction $D(d,n)^3He$ looks like a direct process at forward angles since the angular distribution can be fitted[2] with $l = 0$ stripping-type functions. Following a suggestion of Gammel, we estimate the outgoing neutron polarization at 0° on the assumption that it is the same as in the incoming deuteron. It is clear that the deuteron $D$-state probability will play a role in this estimate. We therefore want to calculate $\langle \sigma_z'(n) \rangle$, the spin polarization of the "neutron in the deuteron," using a suitable deuteron wave function $\Phi$. The assumption is made that the deuteron is in the $m = +1$ state with respect to an axis $z'$ parallel to $\hat{s}$. For $\Phi$, we use that of Blatt and Weisskopf[13]:

$$\Phi(r, \theta, \varphi) = \frac{u(r)}{r}\frac{\chi_{11}}{4\pi} + \frac{w(r)}{r}\left[\left(\tfrac{6}{10}\right)^{1/2} Y_{22}\chi_{1-1} - \left(\tfrac{3}{10}\right)^{1/2} Y_{21}\chi_{10} + \left(\tfrac{1}{10}\right)^{1/2} Y_{20}\chi_{11}\right], \tag{4}$$

where $u$ and $w$ are the radial functions associated with the $S$ and $D$ states, the $Y_{LM}(\theta, \varphi)$ are normalized spherical harmonics, and the $\chi_{sm}$ are the triplet spin functions constructed for a neutron and a proton spin. The result[14] is

$$\langle \sigma_{z'}(n) \rangle = 1 - \tfrac{3}{2} p_D, \tag{5}$$

where $p_D$ is the $D$-state probability, $\int [w(r)]^2 dr$.

Signell[15] in a recent review has quoted values of $p_D$ from two potentials, including $p_D = 7\%$ from the Hamada-Johnston potential and a range of 5 to 7% from the boundary-condition model of Lomon and Feshbach. Taking $p_D = 6\%$, Eq. (4) gives $\langle \sigma_{z'}(n) \rangle = 0.91$. This may be compared with the values of $p_y'(n)_{\max}$ from Table I, which average to 0.82. Thus, about twice as much neutron depolarization occurs as can be accounted for solely on the basis of the $D$ state.

As noted in the introductory paragraph, the reaction $D(d,n)^3He$ has a high yield at 0°; for example,[1] at $E_d = 9$ MeV, $I_0(0°) = 89$ mb/sr (lab).

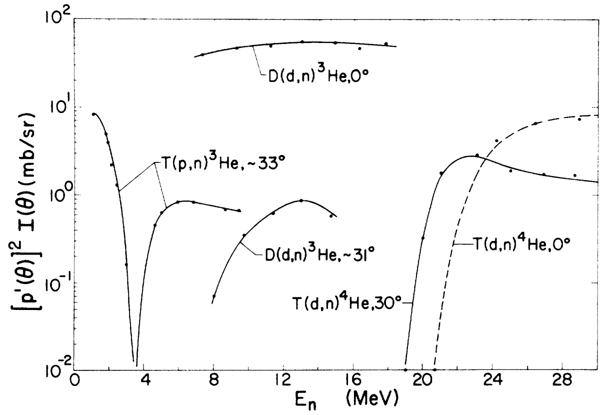

FIG. 1. The polarization criterion $[p'(\theta)]^2I(\theta)$ vs $E_n$ for various neutron-producing reactions. The curves labeled D$(d,n)^3$He, 0° and T$(d,n)^4$He, 0° represent polarization-transfer results of the present paper and of Ref. 4, respectively, while the remaining curves refer to polarized neutron production by unpolarized deuteron beams.

This fact, coupled with the results presented in Table I, means that with an incident vector-polarized deuteron beam, the reaction D$(d,n)^3$He at 0° is a very good source of polarized neutrons with energies near 10 MeV. This point is illustrated in Fig. 1 where the criterion $[p'(\theta)]^2I(\theta)$ is plotted as a function of $E_n$ for several common polarized neutron-producing reactions ($\theta$ is the lab angle). Included are the reaction[3] D$(d,n)^3$He for $\theta \approx 31°$, the reaction[16,17] T$(p,n)^3$He for $\theta \approx 33°$, the reaction[18] T$(d,n)^4$He at $\theta = 30°$, as well as the results for the 0° T$(d,n)^4$He polarization-transfer process[4] and the present results for the 0° D$(d,n)^3$He polarization transfer process. For these latter two cases, the curves were computed from the observed neutron polarization (without normalization to a single incident deuteron polarization) and from the similarly unnormalized polarized cross section $I(\theta)$. It can be seen that there is a factor of order 70 in favor of the D$(d,n)^3$He polarization-transfer process near $E_n = 10$ MeV, which implies that 30 nA of polarized beam is equivalent to 2 $\mu$A of unpolarized beam. In addition, the background conditions with a low-level polarized beam at 0° will generally be favorable. On this basis the D$(d,n)^3$He polarization-transfer process is one of the best sources of fast polarized neutrons.

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[10] We are following the Madison Convention with regard to the notation for beam polarization and analyzing power, and we are distinguishing polarizations of outgoing neutrons from beam polarizations by primes. In terms of the $M$ matrix for the reaction, $A_y(\theta) = \mathrm{Tr}(MS_yM^\dagger)/\mathrm{Tr}(MM^\dagger)$ and $A_{yy}(\theta) = \mathrm{Tr}[M(3S_y^2-2)M^\dagger]/\mathrm{Tr}(MM^\dagger)$, where $S_y$ is the ordinary Cartesian operator for spin 1. We use $P(\theta)$ for the polarization function, defined as $\mathrm{Tr}(MM^\dagger\sigma_y)/\mathrm{Tr}(MM^\dagger)$, where $\sigma_y$ is the Pauli spin-$\frac{1}{2}$ operator. For polarization-transfer tensors we propose to follow a notation introduced by Schumacher and Bethe [Phys. Rev. 121, 1534 (1961)] such that $K_y^{\,y}(\theta)$ represents vector polarization transfer, defined by $K_y^{\,y}(\theta) = \mathrm{Tr}(MS_yM^\dagger\sigma_y)/\mathrm{Tr}(MM^\dagger)$. This notation may be generalized to include polarization transfer from initial tensor to final vector spin polarization as represented by $K_{yy}^{\,y}(\theta) = \mathrm{Tr}[M(3S_y^2-2)M^\dagger\sigma_y]/\mathrm{Tr}(MM^\dagger)$. The quantities here notated by $A_y$, $A_{yy}$, $P$, $K_y^{\,y}$, and $K_{yy}^{\,y}$ correspond to $P_y^{\,0}$, $P_{yy}^{\,0}$, $P_0^{\,y}$, $P_y^{\,y}$, and $P_{yy}^{\,y}$, respectively, as defined in Ref. 9.

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# Evidence for Violation of the Porter-Thomas Postulate in $^{232}$Th†

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The $^{232}$Th neutron-capture cross section has been measured from 20 to 30 keV on the Physics-8 underground explosion. Resonance parameters and systematics for $s$-wave and $p$-wave levels that were obtained in the resolvable region, to 2000 eV, were used directly to calculate the average cross sections in the unresolved region. These calculations were in good agreement with the measured cross section. Our results do not support the Porter-Thomas postulate for single-channel reactions.

In their landmark paper, Lane and Lynn[1] demonstrated that kilovolt-region neutron capture in $^{238}$U and $^{232}$Th could be adequately described using measured $s$-wave resonance parameters, theoretical $p$-wave parameters, and the Porter-Thomas postulate concerning fluctuations in reduced neutron widths.[2] Their work has served as a model for analyzing average capture data for almost fifteen years. Yet, almost every piece of thorium-232 experimental data that was available for their analysis was very poorly known. We have measured neutron capture in thorium in both the resonance and unresolved regions, partly to resolve discrepancies in the many sets of data, but mostly to obtain sufficient data on the $p$-wave population so that kilovolt neutron capture can be directly calculated.

Radiative capture was measured with a beam of neutrons from the Physics-8 underground nuclear detonation. The flight path was about 250 m and the instrumental resolution was ~1 nsec/m. Experimental techniques using modified Moxon-Rae detectors for capture $\gamma$ cascade measurements and the $^6$Li($n$, $\alpha$) reaction for neutron-flux determinations have been described previously.[3] Data were obtained from thorium samples of 970.9 and 201.2 b per atom in thickness, i.e., 0.339 and 1.64 mm, respectively. Area analysis[4] of capture yields provided resonance parameters.

Radiation widths $\Gamma_\gamma$ were obtained for 66 large levels where $\Gamma_n > \Gamma_\gamma$. For these levels, it was also possible to determine $g\Gamma_n$ values by the self-indication method but results were less accurate than those from previously reported transmission measurements. Capture areas were therefore analyzed using neutron widths listed by Stehn *et al.*[5] In the energy interval from 50 to 350 eV, our weighted average $\overline{\Gamma}_\gamma$ is 20.9 meV, that of Ashgar *et al.*[6] is 21.1 meV, and that of Ribon[7] is 21.6 meV. The weighted average for all measured resonances within the 2-keV interval is 20.5 ± 3 meV.

In the case of small levels, where $g\Gamma_n \ll \Gamma_\gamma$, capture areas are insensitive to the radiation width and thus values of $g\Gamma_n$ are provided from area analysis. Some 130 levels are observed from 20 to 2000 eV, of which 91 may be compared with the results of Ribon.[7] The weighted ratio of our values of $g\Gamma_n$ to those of Ribon is 0.99.

Average capture cross sections from 5 to 30 keV are shown in Fig. 1. Since the relative uncertainty in this measurement is ~2.5%, fluctuations in the data are probably real; however, the absolute limit of error is estimated to be ±15%. The agreement of our data with the results of Macklin and Gibbons[8] is good.

As shown in Fig. 2, the values of $g\Gamma_n$ below 500 eV fall into two broad but distinct groups. The trend of values in the upper and lower groups appears to be consistent with $E^{1/2}$ ($s$-wave) and $E^{3/2}$ ($p$-wave) energy dependences, respectively. The average reduced width for the assumed $s$-wave population (22 levels), from values recommended in Ref. 5, is 1.8 ± 0.4 meV. A nuclear radius $R$ of 9.65 fm[7] was used to compute the weighted reduced widths $[g\Gamma_n{}^1 = g\Gamma_n(1+k^2R^2)/k^2R^2E^{1/2}$, where $k = (2.19\times10^{11})E^{1/2}m^{-1}]$ of the $p$-wave population with a resulting average value of 3.9 ± 1.1 meV for the 50 levels included. If a $2J+1$ spin dependence of the level density is assumed, 66