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^{141}Pr(γ,n) Cross Section from Threshold to 24 MeV*

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The ^{141}Pr(γ, n) cross section was measured from threshold to 24 MeV with a photon beam produced by the in-flight annihilation of positrons. The photon beam resolution was determined to be 1.2% (full width at half maximum) by elastically scattering the γ rays from the 15.1-MeV level in ^{12}C. The (γ, n) cross section was found to have a maximum value of ~348 mb and an integrated value up to 24 MeV of 1.72 ± 0.16 MeV b. Within the statistics and the photon resolution of the measurement, the results indicate that there is no structure in the cross section, with the possible exception of a weak bump at approximately 17.5 MeV. The results are compared with previous measurements and with theory; the latter comparison indicates that the widths of states in the dynamic collective theory should be considerably broader than those which have been typically used.

I. INTRODUCTION

A great deal of controversy exists over the possibility of structure in the ^{141}Pr(γ, n) cross section, as is evident from the results of three previous measurements shown in Fig. 1 (taken from Ref. 1). The most recent result, obtained by Cannington, Stewart, and Spicer (CSS),[1] shows three large peaks in the middle of the giant resonance, as well as smaller peaks in other areas. The cross section of Cook *et al.* (CHWBJG)[2] shows pronounced structure in the lower part of the giant resonance, and it differs considerably from that of CSS. Both of these measurements were done with the radioactivity detection technique and with bremsstrahlung beams, although different methods of unfolding data were used. A measurement from Livermore by Bramblett *et al.*[3] shows no structure; these data were taken with a neutron counter and with monoenergetic γ rays from the annihilation of positrons. The calculated resolution for the Livermore γ-ray beam in the 13–17-MeV region[3] was more than sufficient for observing the main structure reported by CSS in this region. However, CSS suggest in the text of their article that the Livermore resolution was not good enough to observe the structure,[1] i.e., that the Livermore resolution was actually worse than stated.

Because of the large controversy about the shape of the cross section and because the cross section is of value in determining the validity of theoretical calculations[1,4] on the shape of the cross section, it was decided that it would be important to perform at this laboratory a careful and independent measurement with monoenergetic γ rays. The present measurement has a number of significant advantages:

(1) Our γ-ray resolution was determined experimentally during the course of the Pr(γ, n) measurement by elastically scattering the γ rays from the 15.11-MeV level in ^{12}C, as described below. With our resolution and counting rates, we had the capability of easily observing the main peaks in the structure reported by either CSS or CHWBJG.

(2) Our γ-ray energy resolution was uniformly good over the entire energy region, since we used the same thin positron-annihilation foil (0.025 cm of Be) for all energies. In contrast, the Livermore group states that their resolution was considerably worse outside of the 13–17-MeV region because of a much thicker annihilation target.[3] Good resolution at low energies is particularly important for checking the validity of the structure in the data of CHWBJG.

(3) In the present measurement, the radioactivity detection method was used to determine the number of (γ, n) events. With this method, the efficiency is completely independent of the outgoing neutron energy, and, in addition, there is no possible ambiguity about which reaction is being studied. Since the present measurement employs the same detection method used in the bremsstrahlung measurements, no differences in the cross section due to the detection method can arise.

II. MEASUREMENT PROCEDURE

A. Measurement of Excitation Functions

The experimental arrangement used for the present cross-section measurements was similar to that used for the ^{63}Cu(γ, n) determination.[5] Positrons and electrons were produced by bombarding a converter with an intense electron beam from the first two sections of a four-section electron linear accelerator (LINAC). In the present experiment, an additional section was used at the beginning of the accelerator to obtain higher electron energies at the converter. Either positrons or

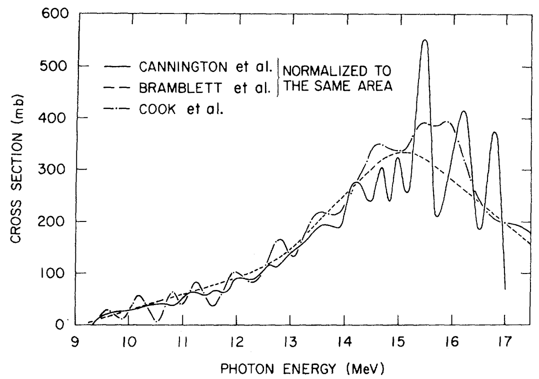

FIG. 1. Comparison of the $^{141}Pr(\gamma,n)$ cross sections obtained by CSS (see Ref. 1), Bramblett *et al.* (see Ref. 3) and CHWBJG (see Ref. 2). (Figure received from authors of Ref. 1.)

electrons were accelerated to the desired energy and then energy-analyzed with a magnet and slit system which had a calculated resolution of 0.9%. The beam then passed through a 2.4-m-thick shield wall and struck a 0.025-cm-thick Be annihilation foil. Practically all of the beam passed through the Be foil and was then bent by a magnet through an angle of 45° into a Faraday cup. The charge collected on this cup served as the beam monitor. The charge measuring system consisted of a picoammeter which was connected to the Faraday cup, and a current integrator which was linked to the picoammeter. The current integration system was operated as a leaky current integrator[6] to compensate automatically for the decay of the ^{140}Pr activity during the irradiation. The Be annihilation foil could be retracted by remote control to check for possible radiation produced in the beam tube system by scattered particles and to check that the foil did not interfere with the beam current measurements. The beam was aligned before each Pr irradiation by steering it through a 1.27-cm-diam hole in a retractable aluminum collimator located immediately in front of the Be foil. About 80% of the positron beam was contained within 1.27 cm, and photographs indicated that the beam was essentially symmetric.

Approximately monoenergetic γ rays from the annihilation of positrons in the Be foil passed through a lead collimator which was 3.65 cm in diameter and extended to 105 cm from the Be foil. A tungsten insert was placed at the exit of the collimator to reduce beam transmission through the collimator edges. Calculations show that edge effects in the tungsten collimator produce a negligible error in the cross-section determination. There was a gap of about 2.5 cm between the end of the tungsten collimator and the sample position. The samples were 4.45-cm-diam by 1.04-cm-thick discs of praseodymium which were canned in thin aluminum containers. The praseodymium discs were checked for uniformity by measuring the dimensions, by weighing, and by x raying them to insure lack of voids. The calculated transmission of photons in passing through an entire Pr sample was about 71% at 15 MeV; almost 80% of the attenuation was caused by pair production, and most of the rest of it was caused by photon scattering. Each sample was irradiated for approximately one half-life of ^{140}Pr (3.4 min) and was then removed from the accelerator area by a pneumatic tube system. The annihilation photons from the positron decay of ^{140}Pr were then counted for four min after a waiting period of 40 sec from the end of the irradiation. Two 12.7-cm-diam NaI detectors, which were 7.6 and 14.7 cm long, were used to detect coincidences between the 511-keV photopeaks. The effects of the bremsstrahlung tail in the photon spectrum produced by positrons incident on the Be foil were evaluated by repeating the measurements with a beam of electrons. The background from the aluminum containers was determined to be insignificant from irradiations under the same conditions as the Pr samples. The electronic components used in the current integration system were stable to within $\frac{1}{2}$%. During the measurements, the current integration system was calibrated and routinely checked with a calibrated current source, and the NaI detection system was routinely checked with a standard ^{22}Na source.

B. Photon Flux and Energy-Resolution Determinations

The modified version of the Monte Carlo code of Cardman and Owens[7] was used to calculate the number of γ rays striking the Pr sample per positron striking the Be foil. A previous article gives information on this code and our experimental verification of the results of the code.[5] The experimental determination of the photon flux agreed very well with the calculation at about 11 MeV, was about 3% higher than the calculated value at 15 MeV, and was about 9% higher than the calculated value at 20.5 MeV.[5] These differences were well within the combined errors of the experiment and the calculation. The input parameters for the present calculation were different from those of the previous calculation[5] because of the narrower positron energy resolution in the present measurement and because the Be annihilation target in the present experiment was one half of the target thickness in the previous experiment. The results of the Monte Carlo calculation with the thinner target should be as accurate or possibly more accurate than the calculation with the thick target, because the average number of positron interactions preceding the annihilation process is lower in the thinner target. Furthermore, the Monte Carlo code was previously checked[5] as a function of the Be target thickness, and the zero-thickness extrapolations for the intensity of photons agreed well with the values computed from the fundamental annihilation cross section. The results of the photon-flux calculations for the present cross-section measurements were fit with the expression $10^{-5} \times (a + bE + cE^2)$ γ rays per positron, where E is the kinetic energy of the positron. The results of a least-squares program gave the parameters: $a = -0.0424$, $b = 0.190$, and $c = -0.002\,54$. The points were fit within 0.2% by this expression.

An important feature of the present experiment was that the resolution of the γ-ray beam was measured during the course of the Pr experiment by elastically scattering the γ rays from the 15.11-MeV level in ^{12}C. In this measurement, a 12.7-cm-diam by 14.7-cm-long NaI crystal and a 12.7-cm-diam by 7.6-cm-long NaI crystal were used to determine the intensity of the scattered γ rays as a function of the energy of the positron beam. The scattered γ rays were detected at angles of 90 and 135° relative to the photons incident on the carbon. Figure 2 shows the measured energy spectrum of photons contained within the 1° collimator and produced by positrons with an energy resolution of ~0.9% striking the 0.025-cm-thick Be foil. The energy resolution of the photon beam derived from these data is 1.2% full width at half maximum (FWHM). Figure 2 also shows the spectrum calculated with the Monte Carlo code of Cardman and Owens.[7] The differences in the measured and calculated spectra probably result from the difference in the shape of the actual energy spectrum of the positron beam and the rectangular shape required in the code, as well as from small differences between the experiment and code in the spatial and angular distribution of positrons. (Although these differences between the experiment and code can affect the energy spectrum, the error in the calculated photon flux, which results from the inexact duplication of the experimental conditions, is small.) The scattering from the 15.11-MeV level in carbon also provided a precise energy calibration for the photon beam.

The FWHM for the Monte Carlo photon spectrum at 15.1 MeV shown in Fig. 2 agrees well with the measured value of 1.2%. Similar Monte Carlo calculations as a function of energy for our particular experimental conditions resulted in resolutions of 1.3% at both 9.7 and 22.6 MeV. The slight increase in percentage resolution at lower energies is caused by the increasing relative importance of the energy loss in the Be foil. At high energies the resolution gets slightly poorer because of the greater energy variation as a function of angle in the basic annihilation process. The result of both of these effects together with the constant percentage resolution of the positron beam produces a percentage photon resolution which is almost independent of energy over the region of the present Pr measurement.

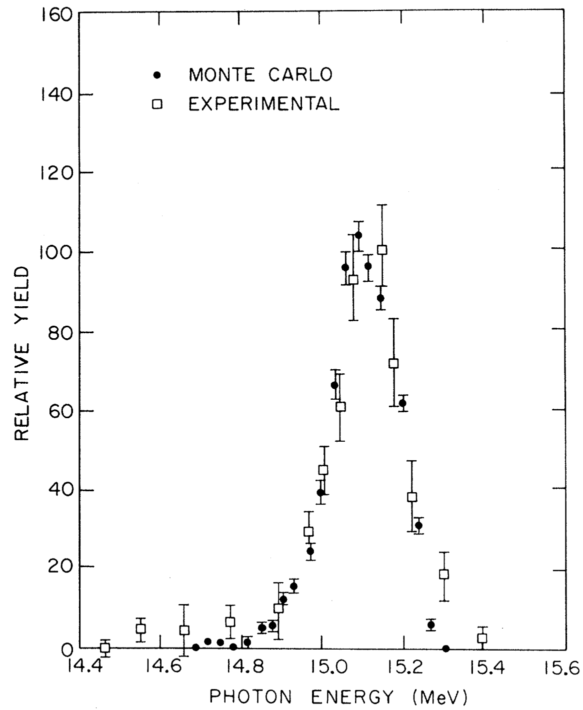

FIG. 2. Spectrum of annihilation γ rays determined by elastic scattering from 15.11-MeV level in ^{12}C. The Monte Carlo calculation of the annihilation spectrum is shown for comparison. The energy scale is greatly expanded to better illustrate the data.

C. Efficiency for Detecting ^{140}Pr Positron Activity

The efficiency of the NaI crystals for detecting positron annihilation γ rays from a Pr sample was measured with an ^{18}F source which was intercalibrated with a National Bureau of Standards calibrated ^{22}Na source.[8] The ^{22}Na source was not used directly for the calibration of the system, because of the interference produced by the coincidence summing of the 511-keV annihilation γ rays and the 1.275-MeV γ rays accompanying the positron decay of ^{22}Na. The intercalibration of the positron activity from ^{22}Na with that from ^{18}F was done by coincidence counting the 511-keV annihilation γ-ray photopeaks in a geometry consisting of the 12.7-cm-diam NaI crystals separated by 154 cm and with the source located midway between them. Because there is no angular correlation between the 1.275-MeV γ rays and the annihilation γ rays, the rate of coincidences involving the 1.275-MeV

γ rays in this expanded geometry was less than 1% of the annihilation γ-ray coincidences. In an independent measurement, a ^{18}F sample was calibrated against the standard ^{22}Na source with a Ge-(Li) detector. In this method, the sources were positioned at a distance from the detector so that the coincidence summing between the 511-keV γ rays and the 1.275-MeV γ rays from the ^{22}Na source removed only 0.3% of the counts from the 511-keV photopeak. The intercalibration and efficiency procedures are described in more detail in a previous article.[5] The combined result of the two measurements for the efficiency for coincidence counting the annihilation γ rays with the source located at the center of a Pr sample was 0.1122 ± 0.0015.

To account for the distributed-source effects in a praseodymium sample, measurements of the counting rate were performed as a function of axial and radial position of the ^{18}F foil within an assembly of praseodymium discs. The efficiency of the detection system varied with radial position by 3 to 5%, depending on the axial position, and the efficiency of the system with the source centered on the cylindrical axis of the sample varied with axial position by 7%. The correction accounting for the distributed source was calculated by weighting these variations with the angular distribution of the annihilation photon beam and with the attenuation of this beam by the sample; the variation in this correction with γ-ray energy was negligibly small. The resulting efficiency was 98.4% of that measured at the center of the praseodmium sample.

To obtain the final efficiency for detecting the ^{140}Pr positrons, a correction was applied for effects caused by bremsstrahlung generated in the slowing down of positrons and also for γ rays which accompany the positron decay. The sum pulses produced by the simultaneous detection of these photons and the annihilation radiation had to be taken into account to obtain the true number of 511-keV photopeak coincidences. The effect of the sum pulses in the efficiency measurements with ^{18}F was negligible, because the positron end-point energy is only 0.65 MeV and no γ rays are emitted in the decay of ^{18}F. In the decay of ^{140}Pr, very few γ rays follow the positron decay; however, a significant number of sum pulses do result from positron bremsstrahlung, since the positron end-point energy is 2.3 MeV, and the Pr is relatively efficient at producing bremsstrahlung. The net loss of photopeak coincidence counts caused by the summing effect was calculated from measured pulse-height spectra and amounted to 7.1%. The resulting absolute efficiency for counting the positron activity from ^{140}Pr was 0.103 ± 0.002.

III. RESULTS

The $^{141}Pr(\gamma, n)$ yields generated by the positron and electron beams incident on the Be foil are shown in Fig. 3. The energy scale in the figure is that of the annihilation photons. The data shown have been corrected slightly for the leakage of secondary electrons from the Faraday cup. The magnitude of this correction was measured during the present experiment in the same manner as described previously[5] and was the largest at high energies. At 24 MeV, the correction resulted in a 1.5% increase for the positron data and a 1.5% decrease for the electron data; at 16 MeV the correction was insignificant. The error bars shown in the figure include the uncertainties in the Faraday cup correction as well as the statistical uncertainties in the activation measurements.

A least-squares polynomial fitting technique was applied to obtain the best fit to the electron data shown in Fig. 3, and the results of this fit were then subtracted from the positron data points shown in the figure. The difference between the curve fit to the electron results and the individual electron data points is reasonable compared with the error bars on the electron data points and is typically small compared with the error bars on the positron data points; consequently, even though the polynomial fit does not include the effect of the detailed shape of the cross section, any errors produced are insignificant compared with the other errors in the subtracted data.

The results for the $^{141}Pr(\gamma, n)$ cross section are

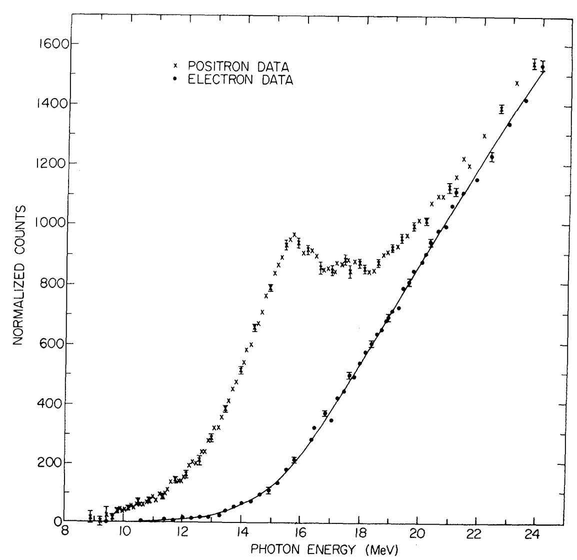

FIG. 3. $^{141}Pr(\gamma, n)$ yield (per current-integrator monitor) produced by positrons or electrons incident on the Be foil. The energy scale is that of the photons from the in-flight annihilation of positrons.

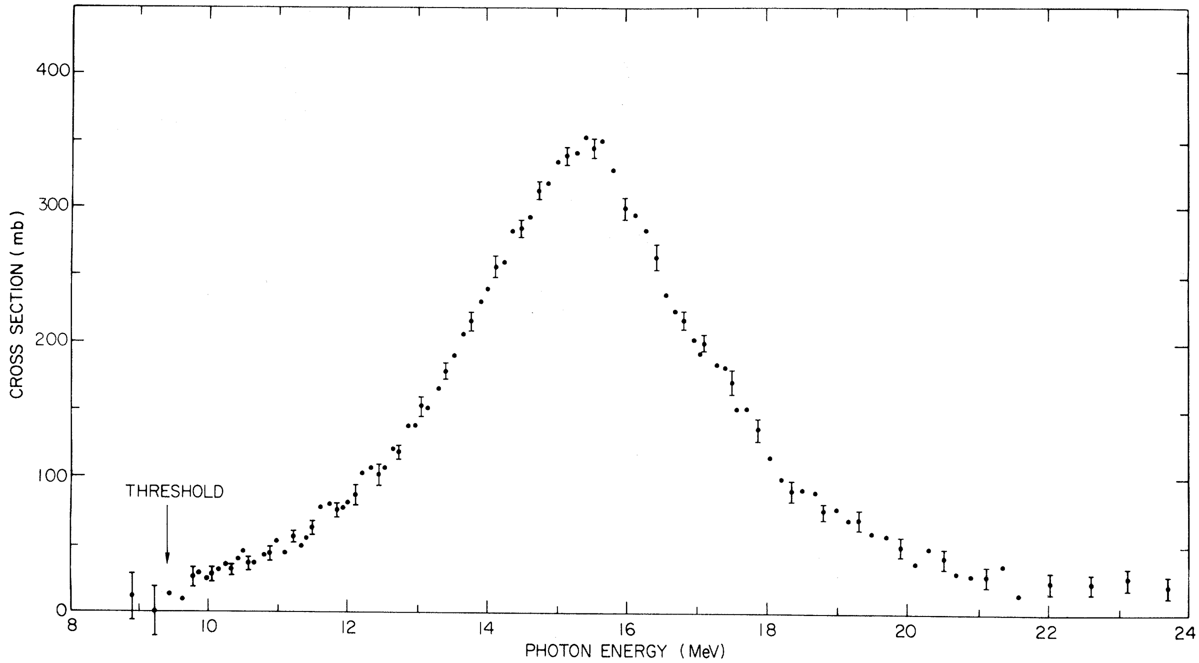

FIG. 4. $^{141}Pr(\gamma, n)$ cross section.

shown in Fig. 4. In the calculation of the cross section, the measured value[9] of 0.75 ± 0.03 was used for the positron-to-K-capture ratio, and the calculated value[10] of 0.11 was used for the L-capture-to-K-capture ratio. The attenuation of the positron annihilation-in-flight γ rays in the Pr sample and the small activity produced by the second interaction of photons which had initially been Compton scattered within the Pr sample were also considered in the calculation of the cross section. The latter effect amounted to ~0 mb at 12 MeV, ~7 mb at 17 MeV, and ~5 mb at 24 MeV; this effect varies smoothly as a function of energy. The error bars shown in Fig. 4 represent the statistical uncertainties in the activation measurements and the uncertainties in the determination of the correction for the emission of secondary electrons from the Faraday cup; the latter uncertainties are small compared with the statistical uncertainties. Additional uncertainties amounting to ±9% are mainly due to uncertainties in the photon flux, the efficiency of the NaI crystals for detecting the positron activities, and the fraction of the ^{140}Pr nuclei which decay by positron emission. There is also an additional systematic uncertainty due to the electron subtraction procedure; this uncertainty varies between ~0 mb at 16 MeV and ±8 mb at 24 MeV.

IV. DISCUSSION

Within the photon resolution and the statistics of the measurements, the present results indicate that there is no structure in the $^{141}Pr(\gamma, n)$ cross section, with the possible exception of a weak bump at approximately 17.5 MeV. This statistically uncertain bump may possibly be explained by theory, as discussed below. Another possible explanation is that it results from a combination of statistics and competition effects due to the onset of the $(\gamma, 2n)$ reaction, which could produce a decrease in the (γ, n) cross section at energies just above the bump.

Figure 5 shows the results of the present measurement compared with those of CSS[1] and CHWBJG[2] after our photon spectrum as a function of energy was folded into the latter two cross sections. Consequently, the resolution-broadened cross section of CSS shown in the figure (or that of CHWBJG in the figure) is the cross section we would obtain with our resolution if the published cross section of CSS (or CHWBJG) were the actual cross section, as measured with infinitely fine resolution. (If the actual resolution of the bremsstrahlung measurements were considered, the peaks in the bremsstrahlung curves shown in Fig. 5 would be even more accentuated.) The data from our photon resolution measurement at 15.1 MeV are also shown in the figure. Figure 5 shows that the present results for the lower part of the giant resonance disagree with the pronounced structure of CHWBJG; however, the statistical uncertainties of the present data are not sufficiently small to

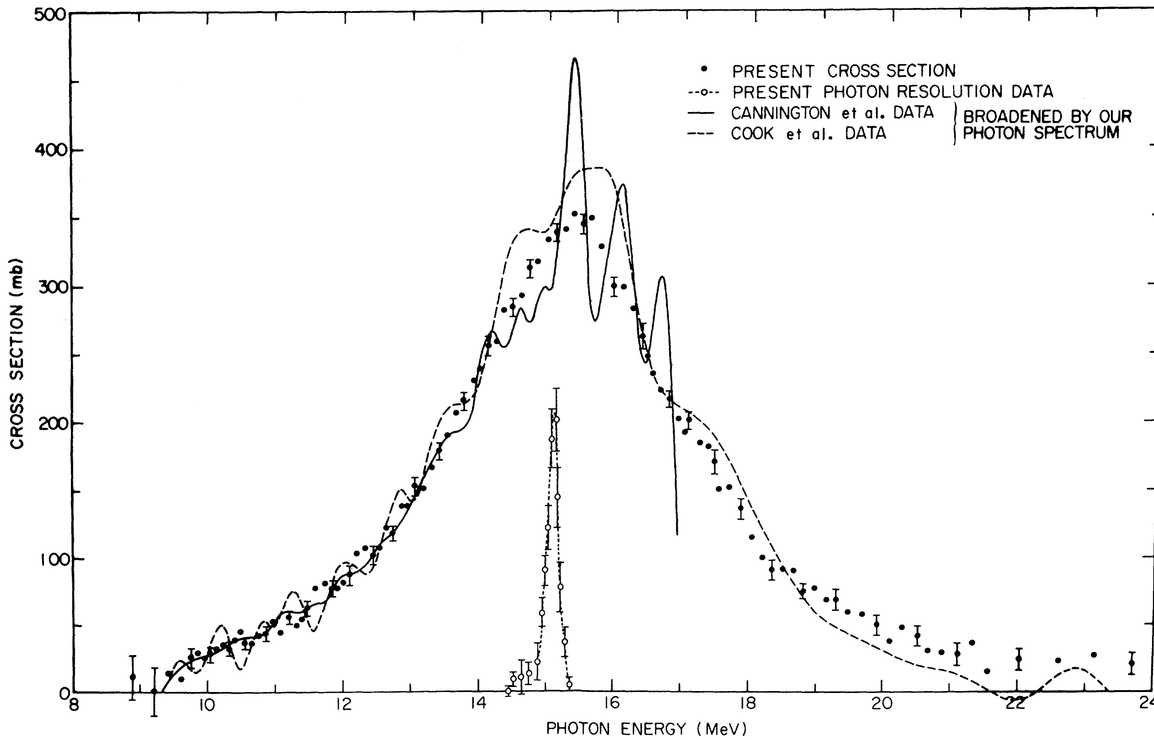

FIG. 5. The present ^{141}Pr(γ, n) cross section compared with those of CSS (see Ref. 1) and CHWBJG (see Ref. 2), after our photon spectrum as a function of energy was folded into the latter two cross sections. Also shown are the results of our photon spectrum measurement at 15.1 MeV.

comment positively on the weak structure reported by CSS below ~13 MeV. In the region of the peak of the giant resonance, there is a marked disagreement between the present cross section and that of CSS. The width of the strong narrow peak that CSS observed at 15.4 MeV is about 300 keV, when measured at half its height above adjacent valleys. The energy difference between this peak and the next higher peak reported by CSS is about 750 keV. Our resolution in this energy region is 180 keV FWHM. In order for us to miss a significant peak in the present experiment, the peak would have to be not only appreciably narrower than our resolution, but also of limited height (the latter depending, of course, on the width). For instance, if we assume a peak which is 50 mb above a smooth cross section of 350 mb and which has a width of 100 keV (so the area in the peak would be roughly 5% of the area in the 15.4-MeV peak observed by CSS), then we can crudely calculate that with our resolution and counting rates we would measure a cross section that would fall four standard deviations away from a smooth cross section.

It should be emphasized that our raw positron data, as given in Fig. 3, show directly whether any structure exists in the cross section within the resolution and statistics of the data. The analysis of the raw Pr data simply consisted of subtracting the electron data from the value of the positron data point at any given energy; this procedure was followed for all of the positron data points, and no unfolding or other complicated analysis was involved in this subtraction procedure. At high energies the electron data is almost as large as the positron data, and the statistics are, therefore, poor on the subtracted result. However, below about 17 MeV, which is the upper end of the region of controversy, the electron data are reasonably small compared with the positron data, and hence the statistical uncertainties for the subtracted result are reasonably small. The results of the positron-electron subtraction essentially give the cross section, except for factors which are either independent of the photon energy or else are very smoothly and slowly varying functions of the photon energy. Examples of such corrections are the efficiency of the NaI crystals for detecting the ^{140}Pr positron activity or the photon flux per positron striking the Be foil. Consequently, although these other factors help determine the absolute cross section, they are unrelated to whether or not there is structure in the data.

The simplicity of the present data analysis is due to the good resolution of the photon beam produced by the in-flight annihilation of positrons. As discussed previously, the photon resolution in the present measurement was experimentally determined at 15.1 MeV, which is in the region where CSS observed the main structure in their cross section. The data given in Fig. 2 show the resolution of the present measurement directly, without the necessity of any additional assumptions or calculations, and show the capability of seeing structure with the present apparatus. In contrast to the narrow γ-ray resolution of the present experiment and the simplicity of the present data analysis, the bremsstrahlung measurements involve the use of a γ-ray spectrum which has only a small part of the intensity in the tip of the bremsstrahlung energy spectrum and which increases in photon intensity with decreasing energy; this bremsstrahlung spectrum requires a much more complicated data analysis to unfold the excitation results. Consequently, in a bremsstrahlung experiment, both the measurement and the data analysis must be done much more precisely so that disturbing effects are not introduced in the data.

The present cross section is compared in Fig. 6 with that obtained by Bramblett *et al.* at Livermore.[3] In the comparison, the Livermore data have been shifted upward in energy by 0.8% to normalize the results to the present measurement. The agreement between the two measurements is very good. The magnitude of the present cross section in the peak is roughly 2% greater than the Livermore result, or considerably less than the over-all uncertainty of each of the measurements. The value of our integrated (γ, n) cross section from threshold to 24 MeV is 1.72 ± 0.16 MeV b. The Livermore integrated $(\gamma, n)+(\gamma, pn)$ cross section up to 24 MeV is 1.64 ± 0.16 MeV b. The agreement in the shapes of the cross sections as well as in the integrated values indicates that the $^{141}Pr(\gamma, pn)$ cross section is small, as would be expected from the height of the Coulomb barrier. Although an essentially smoothly varying $^{141}Pr(\gamma, n)$ cross section was obtained in measurements with γ rays from the in-flight annihilation of positrons at both Livermore and this laboratory, it should be noted that photonuclear cross sections measured with this technique do not always yield smoothly varying or structureless results. A number of cross sections measured at Livermore[11] and some unpublished results for the $^{16}O(\gamma, n)$ cross section measured at this laboratory show considerable structure. Consequently, the lack of structure in the Pr cross section cannot be attributed to the use of γ rays from the in-flight annihilation of positrons.

Recently reported measurements of neutron

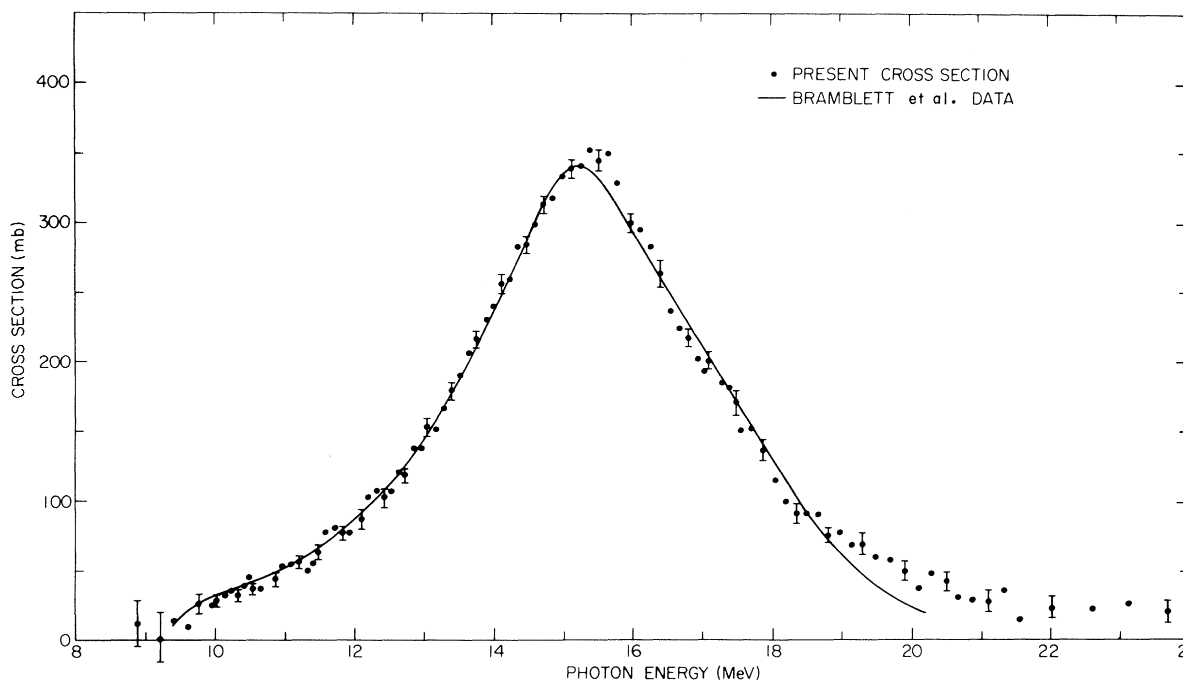

FIG. 6. The $^{141}Pr(\gamma, n)$ cross section from the present measurement and from the measurement of Bramblett *et al.* at Livermore (see Ref. 3). The latter measurement also includes (γ, pn) events; however, the $Pr(\gamma, pn)$ cross section should be small. In the comparison, the Livermore data have been shifted upward in energy by 0.8% to normalize the results to the present measurement. The error bars do not include systematic uncertainties; these are discussed in the text.

spectra from $^{141}Pr(\gamma, n)$ reactions show some structure superimposed on a high continuum.[12] These data were compared[12] with the results of CSS[1] in an attempt to draw conclusions concerning structure in the (γ, n) cross section. The four significant peaks in the neutron spectra[12] are in an energy region where the structure of CSS[1] is very weak, and these four neutron-spectra peaks are only partly consistent with the cross-section curve of CSS. In addition, no neutron-spectra peaks were seen in the energy region where CSS observed the three very large peaks. Therefore, even though the neutron spectra are interesting, it is not clear that they contribute much to resolving the large inconsistencies between the different measurements of (γ, n) cross sections. In any case, if the interpretation of neutron spectral experiments is to be unambiguous, the neutrons must decay to only the ground state of the daughter nucleus; for the Pr measurements,[12] the bremsstrahlung endpoint energy was ~13 to ~19 MeV above the (γ, n) threshold, and the neutrons could decay to one of the many excited states which start as low as 0.1 MeV. Consequently, structure in the neutron spectra could reflect variations (with γ-ray energy) in the neutron branching ratios to states in ^{140}Pr. The uncertainty in the interpretation is further increased by the fact that spin and parity considerations allow $E1$ photon capture followed by s-wave neutron emission to some of the excited ^{140}Pr states, but not to the ground state.

The present measurement of the $^{141}Pr(\gamma, n)$ cross section has some interesting consequences with regard to theoretical calculations of this cross section; these calculations have been done using the dynamic collective theory, in which the coupling of dipole oscillators to surface vibrations is treated.[1,4] The theoretical cross section for an odd-even nucleus like ^{141}Pr is typically obtained from the calculation for a neighboring even-even nucleus, because the effect of the odd particle has not been treated in the dynamic collective theory, and because the effect of the extra particle is usually small compared with the other approximations. Typically, the parameters for the neighboring nuclei do not vary much; however, in the mass region of ^{141}Pr, the amplitude of the surface vibrations and the energy of these vibrations varies considerably,[1] with the result that cross sections with significantly different amounts of structure are predicted.[1,4] The one set of parameters produces a calculated cross section with the main state at 15.2 or 15.6 MeV, depending upon the particular calculation,[1,4] and with a weak state at 17.0 or 17.5 MeV.[1,4] The other reasonable set of parameters predicts a cross section with five fairly strong states between about 14 and 17 MeV.[1] An arbituary width of 1.5 MeV has typically been used for these calculated states.[4] The first set of parameters is in more reasonable agreement with the present data, but still fits the data poorly. However, the first set of parameters with a width of ~4 MeV fits the shape of the experimental data quite well, including the energy region below the giant resonance.[13] In fact, a one-Lorentzian curve, based on the simpler theory with no coupling to surface vibrations, fits the experimental data just about as well. The weak state at 17.0–17.5 MeV predicted by the dynamic collective theory with the first set of parameters may possibly account for the uncertain, weak experimental bump at 17.5 MeV.

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[1]P. H. Cannington, R. J. J. Stewart, and B. M. Spicer, Nucl. Phys. A109, 385 (1968).

[2]B. C. Cook, D. R. Hutchinson, R. C. Waring, J. N. Bradford, R. G. Johnson, and J. E. Griffin, Phys. Rev. 143, 730 (1966).

[3]R. L. Bramblett, J. T. Caldwell, B. L. Berman, R. R. Harvey, and S. C. Fultz, Phys. Rev. 14, 1198 (1966).

[4]M. G. Huber, M. Danos, H. J. Weber, and W. Greiner, Phys. Rev. 155, 1073 (1967).

[5]R. E. Sund, M. P. Baker, L. A. Kull, and R. B. Walton, Phys. Rev. 176, 1366 (1968).

[6]S. C. Snowden, Phys. Rev. 78, 299 (1950).

[7]L. S. Cardman and R. O. Owens, Yale University Internal Report No. EAL 2726-39 (unpublished).

[8]The reason for the discrepancy between the calibrations mentioned in the previous article (Ref. 5) was found; the National Bureau of Standards calibration was used in the present determination. This would decrease the previously reported cross sections (Ref. 5) by 2.8%.

[9]E. I. Biryukov and N. S. Shimanskaya, Izv. Akad. Nauk SSSR, Ser. Fiz. 26, 215 (1962) [transl.: Bull Acad. Sci.:

USSR, Phys. Ser. 26, 215 (1962)]. (Note: The translation has a misprint in the uncertainty for the positron-to-K-capture ratio.)

[10]E. J. Konpinsky and M. E. Rose, in *Alpha-, Beta-, and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (North-Holland Publishing Company, Amsterdam, the Netherlands, 1965), Vol. 2, pp. 1632–1633.

[11]J. T. Caldwell, R. R. Harvey, R. L. Bramblett, and S. C. Fultz, Phys. Letters 6, 213 (1963).

[12]K. G. McNeill, J. W. Jury, and J. S. Hewitt, Can J. Phys. 48, 950 (1970).

[13]We wish to thank R. L. Bramblett for suggestions concerning this.

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Absolute Determination of Spins of Neutron Resonances and the Hyperfine Coupling Constant in Er^{167}†

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The spins of the four lowest neutron resonances in Er^{167} have been determined by measuring the transmission of polarized neutrons through a sample of polarized erbium nuclei. The determination of the spins depends solely on the transmission effect and is independent of any assumption about the sign of the nuclear magnetic moment or the direction of the effective field at the target nuclei. The spins were found to be $J = I + \frac{1}{2} = 4$ for the 0.460-eV resonance and $J = I - \frac{1}{2} = 3$ for the resonances at 0.584, 6.10, and 9.6 eV. The nuclear polarization of the sample, obtained as function of the sample temperature at a fixed energy, was fitted to a theoretical curve, using the magnetic and electric hyperfine splitting constants as fitting parameters. The values found for the magnetic and electric hfs constants are, respectively, $A/k = -0.085 \pm 0.0005$°K and $P/k = -0.005 \pm 0.001$°K. Taking the nuclear magnetic moment of Er^{167} to be $-0.56\mu_N$, the corresponding effective magnetic field at the nucleus is 7.26×10^6 Oe.

I. INTRODUCTION

Transmission measurements with polarized neutrons and targets of polarized nuclei offer a simple and straightforward way to determine the spins of low-energy neutron resonances. At low neutron energies, only s-wave-type interactions between neutrons and target nuclei need to be considered. Hence, a resonance in the slow-neutron cross section corresponds to the formation of a compound nucleus with a definite total angular momentum J, where J is limited to $I \pm \frac{1}{2}$, I being the spin of the target nucleus.

While, in general, the sign of the nuclear polarization, i.e., the sign of the nuclear magnetic moment and the direction of the effective field at the nucleus, must be known in order to make an unambiguous determination of the resonant spin, it is possible in some cases to make an absolute determination, provided the neutron cross section contains at least two observable resonances of opposite spin states. Preliminary results[1] on erbium depended on the assumption of a negative nuclear magnetic moment and a positive effective magnetic hyperfine field. The present work makes use of the fact that the two lowest resonances in the neutron cross section of Er^{167} have opposite spin and that, therefore, the spins can be determined directly from the measurements of the transmission effect without any additional assumptions.

Since erbium has a very large magnetic hyperfine field, large transmission effects could be obtained which allowed the determination of the magnitude and the sign not only of the magnetic hfs constant but also of the electric hfs constant.

II. THEORY OF TRANSMISSION EXPERIMENTS

A. Absolute Spin Determination

The theory describing the interaction of polarized neutrons and polarized nuclei has been developed elsewhere in detail.[2-4] Therefore, it is only necessary to present some of the pertinent equations here.

In order to represent the measurements with polarized neutrons parallel and antiparallel to the spin of the target nuclei, it is convenient to define a quantity $\langle \mathcal{E} \rangle$, the transmission effect,

$$\langle \mathcal{E} \rangle = \frac{\mathcal{T}_P - \mathcal{T}_A}{\mathcal{T}_P + \mathcal{T}_A} = \frac{C_P - C_A}{C_P + C_A}, \qquad (1)$$

where $\mathcal{T}_P$, $\mathcal{T}_A$ and C_P, C_A are, respectively, the transmissions and counting rates for parallel and antiparallel combination of neutron and target spin.