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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 γ cascade measurements and the ^{6}Li(n, α) 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 Γ_γ 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

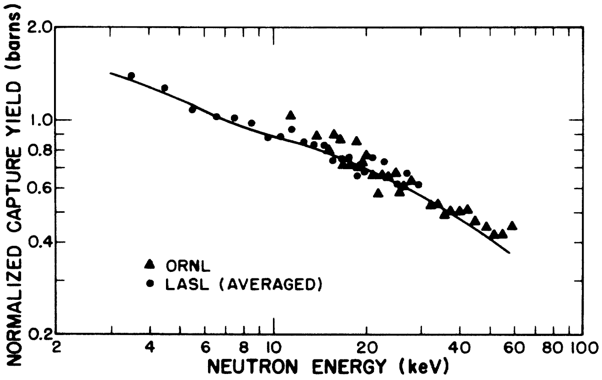

FIG. 1. Neutron capture yield data, averaged over kilovolt increments and normalized to sample thickness, from this work, and the capture–cross-section data of Macklin and Gibbons (Ref. 8) (Oak Ridge National Laboratory. The cross-section curve shown was calculated from Eq. (1) using the parameters $\Gamma_\gamma=21$ meV, $\langle g\Gamma_n^0\rangle=1.8$ meV, $\langle g\Gamma_n^1\rangle=3.9$ meV, $D_{1/2}=22.7$ eV, $D_{3/2}=11.4$ eV, $F_1=1$, and F_0, the neutron width fluctuation factor, calculated from the s-wave neutron width distribution in Fig. 3.

p-wave levels should have been observed in this energy interval; however, it is quite likely that a number of levels were missed in the vicinity of the large s-wave resonances. It was further assumed that the weighted reduced widths for the two compound nuclear states due to the p-wave interaction, $J=\frac{1}{2}$ and $J=\frac{3}{2}$, were equal: $g_{1/2}\Gamma_{n,1,1/2}=g_{3/2}\Gamma_{n,1,3/2}$.

The distributions of the s-wave and p-wave (normalized by the factor $\frac{1}{3}\times\frac{66}{50}$) levels are shown in Fig. 3. Considering the small number of levels within the s-wave population, the agreement between the two groups is remarkable, and both seem inconsistent with a χ^2 distribution of one degree of freedom (Porter-Thomas distribution). Six of the larger assumed p-wave levels have been considered as small s-wave levels in the treatment of Garg *et al.*[9]; however, a χ^2 test for these assumed 28 s-wave levels gives a goodness of fit of only 0.28 (eight equally likely intervals) for the Porter-Thomas distribution. Moreover, when these levels are removed from the p-wave population, the average value of $g\Gamma_n^{\,1}$ is reduced by more than a factor of 2; and this will be shown to be inconsistent with the high-energy cross-section data. The distribution of all levels to 3 keV with $g\Gamma_n/E^{1/2}>0.45$, presumed s wave, can be shown to be in agreement with the 0–500-eV results.

The results of the analysis in the resonance region have been used to calculate the average cross section from 5 to 55 keV where $\overline{\Gamma}/D\ll 1$

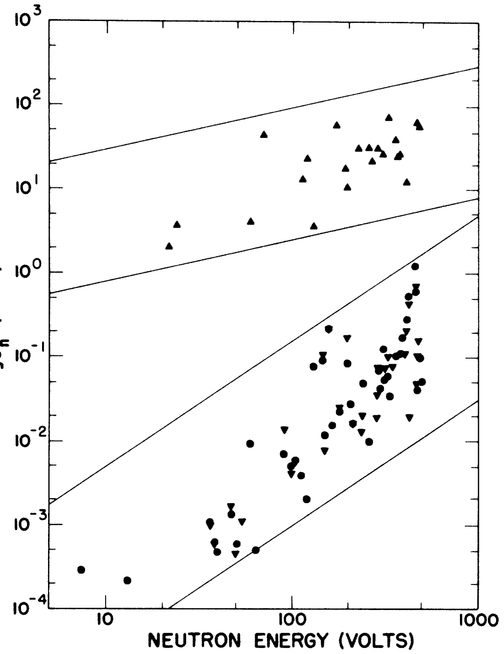

FIG. 2. Plot of $g\Gamma_n$ values as a function of energy. The larger subset (triangles) was taken from Ref. 5 and the smaller values are from this work (inverted triangles) and from Ref. 7 (circles). The boundaries of the two groupings are arbitrary in position, but follow $E^{1/2}$ (s-wave) and $E^{3/2}$ (p-wave) energy dependences.

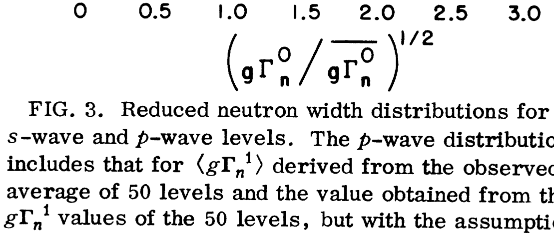

FIG. 3. Reduced neutron width distributions for the s-wave and p-wave levels. The p-wave distribution includes that for $\langle g\Gamma_n^1\rangle$ derived from the observed average of 50 levels and the value obtained from the $g\Gamma_n^1$ values of the 50 levels, but with the assumption that 66 levels should have been observed

$$\left[\langle g\Gamma_n^1\rangle=\sum_{i=1}^{50} g\Gamma_n^1(i)/66\right].$$

The $\nu=1.0$ curve is a χ^2 distribution of one degree of freedom consistent with 28 s-wave levels expected from 0 to 500 eV by the treatment of Garg *et al.* (Ref. 9). The $\nu=2$ curve is the χ^2 distribution of two degrees of freedom consistent with the 22 s-wave levels of this work.

and the single-level Breit-Wigner formula is appropriate. Computer calculations using the measured distributions of reduced widths showed also that the thin-sample approximation was valid within 10%. Therefore, the thin-sample theoretical expression for average capture cross sections[1] is appropriate:

$$\bar{\sigma}_\gamma(E) = 2\pi^2\lambda_0{}^2\left[\frac{g_{1/2}\bar{\Gamma}_{n,0}\bar{\Gamma}_\gamma F_0}{D_{1/2}(\bar{\Gamma}_{n,0}+\bar{\Gamma}_\gamma)} + \frac{g_{1/2}\bar{\Gamma}_{n,1,1/2}\bar{\Gamma}_\gamma F_1}{D_{1/2}(\bar{\Gamma}_{n,1,1/2}+\bar{\Gamma}_\gamma)} + \frac{g_{3/2}\bar{\Gamma}_{n,1,3/2}\bar{\Gamma}_\gamma F_1}{D_{3/2}(\bar{\Gamma}_{n,1,3/2}+\bar{\Gamma}_\gamma)}\right]. \tag{1}$$

In this equation, $\bar{\sigma}_\gamma(E)$ is the average capture cross section at neutron energy E, λ_0 is the neutron wavelength, $g_{1/2}=1$ and $g_{3/2}=2$ are the statistical weight factors for $\frac{1}{2}$ and $\frac{3}{2}$ compound states, $\bar{\Gamma}_\gamma$ is the average radiation width (assumed spin independent and nonfluctuating), $\bar{\Gamma}_{n,0}$ is the average s-wave neutron width at energy E and $\bar{\Gamma}_{n,1,1/2}$ and $\bar{\Gamma}_{n,1,3/2}$ are similar quantities for p-wave widths of $\frac{1}{2}$ and $\frac{3}{2}$ states, $D_{1/2}$ is the spacing of spin $\frac{1}{2}^+$ or $\frac{1}{2}^-$ levels (assumed equal), $D_{3/2}$ is the spacing of $\frac{3}{2}$ levels, and F_l is the neutron width fluctuation correction $[\langle\Gamma_n\Gamma_\gamma/\Gamma\rangle(\bar{\Gamma}_n\bar{\Gamma}_\gamma/\bar{\Gamma})^{-1}]$. Since analysis of the resonances could not distinguish between the $\frac{1}{2}$ and $\frac{3}{2}$ states for p waves, the further assumptions were made that $2D_{3/2}=D_{1/2}$ and $g_{1/2}\Gamma_{n,1,1/2}=g_{3/2}\Gamma_{n,1,3/2}$. The quantity F_0 was derived from the measured distribution of s-wave reduced widths (Fig. 3) and ranged from 0.92 to 0.95 between 5 and 55 keV. If F_0 had been computed using a Porter-Thomas distribution, the values would have been much smaller, typically ~0.75.[2] This factor for the p wave, F_1, was set equal to 1.0 since the distribution could not be unequivocally determined from the data; however, if the s-wave fluctuation factor were used, the calculated values of $\bar{\sigma}_\gamma(E)$ would have been decreased by less than 10%. An uncertainty in the calculation of $\bar{\sigma}_\gamma(E)$ of ±30% was assigned from the statistics associated with the s-wave level spacing and the systematic error in the determination of $g\Gamma_n$. The results appear in Fig. 1. There is excellent agreement between the calculations and experimental results.

Most of the assumptions imposed on the above analysis may be reviewed in terms of basic considerations. Identification of s-wave and p-wave levels by the observed grouping of $g\Gamma_n$ values, bounded by $E^{1/2}$ and $E^{3/2}$ energy dependences, is consistent with formulation of barrier penetration probabilities. The distinctness of these regions is inconsistent with the Porter-Thomas postulate. It is doubtful that any small s-wave levels were missed within the observed resonances, and the probability of finding no s-wave levels between these two groupings, based upon the Porter-Thomas distribution, is less than 1%. The $2J+1$ level density assumption used for the p-wave analysis is actually consistent with the experimental results; from 0 to 500 eV, the number of p-wave levels thus calculated from the s-wave population (22 levels) is 66 ± 14 (Poisson statistics) or 66 ± 7.5 (Wigner distribution),[9] which is in some agreement with the 50 levels observed. Since present notions concerning neutron widths require that $\Gamma_{n,l,J}$ be proportional to D_J, the assumption $g_{1/2}\Gamma_{n,1,1/2}=g_{3/2}\Gamma_{n,1,3/2}$ $(g_{1/2}=1,\ g_{3/2}=2)$ is then a consequence of the $2J+1$ level density dependence, provided that the strength functions are spin independent. The assumption that D_J and $\bar{\Gamma}_\gamma$ are not functions of energy from 0 to 55 keV is related to the fact that kinetic-energy considerations are a small perturbation, ~1%, when compared with the excitation of the compound nucleus. It is also noted that resonance parameters were obtained by capture-area analysis with the use of basically the same formulation as employed for the calculation of the average capture cross section; thus, this analysis is consistent.

The assumption that the average radiation width for p-wave levels is the same as that for s-wave resonances is open to question. Indeed, there is some evidence to the contrary, though it is insufficient to estimate a difference in thorium. If our method of analysis is correct, $1.4 > \bar{\Gamma}_\gamma(p\text{ wave})/\bar{\Gamma}_\gamma(s\text{ wave}) > 0.8$.

We have been able to describe the ^{232}Th average capture cross section in the unresolved region with the observed resonance parameters of p-wave and s-wave levels. Our results do not support the Porter-Thomas postulate for single-channel reactions although the calculated s-wave component of the higher energy cross section is similar for the two approaches. However, if the postulate were conserved by including large p-wave levels within the s-wave distribution, as has been strongly suggested by the treatment of Garg *et al.*,[9] the calculated p-wave contribution to the average cross section at higher energies would be more than 50% lower, and inconsistent with the measured data.

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π^+ Photoproduction from Hydrogen with Linearly Polarized Photons at 12 GeV*

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The process $\gamma+p\to\pi^++n$ has been studied with 12-GeV linearly polarized photons for momentum transfer t from -0.04 to -1.0 (GeV/c)^2. The experiment used a coherent bremsstrahlung beam produced by a diamond crystal. The measured asymmetry, $(d\sigma_\perp - d\sigma_\parallel)/(d\sigma_\perp+d\sigma_\parallel)$, is positive throughout this t range and is similar to measurements at lower energies.

We report here our measurements of the asymmetry in the reaction $\gamma+p\to\pi^++n$ with linearly polarized photons at 12 GeV in an experiment performed at the Stanford Linear Accelerator Center (SLAC). The asymmetry Σ is defined as

$$\Sigma=(d\sigma_\perp-d\sigma_\parallel)/(d\sigma_\perp+d\sigma_\parallel),$$

where $d\sigma_\perp$ ($d\sigma_\parallel$) is the differential cross section for photons polarized perpendicular (parallel) to the production plane. Asymmetry measurements provide a sensitive view of photoproduction dynamics, and it is of interest to compare the energy dependence of Σ with other photoproduction measurements, most of which have shown remarkably simple energy dependences.[1]

The source of polarized photons for this experiment was a coherent bremsstrahlung beam[2] produced by 16-GeV electrons striking a suitably oriented diamond crystal such that the major spike in the spectrum occurred at an energy of 12 GeV, and had an average polarization of 45%. The major experimental problem was the detection of single π^+ events originating from this polarized spike against a large background due to multiple-pion events initiated by high-energy photons. We used the SLAC 20-GeV spectrometer and many of the experimental techniques previously employed in photoproduction experiments at SLAC[3] to measure pion yields and to detect a step structure in these yields due to single-pion production by the major coherent spike.

Angle tolerances of 5×10^{-5} rad were required of the diamond planes, of the stability of the diamond mount, and of the primary electron beam divergence so that the spread in energy of the leading edge of the coherent spike could be kept to $\frac{1}{2}$% or less. After an intensive search that included examinations using a double crystal spec-