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DETECTION OF NONRESONANT NEUTRON CAPTURE IN Pb^{207} VIA THE THRESHOLD PHOTONEUTRON CROSS SECTION FOR Pb^{208}†

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A nonresonant neutron-capture cross section was found in Pb^{207} by measuring the asymmetry of a resonance in the threshold photoneutron cross section for Pb^{208}. The magnitude of the nonresonant component is too large to be accounted for solely by the direct-capture mechanism of Lane and Lynn, but it might be accounted for by Brown's semidirect reaction mechanism.

A direct nucleon-capture mechanism was proposed by Lane[1] in 1959 when it was recognized that the compound-nucleus theory failed to explain high-energy (10 MeV) nucleon capture. Subsequently the theory was extended by several authors to include slow neutron capture.[2] More detailed calculations by Daly, Rook, and Hodgson[3] showed that even with the direct-capture model, serious discrepancies still existed between theory and experiment for high-energy nucleon capture. However, in 1964 Brown[4] proposed a semidirect-capture mechanism in which a high-energy neutron is captured directly into a bound orbit; the energy released excites the giant dipole resonance with width $\overline{\Gamma}$, which then decays by γ-ray emission with a delay $\approx\hbar/\overline{\Gamma}$, whence the description as a semidirect process. This model greatly improved the fit to the high-energy data, with respect to both magnitude and shape of the observed cross section. The model was improved by Clement, Lane, and Rook[5] and by Longo and Saporetti,[6] who included both direct and semidirect processes. Subsequently, Longo and Saporetti[7] introduced a further improvement by including the interference between direct and semidirect processes; this interference sometimes results in dramatic effects and thus demonstrates the importance of taking account of both mechanisms.

This paper is concerned primarily with the detection of either of the capture mechanisms in reactions involving low-energy neutrons. Evidence for these mechanisms can be obtained by measuring an interference between a nonresonant and resonant neutron-capture γ ray as a function of neutron energy. Positive evidence can be difficult to obtain, however, owing to problems with resonance-resonance interference. Experimental limitations usually exist which limit the energy range over which measurements of the required accuracy can be made so that perhaps not all resonances which influence the cross section near a particular resonance can be measured. Also the measurements must be made at low energies, where the influence of bound states, which cannot be measured, is bothersome. Nevertheless, evidence has been obtained for a nonresonant amplitude in experiments on U^{238} and Co^{59} with a reactor chopper neutron source[8,9] and on Co^{59} using an electron linear accelerator as a pulsed neutron source.[10] However, the possibility of semidirect effects was not included in the analyses of the above experiments, and the equations used for the analysis therefore are incorrect to the degree that a semidirect amplitude is present.

The purpose of this paper is to report a measurement of the threshold photoneutron cross section for Pb^{208}, in which nonresonant neutron capture (or photoneutron reaction) was found, and to demonstrate that for $Pb^{207}(n,\gamma)$ semidirect capture must be included to obtain the magnitude of the observed nonresonant component.

In the threshold photoneutron technique,[11] bremsstrahlung from a pulsed, nearly monoenergetic electron beam is directed at a nuclear sample; the neutrons ejected in the (γ, n) reaction are detected and the energy measured by the neutron time-of-flight technique. The detector, which consisted of a U^{235} plate with a surrounding scintillator, provided a 25-cm-diam sensitive area and allowed fast and efficient detection of keV neutrons.[12] The energy of the electron beam is adjusted so that the bremsstrahlung endpoint energy barely exceeds the (γ, n) threshold. The excitation energy therefore is limited so that neutron emission can take place only to the ground state of the residual nucleus. A measurement of the neutron energy therefore serves to measure the photon energy. Further, since the absolute uncertainties in neutron and photon energies are the same and a neutron energy resolution of 1% is obtained easily, the effective photon-energy resolution is 0.01% or better. Thus, fine structure near the threshold in the (γ, n) cross section which previously could not be seen can be studied in detail with this technique.[13]

The results for natural Pb are shown in Fig. 1, where the photoneutron cross section in mb/sr is plotted against laboratory neutron energy. The principal measurement was performed on natural Pb, a large sample of which was available so that good statistical accuracy could be obtained simultaneously with high energy resolution. The measurements, which were made at an angle of 135° with the photon beam and with an electron energy of 9.0 MeV, also have been made on separated isotopes of Pb, so that each peak could be assigned to the proper isotope. Peaks not belonging to Pb^{208} are indicated by vertical arrows. There are three 1^- states in this spectrum, located at 41, 257, and 319 keV. The spins and parities of these states were determined by comparing measurements taken at 90° and 135°. The

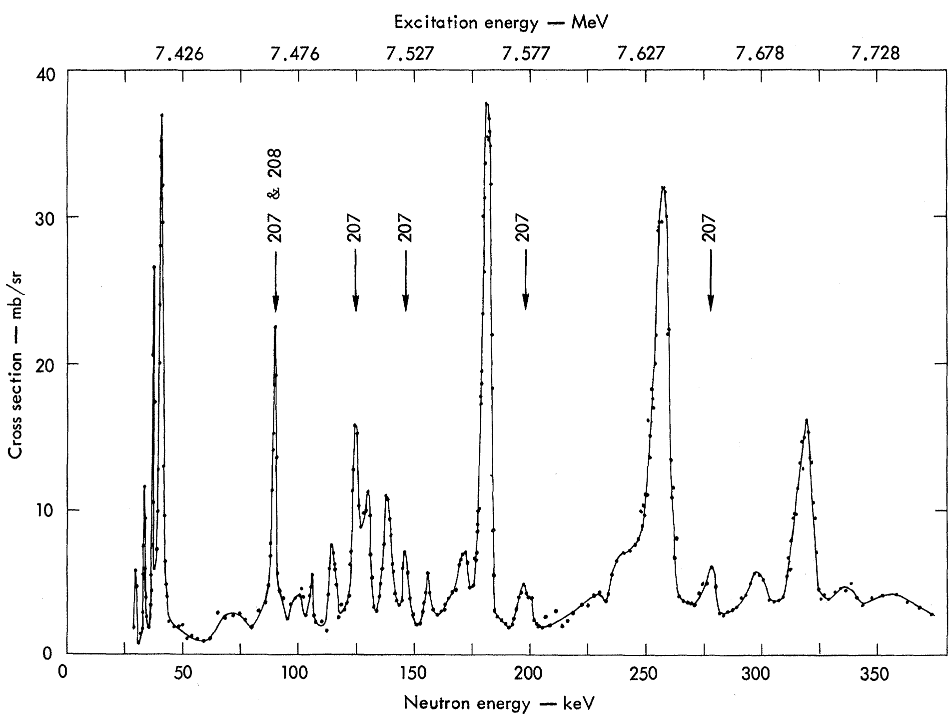

FIG. 1. Threshold photoneutron cross section in mb/sr for natural lead derived from the neutron spectrum emitted at 135° as a function of both laboratory neutron energy and incident photon energy. Levels not Pb^{208} are designated by vertical arrows.

attention of this paper is focused particularly on the peak at 41 keV, which is a well-known state in Pb^{208}, seen in both neutron-capture and total cross-section measurements on Pb^{207}. The (γ, n) cross section was normalized to the (n, γ) cross section of the same peak.[14]

The points of Fig. 1 are replotted in Fig. 2 on a wider scale. The peak at 37.5 keV has a total width (~30 eV) much narrower than the resolution function of the experimental apparatus, and thus serves as a lower limit for the experimental resolution function. The peak at 41 keV, which shows the asymmetry, is several times wider than the resolution so determined, and therefore it is resolved nearly completely. The slight asymmetry of the 37.5-keV peak is not a consequence of multiple scattering in the lead since both the probability for scattering in the lead and the energy loss upon scattering are small. The asymmetry results from scattering in the U^{235} plate before the neutron induces a fission event. The detector scattering is manifested as a tail on the resolution function and is therefore properly taken into account for the 41-keV peak by measuring the resolution function with the 37.5-keV peak.

The data points have been fitted with an expression which can be written for neutron capture as

$$\sigma_{n\gamma}=\frac{\pi}{k_n^2}g_n\left|D-\frac{(\overline{\Gamma}_\gamma\overline{\Gamma}_n)^{1/2}}{(E_n+B-\overline{E})+\frac{1}{2}i\overline{\Gamma}}-\frac{e^{-i\varphi}(\Gamma_n\Gamma_{\gamma 0})^{1/2}}{(E_n-E_0)+\frac{1}{2}i\Gamma}\right|^2. \tag{1}$$

The parameters k_n and g_n are, respectively, the wave number and statistical factor for the neutron. By reciprocity, $\sigma_{n\gamma}=\sigma_{\gamma n}(k_\gamma^2 g_n/k_n^2 g_\gamma)$. The first term in Eq. (1) is the direct capture derived by Lane and Lynn,[2] and the second term is the semidirect capture discussed by Longo and Saporetti.[7] In the second term, B is the separation energy of the neutron in Pb^{208}, $\overline{\Gamma}$ is the total width of the giant dipole resonance (GDR), $\overline{\Gamma}_n\overline{\Gamma}_\gamma$ is proportional to that portion of the GDR decaying to the ground state of the residual nucleus, and $\overline{E}$ is the energy of the GDR. The latter three parameters can be obtained by a fit to the GDR. The last term in the equation is the compound-nucleus Breit-Wigner amplitude as written by Lane and Lynn but multiplied by $-i$. Equation (1) can be rewritten in the following form:

$$\sigma_{n\gamma}=\frac{\pi}{k_n k_n^0}\frac{2J+1}{2(2I+1)}\left[d^{0\,2}-\frac{4d^0(\Gamma_n^0\Gamma_{\gamma 0}/\Gamma^2)^{1/2}}{1+\chi^2}(\chi\cos\nu-\sin\nu)+\frac{4\Gamma_n^0\Gamma_{\gamma 0}/\Gamma^2}{1+\chi^2}\right], \tag{2}$$

where k_n^0, d^0, Γ_n^0 represent these quantities evaluated at 1 eV and $\chi=2(E-E_0)/\Gamma$. All of the quantities in Eq. (2) are real. Both direct terms have been combined into the term d^0 where

$$d=d^0(E_n)^{1/2}=D^2+b^2-2Db\cos(\alpha-\beta-\theta+\tfrac{1}{2}\pi)$$

with E_n measured in eV,

$$b\equiv 2\cos\theta(\overline{\Gamma}_\gamma\overline{\Gamma}_n)^{1/2}/\overline{\Gamma},\quad \beta\equiv\tan^{-1}(\mathrm{Im}\overline{\Gamma}_n^{1/2}/\mathrm{Re}\overline{\Gamma}_n^{1/2}),$$

and

$$\theta\equiv\tan^{-1}2(E_n+B-\overline{E})/\overline{\Gamma}.$$

The angle $\nu=(\eta-\gamma+\varphi)$, with $\gamma\equiv\tan^{-1}(\mathrm{Im}\Gamma_{\gamma 0}^{1/2}/\mathrm{Re}\Gamma_{\gamma 0}^{1/2})$, $\varphi\equiv k_nR$, and

$$\eta\equiv\tan^{-1}\{[D\sin\alpha-b\sin(\beta+\theta-\tfrac{1}{2}\pi)][D\cos\alpha-b\cos(\beta+\theta-\tfrac{1}{2}\pi]^{-1}\}.$$

Of the four terms in Eq. (2), the first contains the direct and semidirect effects, the fourth is the Breit-Wigner resonance term, the second represents asymmetric interference between the first and fourth terms, and the third is a symmetric term which adds or subtracts from the last term.

The fit with Eq. (2) to the 41-keV peak is shown by the line through the points in Fig. 2. Two solutions are possible. The direct cross section required is 1.2 mb/sr and $\Gamma_n=1520$ eV. For $\nu=-44°$, $\Gamma_{\gamma 0}=6.44$ eV, while for $\nu=27°$, $\Gamma_{\gamma 0}=4.18$ eV. The line falls below the experimental data above 42 keV, probably owing to small high-spin resonances in Pb^{208} or resonances in other isotopes which appear weakly in this energy range.

It should be mentioned here that the differential cross section has been fitted, not the total cross section for which Eq. (2) is applicable. However, for 1^- states in Pb^{208} only $l=0$ neutrons are emitted and the total cross section can be obtained from Figs. 1 and 2 by multiplying by 4π.

There is some possibility that there may be a

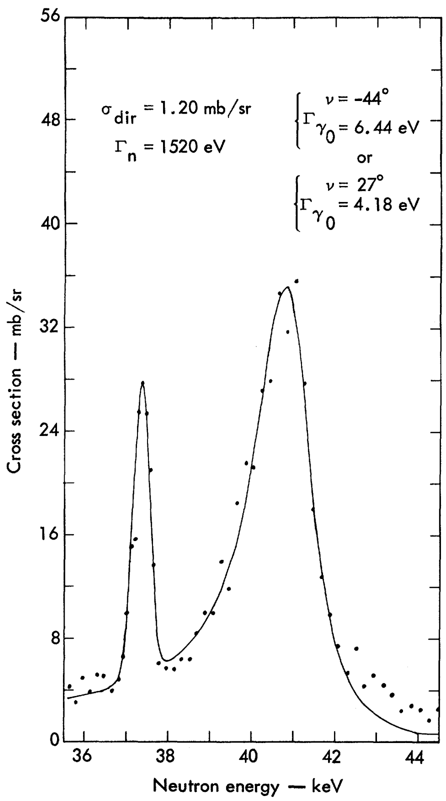

FIG. 2. The data of this figure are taken from Fig. 1. The solid curve is a shape fitted to the data using the resolution determined from the narrow peak at 37.3 keV. The spins for the 37.3- and 40.7-keV peaks are 2^+ and 1^-, respectively (Ref. 14), so there is no interference between them.

background under all the data points which was not subtracted out. However, even if the background is not known precisely, the asymmetry in the peak requires some direct cross section since there are no nearby resonances of the same spin with which the 41-keV resonance can interfere. Since the interference is a maximum when $\nu = 180°$, the minimum amount of direct cross section required for the fit occurs at that angle. In this case the direct cross section is 0.8 mb/sr, $\Gamma_n = 1520$ eV and $\Gamma_{\gamma0} = 5.0$ eV. Therefore, this experiment sets the following limits on these parameters: $0.8 < \sigma_{dir} < 1.2$ mb/sr, $\Gamma_n = 1520$ eV, $4.18 < \Gamma_{\gamma0} < 6.44$, and $27° > \nu > -44°$.

Lane and Lynn[2] predict an (n, γ) cross section of 0.045 mb/sr at thermal energies. This translates, using a $(E_n)^{-1/2}$ dependence, into a (γ, n) cross section of 0.005 mb/sr at 40 keV, a factor of 200 less than that measured here. Although more realistic calculations of direct capture might be expected to be in better agreement, Daly, Rook, and Hodgson[3] found, for other nuclei, that improved calculations gave even poorer agreement with experiment. Thus it is necessary to include additional nonresonant capture from some other source. An upper limit of semidirect capture at the resonance can be obtained by fitting the giant resonance in Pb^{208} with the amplitude given by the second term of Eq. (1), and by assuming that the GDR decays exclusively by neutron emission to the ground state of Pb^{207}. The values for $\overline{\Gamma}$, $\overline{E}$, and peak height obtained from Harvey et al.[15] are 3.78 MeV, 13.6 MeV, and 495 mb, respectively. Assuming that the entire energy dependence is in the giant-resonance denominator, the nonresonant cross section at $E_\gamma = 7.415$ MeV ($E_n = 40$ keV) is 3.4 mb/sr. Preliminary analysis indicates that a nonresonant capture amplitude of the same magnitude also is required to explain the asymmetry in the 257- and 319-keV resonances.

In summary, the asymmetry in the resonance at $E_n = 40$ keV in the threshold photoneutron cross section for Pb^{208} requires a nonresonant reaction which is roughly two orders of magnitude larger than that predicted by the direct-capture model, but which possibly can be accounted for with the semidirect-capture model.

The authors are grateful to Dr. M. S. Weiss, Dr. C. M. Shakin, and Dr. A. K. Kerman for valuable discussions during the progress of this work.

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

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PHOTOPROTON REACTIONS THROUGH ISOBARIC ANALOG STATES IN ^{88}Sr AND ^{90}Zr

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We have measured the photoproton cross sections of ^{88}Sr and ^{90}Zr for production of ground and low-energy residual states. The results are in agreement with predictions of the particle-hole model for isobaric analog states. Strong and broad resonances are found around 21 MeV in ^{88}Sr and around 20 and 22 MeV in ^{90}Zr which agree with coherent states expected by the theory.

Isobaric analog states (hereafter referred to as IAS) have already been found in (γ,p) and (p,γ) reactions.[1-4] These electric dipole states are useful for studying the particle-hole nature of IAS. Goulard, Hughes, and Fallieros[5] and Hughes and Fallieros[6] applied the particle-hole model to the dipole states in heavy nuclei. Their calculation includes not only one-particle, one-hole configurations but also two-particle, two-hole excitations so that the states obtained have good quantum numbers. They made numerical calculations[5,6] for the nuclei ^{88}Sr and ^{90}Zr and obtained many $E1$ IAS including coherent states. In the following an experiment using these targets is described; the results are compared with the predictions of Refs. 5 and 6.

Self-supporting metal foils of natural Sr (7.6 mg/cm^2 thick) and ^{90}Zr (97.8% enriched, 5.1 mg/cm^2 thick) were bombarded by the electron beam from the Tohoku University linear accelerator. The energy distributions of photoprotons from the $(e,e'p)$ reaction were measured by means of a broad-range magnetic spectrometer which contained 50 solid-state detectors. Electron energies of 16.8, 18.0, 19.5, 21.5, and 30.0 MeV were used for the ^{88}Sr and energies varying in 1-MeV steps from 16.0 to 24.0 MeV for the ^{90}Zr. The energy resolutions of the spectra of protons were about ±120 keV for ^{88}Sr and ±85 keV for ^{90}Zr at 8 MeV of proton energy.

The (γ,p_0) cross sections can be made from the components obtained from the maximum-energy part of the spectra by dividing by the number of virtual photons[7] under the assumption that only p_0 emission (to the ground state) contributes. Contributions of photoprotons which leave the residual nucleus in excited states are not strong in these maximum-energy parts of the proton spectra, therefore the above assumption seems to be reasonable. The validity of this assumption is shown by the following two facts. First, the maximum proton energy in every spectrum just agrees with that calculated for p_0 from the Q value. Second, each component cross section mentioned above joins smoothly with its neighbors. This condition would not be met if protons leaving the residual nuclei in excited states contribute very much. In the region above 21 MeV for ^{88}Sr, the cross section is estimated from the data from the 30-MeV irradiation after subtraction of a smooth proton spectrum corresponding to population of excited states of the residual nucleus. The cross section below 15 MeV on ^{90}Zr is obtained only from the 16-MeV data under the assumption of pure p_0 emission. In the case of ^{90}Zr, $\sigma(\gamma,p_2+p_3)$ is also calculated by a method analogous to that for $\sigma(\gamma,p_0)$ after subtraction of the p_0 component.

The results are shown in Figs. 1 and 2. In each figure, the theoretical results on IAS are shown for the particle-hole model.[5,6] The length of the vertical lines is proportional to Γ_γ, and the curve is an averaging of the radiative strength with Breit-Wigner functions and with a spreading width of 0.5 MeV as shown in the original paper.[6]

The position of the strong IAS in the present result seems to agree with the calculated results within several hundred keV which seems not