Neutron Photoproduction Cross Sections of Lanthanum and Praseodymium

L. B. RICE, L. N. BOLEN, AND W. D. WHITEHEAD
Department of Physics, University of Virginia, Charlottesville, Virginia
(Received 23 December 1963)

The (γ,n) cross sections for La and Pr have been determined from threshold to 30 MeV. The two cross sections are similar, and both deviate from a Lorentz line shape. The parameters for the two cross sections are La, $\sigma_m=304$ mb $E_m=14.5$ MeV, $\sigma_{\text{int}}=1.36$ MeVb, $\Gamma_{\text{Lor}}=3.3$ MeV; Pr $\sigma_m=305$ mb, $E_m=14.8$ MeV, $\sigma_{\text{int}}=1.47$ MeVb, $\Gamma_{\text{Lor}}=3.3$ MeV.

I. INTRODUCTION

THE widths of the photonuclear giant resonances determined experimentally have been shown to be closely correlated with the shape of the nucleus. The hydrodynamic model predicts that the widths of the giant resonance in deformed nuclei should broaden and in some cases there should be a splitting into two resonances.[1,2] The shell-model theory also predicts a similar splitting for highly deformed nuclei.[3] Careful experiments on deformed nuclei have shown these predictions to be true, and similar experiments on undeformed nuclei in the closed shell regions of $N=50$ and $Z=82$ have found a single narrow width.[4] We have made a careful investigation of the (γ,n) cross section of lanthanum and praseodymium as both have $N=82$, both are monoisotopic, and they differ only by two protons. This experiment was undertaken to attempt to obtain more accurately the various resonance parameters of these elements. The yield curves were obtained with statistical errors less than 0.1%. The absolute photoneutron cross sections of lanthanum and praseodymiun were measured using the bremsstrahlung from the 70-MeV synchrotron at the University of Virginia, a NBS-type ionization chamber to monitor the gamma-ray beam, and a calibrated Ra-Be neutron source to measure the efficiency of the counting system.

II. EXPERIMENTAL PROCEDURE

The neutrons were detected using a Halpern-type paraffin neutron house with eight BF_3 tubes mounted concentrically 13.5 cm from the sample tube.[5] The counting tubes were arranged in two sets, and two separate systems of electronics were used. The counting efficiency of the system was determined using a 10 mc Ra-Be neutron source which had been calibrated by the National Bureau of Standards. The gamma flux was monitored by a parallel-plate ionization chamber which duplicated chambers designed and calibrated by the National Bureau of Standards.[6] This chamber has been modified for use as a thin-walled transmission chamber by removing three thick dural-face plates. Measurements of the change in the response function of the chamber have been made in this laboratory. The counting efficiency and ion-chamber drift were monitored daily and varied less than 2% over the duration of the experiment. The lanthanum and praseodymium targets were cylinders 4.3 cm in diameter and 5.22 and 5.57 cm in length, respectively, and contained less than 0.5% total impurities. The samples were encased in glass cylinders filled with dry nitrogen to prevent oxidation and an identical empty cylinder was used in all background measurements.

The energy scale of the synchrotron had been established using the (γ,n) thresholds of carbon and copper with less than 200-keV uncertainty at 15 MeV. The (γ,n) yield points were taken at 0.5-MeV intervals from threshold to 30 MeV. A total of 24 runs per element were made with more than one million counts accumulated at each yield point above 15 MeV. Counting statistics were better than one percent for all points one MeV above threshold. The errors in the yield which were used in determining the errors in each cross section

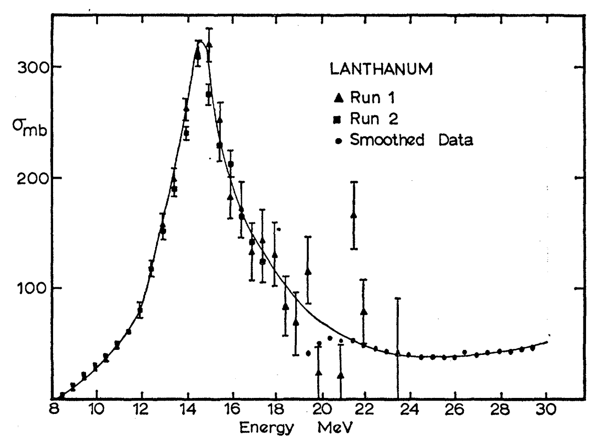

FIG. 1. Lanthanum (γ,n) cross section uncorrected for neutron multiplicity.

[1] M. Danos, Nucl. Phys. **5**, 23 (1958).
[2] K. Okamoto, Phys. Rev. **110**, 143 (1958).
[3] D. H. Wilkinson, Phil. Mag. **3**, 567 (1958).
[4] P. F. Yergin and B. P. Fabricand, Phys. Rev. **104**, 1334 (1956).
[5] P. A. Flournoy, R. S. Tickle, and W. D. Whitehead, Phys. Rev. **120**, 1424 (1960).
[6] J. S. Pruitt and S. R. Domen, *Determination of Total X-Ray Beam Energy with a Calibrated Ionization Sample* (National Bureau of Standards Monograph 48, U. S. Government Printing Office, Washington, D. C., 1962).

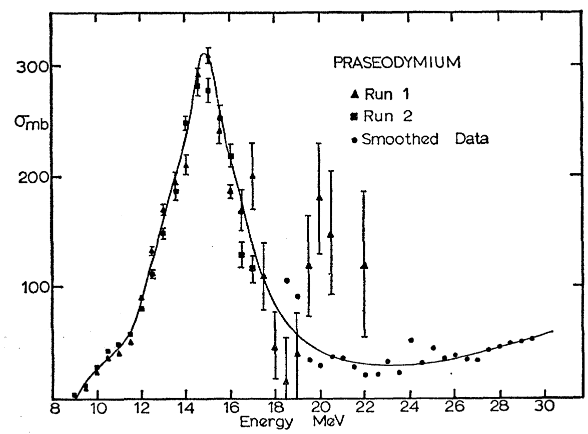

FIG. 2. Praseodymium (γ,n) cross section uncorrected for neutron multiplicity.

were the standard deviations at each energy point and not counting statistics alone. The standard deviations give a more realistic value for the daily reproducibility and were found to average about 1.5 times counting statistics.

The data were unfolded by the Leiss-Penfold technique using two interlacing 1-MeV bin widths.[7] The errors in cross sections were found by projecting the standard deviations of the yield at each energy point through the matrix. Because of fluctuations introduced by this method of unfolding the data, it was necessary to smooth both sets of data above 18 MeV in order to determine the magnitude of the cross section at high energies. The yield curves were smoothed to second differences above 18 MeV. In most cases, the smoothed yield points lay within the standard deviations of the raw yield. Thus, even though the yield has been smoothed, it should produce reasonable values of the cross section up to 30 MeV.

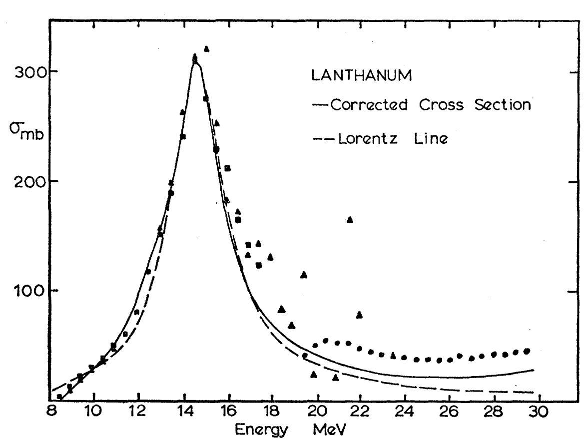

FIG. 3. Lanthanum (γ,n) cross section with neutron multiplicity correction (solid line); Lorentz line fitting to data points (dashed line).

[7] A. S. Penfold and J. E. Leiss, Phys. Rev. **114**, 1332 (1959).

III. RESULTS

The photoneutron cross sections of lanthanum and praseodymium are shown in Figs. 1 and 2 by the solid lines. The data points are the result of two separate yield curve determinations, and the error bars represent the standard deviations at each point. The two cross sections are similar in maximum cross section, in integrated cross section, and in the energy at which the resonance peaks. The praseodymium cross section, however, displays more structure on the front side of the peak, suggesting that several smaller resonances contribute to the cross section. An application of the particle-hole model would perhaps give a more complete theoretical description of the cross sections, but due to the complexity in the large number of transitions and the high density of states no calculations in this region have been attempted. The data were treated within the realm of the hydrodynamic model and Lorentz curves were fitted to each set of data points. Since the quantity computed directly from the yield curve is $\sigma(\gamma,n)+\sigma(\gamma,np)+2\sigma(\gamma,2n)+\cdots$, and since the $(\gamma,2n)$ thresholds are 14.25 MeV and 16.25 MeV for La and Pr, respectively, it is necessary to make a multiplicity correction to obtain accurately the shape of the (γ,xn) cross section. In order to make this correction the ratio of the $(\gamma,2n)$ cross section to the (γ,n) cross section was calculated using the assumptions of the statistical model.[8] The nuclear temperature is given by $\theta=(\epsilon'/a)$ where ϵ' is the energy of the absorbed photon in excess of the (γ,n) threshold and a, the nuclear level density parameter, was chosen to have the value 9 MeV^{-1} for these nuclei.

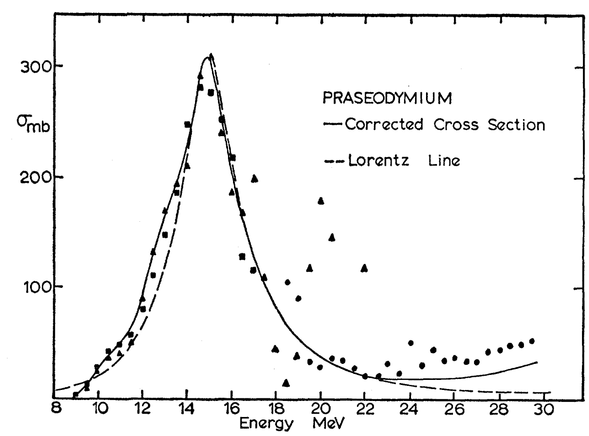

FIG. 4. Praseodymium (γ,n) cross section with neutron multiplicity correction (solid line); Lorentz line fitting to data points (dashed line).

The results of these calculations are shown in Figs. 3 and 4 where the solid curve gives the cross sections corrected for the neutron multiplicity and the dotted

[8] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley & Sons Inc., New York, 1952).

TABLE I. Experimentally determined parameters for the neutron photoproduction cross sections σ_m, maximum value of cross sections; E_m, energy at which maximum occurs; DSR, classical dipole-sum rule limit; Γ_0 twice the energy from half-maximum on low-energy side of curve to E_m, Γ_{Lor} width used to fit the Lorentz curve

	σ_m mb	E_m MeV	$\int_{Thr}^{30} \sigma dE$ MeV-b	DSR MeV-b	Γ_0 MeV	Γ_{Lor} MeV
		Uncorrected for multiplicity				
La	315±15	14.8±0.4	1.76	2.02		
Pr	305±10	14.8±0.4	1.74	2.06		
		Corrected for $(\gamma,2n)$				
La	304	14.5	1.36	2.02	3.2±0.2	3.3
Pr	305	14.8	1.47	2.06	4.0±0.2	3.3

line in each figure is a result of a Lorentz curve fitting to the low-lying points on the low-energy side of the peak.

Table I gives the results of the maximum cross section, the energy at which the peak occurs, and the integrated cross section to 30 MeV for both the raw and corrected data as well as the results of the classical dipole-sum rule calculation for these elements. Also included are the measured half-widths of the curves: Γ_0 gives the value of twice the energy from one half-maximum on the low-energy side to the peak found from the corrected data; Γ_{Lor} is the width of the Lorentz curve used to fit each set of corrected data.

The integrated cross sections to 30 MeV are lower than those obtained from the classical Levinger and Bethe sum rule, but the cross section curves indicate that some dipole strength exists above 30 MeV. Each cross section displays a similar narrow resonance region in agreement with the prediction of hydrodynamic model for closed shell nuclei, but there is evidence for more complicated resonance phenomena, especially in praseodymium, and both cross sections deviate from the shape of a single Lorentz curve fitting.

PHYSICAL REVIEW VOLUME 134, NUMBER 3B 11 MAY 1964

Cross Sections and Isomer Ratios for the Isomeric Pair Y^{90g} and Y^{90m} in the $Rb^{87}(\alpha,n)$ and $Y^{89}(d,p)$ Reactions*

CLYDE RILEY AND BRUNO LINDER
Department of Chemistry, Florida State University, Tallahassee, Florida
(Received 22 August 1963, revised manuscript received 10 January 1964)

Excitation functions and cross section ratios for the isomeric pair Y^{90g} and Y^{90m} produced from Rb^{87} by (α,n) reaction and from Y^{89} by (d,p) reaction were measured from 11–18 and 5–12 MeV, respectively. The isomer ratios produced in (d,p) reaction are approximately an order of magnitude smaller than those obtained by (α,n) reaction; the total cross sections for both reactions are comparable. The differences in the isomer ratio curves are accounted for by differences in mechanism. The experimental isomer ratios obtained in the (α,n) reaction are compared with the predicted values calculated in the manner of Huizenga and Vandenbosch. The results are discussed.

I. INTRODUCTION

In recent years, a great deal of attention has been focused on the experimental and theoretical aspects of nuclear reactions in which isomers are produced.[1–6] An exact prediction of a nuclear reaction can, in general, not be attempted without having detailed knowledge of the structure of the nucleus. However, when a process is known to proceed via the formation of a compound nucleus and the energy of the impinging particle is sufficiently great, it is possible to make certain predictions regarding the cross section which will depend only upon the charge and mass of the target nucleus and the charge and energy of the incident particle. Isomer ratios, however, require a somewhat more detailed knowledge of the decay process in which angular momentum is now a more important entity. Several explanations have been offered to account for the observed isomer ratios, all of which invoke the law of conservation of angular momentum and make explicit use of the spin dependence of energy states. The most quantitative calculations were carried out by Huizenga and Vandenbosch[3] and by Need.[6]

In this work we have determined the cross sections and isomer ratios for the reactions $Rb^{87}(\alpha,n)$, $Y^{90g,90m}$, and $Y^{89}(d,p)Y^{90g,90m}$. These reactions are of particular interest because the same final states are obtained by

* Supported by the U. S. Atomic Energy Commission.
[1] J. W. Meadows, R. M. Diamond, and R. A. Sharp, Phys. Rev. **102**, 190 (1956).
[2] B. Linder and R. A. James, Phys. Rev. **114**, 322 (1959).
[3] J. R. Huizenga and R. Vandenbosch, Phys. Rev. **120**, 1305, 1313 (1960).
[4] G. R. Choppin and T. Sikkland, J. Inorg. Nucl. Chem. **21**, 201 (1961).
[5] J. L. Need and B. Linder, Phys. Rev. **129**, 1298 (1963).
[6] J. L. Need, Phys. Rev. **129**, 1302 (1963).