Excitation Functions for the (p,pn) and $(p,2p)$ Reactions on Ce^{142}, 0.37 to 2.85 BeV*

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The cross sections for the reactions $Ce^{142}(p,pn)Ce^{141}$ and $Ce^{142}(p,2p)La^{141}$ have been measured at 0.37, 1.0, 2.0, and 2.85 BeV. Radiochemical techniques were used. The results indicate that over this energy range the (p,pn) cross section declines gradually from about 70 to about 60 mb, while the $(p,2p)$ cross section declines from about 20 to about 15 mb. These results are in sharp contrast to some of those obtained for the same reactions in other investigations. The discrepancy is discussed and it is concluded that the present results are more reliable because of improvements in experimental procedures and because of greater consistency with other (p,pn) and $(p,2p)$ reactions.

INTRODUCTION

THE cross sections for the reactions $Ce^{142}(p,pn)Ce^{141}$ and $Ce^{142}(p,2p)La^{141}$ have been measured previously in the energy range 0.4 to 3.0 BeV.[1] The results of these measurements indicate that the cross sections decrease rapidly as the proton energy is increased from 0.4 to 3.0 BeV, while all other measured (p,pn) and $(p,2p)$ excitation functions are more or less flat in this energy region.[2–4] In addition, the previous measurements are in disagreement with some unpublished data of Benioff,[5] who finds the $Ce^{142}(p,pn)$ and $(p,2p)$ cross sections constant at about 70 and 15 mb, respectively, in this energy range. It was therefore considered advisable to remeasure the cross sections for these reactions in this energy range, because if the anomalous behavior observed by Caretto and Friedlander could be confirmed, it might have important implications regarding nuclear structure in this mass-number region.

EXPERIMENTAL PROCEDURES

The bombardments were performed on enriched Ce^{142} [$(90.08\pm0.06)\%$ Ce^{142}; $(9.92\pm0.06)\%$ Ce^{140}][6] which was electrodeposited on nickel by the following procedure[7]:

Sixty mg of cerous chloride was added to 50 ml of 95% ethanol. The cerous chloride did not dissolve completely. The resulting suspension was stirred until the particles were judged to be uniformly finely divided and then 4 ml of the suspension was placed in a glass chimney closed at the bottom by a 0.001-in.-thick nickel foil which served as the cathode. The anode was a spiral of platinum wire which was rotated at low speed for stirring. The cerium, presumably as the oxide, was deposited on the nickel foil. When currents of 10–30 mA were passed at 100–300 V for 15 min, yields of 60–70% were obtained. A few drops of a solution of water glass were placed on the target and dried to bind the cerium deposit to the nickel plate. No reasonably convenient method of determining the target uniformity was found; the water glass coating was found to interfere seriously with all methods that were tried. A few targets were rejected because of large easily visible thin spots.

The bombardments at 0.37 BeV were performed in the internal beam of Columbia University's Nevis cyclotron with a target stack arranged as shown in Fig. 1(a). The foils marked A and B were used as monitor foils to determine the beam intensity by means of the reaction $Al^{27}(p,3pn)Na^{24}$, whose cross section has been measured.[8] The disintegration rate of Na^{24} was determined by the β-γ coincidence technique. Aluminum foil C was combined with the target foil for the chemical operations.

The bombardments at 1.0, 2.0, and 2.85 BeV were performed with a rammed target in the internal beam of the Cosmotron at the Brookhaven National Laboratory. The target stack was arranged as shown in Fig. 1(b). The first aluminum foil was the monitor foil and was treated exactly as described above except that correction was made for recoil losses.[9] The second aluminum foil was dissolved for chemical processing along with the target foil.

After bombardment, the entire target stack was punched through to ensure the alignment of the monitor and target foils. The disk thus cut from the target foil and the corresponding disk from the cover foil were dissolved in a mixture of concentrated hydrochloric and nitric acids. Chemical separations and purifications were performed as described in a previous paper[10] except that a fluoride precipitation was performed at the beginning in order to separate the rare-earth elements from nickel and other contaminants.

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[7] Mea Lindner (private communication).

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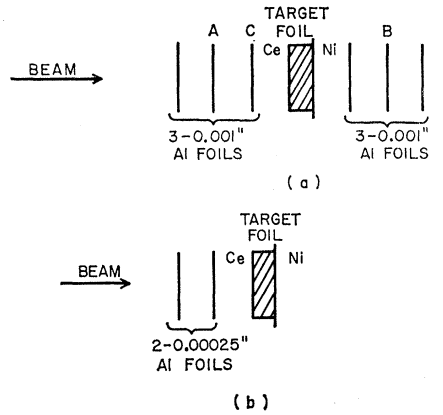

FIG. 1. Target foil arrangements (a) for Nevis runs and (b) for Cosmotron runs.

The cross sections for the $(p,2p)$ reaction were determined, not from the La^{141} activity, but from the Ce^{141} daughter activity in a manner which has been described previously.[10] The disintegration rates of the two Ce^{141} fractions from each bombardment were determined through measurement of the intensity of the 145-keV gamma ray with a NaI scintillation detector of known efficiency.

There was an appreciable amount of the 166-keV gamma ray of Ce^{139} present in all samples. The Ce^{139} in the original cerium fraction was produced in the (p,pn) reaction on the Ce^{140} present in the starting material and in the $(p,p3n)$ reaction on Ce^{142}. The Ce^{139} in the cerium sample obtained from the lanthanum fraction grew in as the daughter of Pr^{139} produced in the $(p,2n)$ reaction on Ce^{140} and the $(p,4n)$ reaction on Ce^{142}. The two gamma rays were not quite resolved by the detector, but their contributions to the total counting rate were determined by an IBM-7090 computer program whose input data were the "unknown" spectrum and spectra of the pure activities. The program calculated a spectrum which was a linear combination of the pure Ce^{139} and Ce^{141} spectra by doing a least-squares fit of the coefficients of this linear combination to the experimentally determined spectrum. The contribution of Ce^{141} to the observed spectra, as determined by this method, ranged from 60% to 90%.

The beta counting rates of all samples were also determined and the decay of the activity was followed for purposes of comparison with the gamma counting rates and with the results of Caretto and Friedlander.[1] A few of the decay curves were carefully resolved into components and no half-lives that could not be ascribed to isotopes of cerium were found.

Note added in proof. From one of the essentially pure Ce^{141} samples obtained in the work reported in Ref. 10, the K conversion coefficient, α_K, of the 145-keV gamma ray was determined to be 0.41. Combined with the $K/(L+M)$ conversion ratio of 6, the β-branching ratio of 70% to the excited state [*Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington 25, D. C.)], and the K-shell fluorescence yield of 0.90 for praseodymium [Peter R. Gray, Phys. Rev. **101**, 1306 (1956)], this gives an absolute abundance of 47.3% for 145-keV photons per β decay of Ce^{141}. This value was used in determining the cross sections reported in this paper and in Ref. 10.

RESULTS

The cross sections determined in this study are listed in Table I. The numbers given are the averages of replicate runs. The errors given are standard deviations of the mean. The data on gamma counting rates were lost in one of the runs at 1.0 BeV, but beta-counting data were available for the determination of the cross-section ratio.

TABLE I. Cross sections for the reactions $Ce^{142}(p,pn)Ce^{141}$ and $Ce^{142}(p,2p)La^{141}$.

E (BeV)	σ (mb) (p,pn)	$(p,2p)$	$R=\frac{\sigma(p,pn)}{\sigma(p,2p)}$	No. of runs
0.37	79.0±7.9	20.0±2.3	3.94±0.24	3
1.0	62.4	21.0	2.97±0.18	1(2)
2.0	65.2±6.7	14.5±2.9	4.49±0.76	2
2.85	58.1±5.4	17.7±1.9	3.29±0.19	2

The cross sections are plotted in Fig. 2. Also given for comparison are the results of Caretto and Friedlander,[1] of Ware and Wiig,[11] and of Strohal and Caretto[12] for the

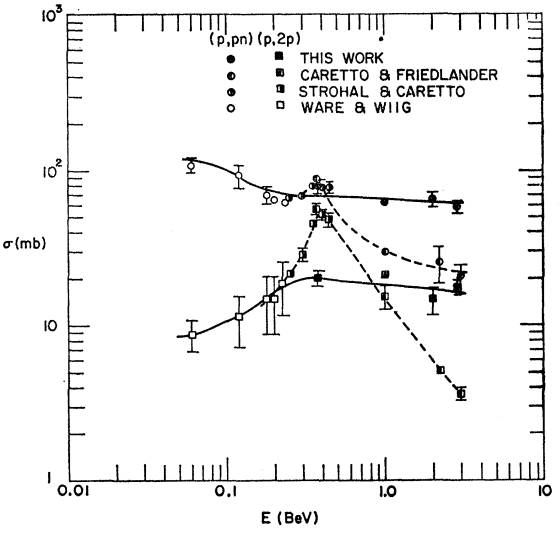

FIG. 2. Excitation functions for the reactions $Ce^{142}(p,pn)Ce^{141}$ and $Ce^{142}(p,2p)La^{141}$.

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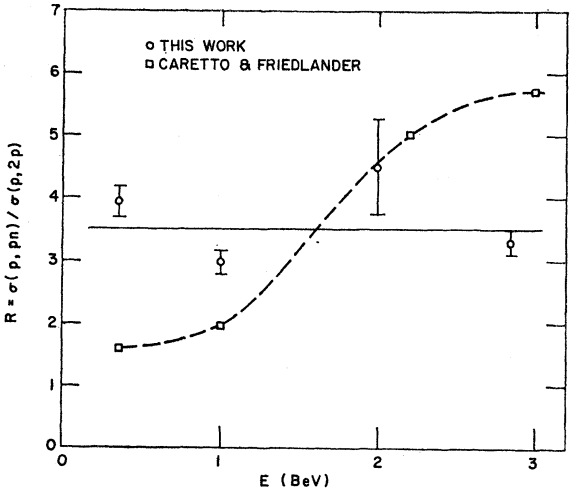

FIG. 3. Cross-section ratio R as a function of energy.

same reactions, corrected to the monitor cross sections used in this work.

In Fig. 3, the ratios of the (p,pn) to $(p,2p)$ cross sections at various bombarding energies obtained in this work are compared to those reported by Caretto and Friedlander.[1]

DISCUSSION

The disagreement between the results of this work and those of Caretto and co-workers[1,12] is obvious as shown in Figs. 2 and 3. Both sets of data, however, are compatible with the results of Ware and Wiig[11] for proton energies below 240 MeV.

The reason for this discrepancy is very difficult to find. It will be noted that the $(p,2p)$ cross section at 0.37 BeV as reported in the previous work[1,12] is higher than the $(p,2p)$ cross sections determined in this work by about a factor of 2.5, but lower at 3 BeV by about a factor of 5. This sort of behavior leads one to suspect that there must be two opposite effects influencing the accuracy of the measurements; whatever explanation one might adduce to explain the discrepancy at 0.37 BeV must not apply at 3.0 BeV and vice versa. For example, if one proposes a previously undetected isomeric state of some cerium isotope which could masquerade as Ce^{141} through having a closely similar half-life or gamma-ray energy in one or the other set of experiments, one would expect the cross sections as determined in those experiments to be consistently high, or at least certainly never lower than the true values. The same argument applies to any proposed explanation involving impurities in the targets or counting samples or involving faulty resolution of decay curves or gamma spectra. Other sources of error such as erroneous determinations of target thickness, chemical yields, etc., should give no consistent trend, yet all the points determined by any one group of investigators fall on a smooth curve. Furthermore, the cross section found at 0.37 BeV in this work has been confirmed by Benioff,[5] and the conflicting higher cross sections at about this energy have also been found more or less independently by two sets of investigators.[1,12]

The discrepancy is not quite so large for the (p,pn) reaction. In fact, there is excellent agreement at 0.37 BeV and only at higher energies do the results of Caretto and Friedlander[1] fall below those of this work by a factor of two or three. Still there is no clue in a comparison of this work and Ref. 1 as to the reason for the discrepancy.

The results reported in this paper are considered to be more reliable than the earlier ones[1,12] for the following reasons:

(1) Enriched Ce^{142} was used rather than natural cerium, thus increasing the relative contribution of Ce^{141} to the total counting rates of the cerium fractions.

(2) The use of gamma detection allows a more specific identification of products as well as a better knowledge of detection efficiency.

(3) The oxidizing agent used in the solvent extraction of cerium was potassium peroxydisulfate instead of sodium bromate. Some early unpublished experiments of this author indicated that bromate does not always yield complete oxidation of cerium.

(4) The excitation functions that were obtained in this work agree in shape and magnitude with those for other (p,pn) and $(p,2p)$ reactions obtained in this energy region,[2–4] particularly with those obtained by Benioff[5] for the same reactions.

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