ground state, 22% to the 440-keV first-excited state, 12% to the 2.64-MeV state, and 3% to the 2.98-MeV state. The possibility that the 4.78- and 4.43-MeV states are involved cannot be definitely ruled out but the energy differences would favor the scheme given.

In general, the agreement between this work and that of Singh *et al.*[3] and Braben *et al.*[4] and, in fact, between these two groups themselves is rather poor, but this can easily be accounted for by the difficulties associated with the analysis of data from (p,γ) reactions. In particular, for this case the difference in energy between the resonance state at 9.75- and the 2.64-MeV state is just the energy of the 7.10-MeV state. Since the decay of the 9.75-MeV state to the 2.64-MeV state is probably preferred,[4] the observation of the decay to the 7.10-MeV level and its subsequent decay would be very difficult. Of course, it is possible that different states are involved in the two cases, but this seems quite unlikely.

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$Ce^{142}(p,pn)Ce^{141}$ and $Ce^{142}(p,2p)La^{141}$ Reactions from 0.4 to 28 GeV*

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Cross sections for the $Ce^{142}(p,pn)Ce^{141}$ and $Ce^{142}(p,2p)La^{111}$ reactions have been measured in the energy region from 0.4 to 28 GeV. The (p,pn) cross section decreases to a value of ≈ 50 mb in the GeV region. The $(p,2p)$ cross section shows a significant rise between 0.4 and 1 GeV and then a gradual decrease. Correlations between these data and the total cross sections for $p-p$ and $p-n$ interactions are discussed.

INTRODUCTION

THEORETICAL treatments of nuclear reactions between high-energy particles and complex nuclei have generally made use of the "impulse approximation"[1] in which the bombarding particle interacts with only one of the target nucleons at a time. Monte Carlo calculations based on this model[2-4] give reasonably good predictions for many of the features observed in high-energy nuclear reactions. For very simple reactions, those involving a single collision between the bombarding particle and a target nucleon, it is expected that the elementary-particle cross sections will play a more obvious role in determining the shapes of excitation functions than they would for more complex reactions. That this is the case has been clearly shown for the $C^{12}(\pi^-,\pi^-n)C^{11}$ reaction.[5,6] Here, observed structure including a pronounced peak at 190 MeV in the (π^-,π^-n) cross section corresponds to the general features of the free-particle π^-n total cross section.

(Nucleon, 2 nucleon) reactions are a class of simple high-energy reactions that have been studied extensively; the experimental data and interpretation are the subject of a forthcoming review[7] and compilation.[8] Unfortunately, no structural features as pronounced as the pion-nucleon resonances occur in the nucleon-nucleon cross sections. The pp and pn total cross sections as summarized by Barashenkov and Maltsev[9] are shown in Fig. 1. The most pronounced feature is the factor of two rise in σ_{pp} between 0.3 and 1 GeV due to inelastic processes involving meson production. Reeder[10] has measured cross sections for the $Fe^{57}(p,2p)Mn^{56}$ and $Zn^{68}(p,2p)Cu^{67}$ reactions to see whether a corresponding feature could be observed. Although a rise was observed in both cross sections between 0.4 and 0.72 GeV, its significance is marginal because of the magnitude of the experimental errors.

The present experiment, a study of (p,pn) and $(p,2p)$ reactions on Ce^{142}, was undertaken to further examine to what extent the cross sections, particularly the $(p,2p)$ cross section, could be correlated with the elementary-particle cross sections. This target system has been the subject of previous investigations[11-15] as

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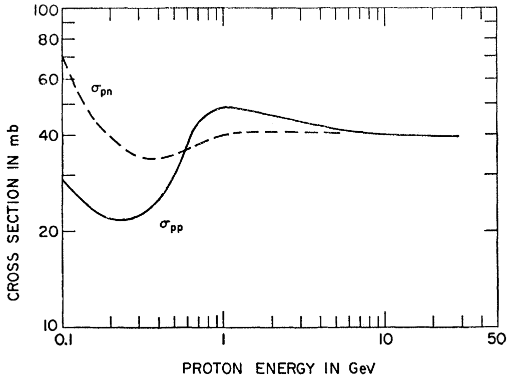

FIG. 1. The total cross sections for *p-p* interactions (solid curve) and *p-n* interactions (dashed curve) taken from the summary of Barashenkov and Maltsev (Ref. 9).

it is one of the few for which both (p,pn) and $(p,2p)$ cross sections can be measured by radiochemical techniques. The recent results of Foreman[14] in general agree with the unpublished work of Benioff,[15] but indicate substantially different excitation functions from the earlier results of Caretto and Friedlander[11] and of Strohal and Caretto.[13] It was hoped the present experiment would obtain data of higher precision and help resolve this large discrepancy.

EXPERIMENTAL

Thirteen irradiations of cerium oxide targets were performed at energies from 0.42 to 2.8 GeV at the Brookhaven Cosmotron and at 10 and 28 GeV at the Alternating Gradient Synchrotron (AGS). The targets were prepared by vacuum deposition of CeO_2 from a tungsten filament onto 0.00025-in. Mylar foil. Several 1-in. square targets were prepared simultaneously and the cerium content of one determined by chemical analysis. From weights of the foils it was inferred that the same amount of CeO_2 was deposited on all the foils in a given evaporation. The targets appeared visually as uniform brown layers and showed good mechanical properties. They could be handled and cut with scissors without flaking. Spectrographic and x-ray fluorescence analyses showed no impurities[16] which would interfere with the reactions studied.

The target stacks consisted, in the order seen by the beam, of three layers of 0.001-in. aluminum, the Mylar backing, the CeO_2, and a final layer of 0.001-in. aluminum.[17] The center aluminum of the sandwich was used as the beam monitor. Total target thickness was ≈ 40 mg/cm^2. For Cosmotron irradiations, the leading edges of the foils were aligned by shearing before irradiation and held together with Scotch tape. Alignment of the AGS targets was insured by punching $\frac{1}{2}$-in. disks after irradiation. The general techniques of the irradiations were the same as previously described.[18]

After irradiation, the foils were cut or punched from the target stack and weighed. No losses of CeO_2 were observed in the Cosmotron irradiations. However, the weights did indicate losses[19] in the AGS irradiations, particularly those at the highest beam intensities. Correction was made on the basis of the foil weights and, in the case of the largest loss, on the basis of a cerium analysis of an aliquot of the target solution also. The internal agreement of the AGS results appears to indicate that this is justified.

The irradiated CeO_2 plus Mylar were dissolved in concentrated sulfuric acid containing lanthanum carrier by heating and then cautiously diluted to 18-*N* acid. The solution was further diluted and the mixed hydroxides were precipitated by the addition of ammonia. They were dissolved in 10-*N* nitric acid and the cerium oxidized with sodium bromate and extracted into 0.75-*M* di(2-ethylhexyl) acid orthophosphate in *n*-heptane by a procedure which has been described.[20] The organic phase cerium, designated "*PPN*," contains the Ce^{141} formed directly plus that from decay of the La^{141} during the irradiation and prior to the separation. Additional inactive cerium was added to and extracted from the aqueous phase to insure complete removal of the active cerium. The aqueous phase containing the lanthanum with added cerium carrier was allowed to stand ≈ 2 days so that the La^{141} (half-life 3.9 h) had decayed to its Ce^{141} daughter (half-life 32.5 days). This cerium, designated "*P2P*," and the *PPN* were purified and mounted as $Ce(IO_3)_4$.

Gamma rays from the samples were assayed with a 3-in.×3-in. NaI(Tl) scintillator and multichannel pulse-height analyzer. A geometry of $\approx 2\pi$ was used since the counting rates were low. Spectra of each sample were obtained at ≈ 10 and ≈ 20 days from the end of the irradiation. In some cases additional data were obtained at times up to 70 days. Only Ce^{141} (145-keV gamma rays) and Ce^{139} (166-keV gamma rays) were observed in the *P2P* samples. However, some Ce^{134} (half-life 72 h) and Ce^{137m} (half-life 34 h) were present in the *PPN* samples at 10 days. These were much reduced in the counts at 20 days and essentially absent in the later countings. Correction for these isotopes was made by assuming they contribute a flat background in the 145–166-keV region. Agreement

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[16] Some tungsten ($\leqslant 1.4\%$) was detected in the early batches of targets. This is not expected to contribute significantly to Ce^{141} or La^{141} production, e.g., see J. R. Grover, Phys. Rev. **126**, 1540 (1962). No tungsten was detected in the later batches of targets where filament temperature was more carefully controlled.

[17] This forward recoil catcher was assayed for Ce^{141} in irradiations at 0.4, 1, and 10 GeV. The observed activities indicated less than 1% recoil loss from our ≈ 13 mg/cm^2 targets, hence no correction has been made.

[18] J. B. Cumming, J. Hudis, A. M. Poskanzer, and S. Kaufman, Phys. Rev. **128**, 2392 (1962).

[19] The losses were 12, 34, and 72% in the 28-GeV irradiations and 8% at 10 GeV. The losses of CeO_2 appeared to be uniform over the $\frac{1}{2}$-in.-diam circles.

[20] D. F. Peppard, G. W. Mason, and S. W. Moline, J. Inorg. Nucl. Chem. **5**, 141 (1957).

between the Ce^{141} results for a given sample at times from 10 to 70 days indicates no significant interference from the Ce^{134} and Ce^{137m}.

Resolution of the 145- and 166-keV gamma rays is difficult because of the unfavorable Ce^{141}/Ce^{139} ratio. In the *PPN* samples, the Ce^{141} appears only as a shoulder on the low energy side of the 166 keV photopeak. In the best *P2P* samples, the 145 and 166-keV photopeaks were comparable in height. Each spectrum was resolved independently by both authors using a least squares procedure similar to that of Foreman.[14] Spectra of pure Ce^{141} and Ce^{139} were taken as standards for this analysis. For the calculation of cross sections, the Ce^{141} analyses of both authors were averaged. From the agreement between the analyses a precision of ±7% is deduced for the Ce^{141} gamma counting rates. We have also assigned a ±7% systematic error to the final averaged results for uncertainties in the gamma-ray resolution.

The efficiency of the detection system for Ce^{141} was determined in two ways. Gamma-ray standards of Am^{241}, Co^{57}, and Ce^{139} were counted in the same geometry and the efficiency for 145-keV gamma rays obtained by interpolation. When combined with a value[21] of 0.476 gamma rays per disintegration this gave an overall efficiency of 20.2%. A Ce^{141} beta-ray standard was also counted and gave an over-all efficiency of 19.9%. The latter value was used since uncertainties in the decay scheme do not enter.

Proton fluxes incident on the target areas were obtained from beta counts in a calibrated detector of the Na^{24} in the aluminum monitors. The $Al^{27}(p,3pn)Na^{24}$ cross sections summarized by Cumming[22] were used. Because of the large size of the monitor foils from the Cosmotron irradiations, corrections of $\approx 5\%$ were necessary to the counter efficiency which had been calibrated with a smaller ($\frac{1}{2}$-in. diam) source. As a check, Na^{22} in each monitor was assayed in a calibrated well-type NaI(Tl) scintillator (biased to reject Be^7). Since the $Al^{27}(p,3p3n)Na^{22}$ cross section is not well known over the entire energy range of interest here, the Na^{22} results were used to calculate cross-section ratios for $Al^{27}(p,3p3n)Na^{22}/Al^{27}(p,3pn)Na^{24}$. These are listed in Table I as a function of energy with some of the recently measured values.[18,23,24] The results from the present work are in good agreement with the existing values.

TABLE I. The $\sigma_{Al}(Na^{22})/\sigma_{Al}(Na^{24})$ ratio as a function of proton energy.

Proton energy (GeV)	$\sigma_{Al}(Na^{22})/\sigma_{Al}(Na^{24})$
0.37[a]	1.46±0.05
0.42	1.47±0.06
0.7	1.33±0.05
1.0	1.29±0.05
2.0[b]	1.29±0.06
2.8	1.23±0.05
2.9[b]	1.21±0.04
10	1.23±0.05
28	1.17±0.05
28[c]	1.18±0.04

[a] From Ref. 23.
[b] From Ref. 18.
[c] From Ref. 24.

RESULTS

The cross sections obtained in this experiment are listed in Table II. The (p,pn) values have been corrected for feeding from La^{141} during the irradiations and prior to separation. The correction amounted to $\frac{1}{3}$–$\frac{1}{2}$ of the mean $(p,2p)$ cross sections. The precision of a single measurement is estimated to be ±8.5%, the major contribution being the ±7% estimated precision of the gamma spectra resolution. From agreement of the duplicate and triplicate measurements a standard deviation of 7.3% is deduced for a single value; hence the major random errors appear to be accounted for. Sources of systematic errors are estimated to be: gamma spectrum analysis, 7%; target thickness, 4%; counting efficiency, 2%; and beam monitoring, 2%, or an rms sum of 8.5%. This does not include errors in values of the absolute cross section for the monitor reaction. Only the precision estimates are given with the mean values in Table II. Inclusion of the systematic effects leads to over-all errors of 10% where duplicate or triplicate measurements were performed and 12% for the single measurement at 10 GeV.

TABLE II. $Ce^{142}(p,pn)Ce^{141}$ and $Ce^{142}(p,2p)La^{141}$ cross sections obtained in the present experiment.

Proton energy (GeV)	$(p,2p)$ Cross sections (mb) Individual values[a]	Mean value[b]	(p,pn) Cross sections (mb) Individual values[a]	Mean value[b]
0.42	15.4		62.9	
	16.9	16.1±1.0	61.3	62.1±3.7
0.70	17.0		52.0	
	22.3	19.6±1.2	51.0	51.5±3.1
1.0	22.6		50.4	
	24.5	23.6±1.4	57.7	54.1±3.2
2.8	22.1		50.3	
	17.4		41.0	
	18.7	19.4±1.0	47.0	46.1±2.3
10	18.8	18.8±1.6	52.3	52.3±4.4
28	···		55.0	
	17.1		48.5	
	15.5	16.3±1.0	52.5	52.0±2.6

[a] Precision of a single measurement is estimated at 8.5%.
[b] Errors (standard deviations) indicate precision only. Systematic errors are estimated at 8.5%.

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[21] This value assumes 70% of the beta transitions feed the 145-keV level, a value of $\alpha_K = 0.40$, and a $K/LM \approx 5$. These values and the 3.9-h half-life of La^{141}, the 32.5-day half-life of Ce^{141}, and the 140-day half-life of Ce^{139} are consistent with results quoted in *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences–National Research Council, Washington, D. C., 1963).

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[23] L. P. Remsberg and J. M. Miller, Phys. Rev. **130**, 2069 (1963).

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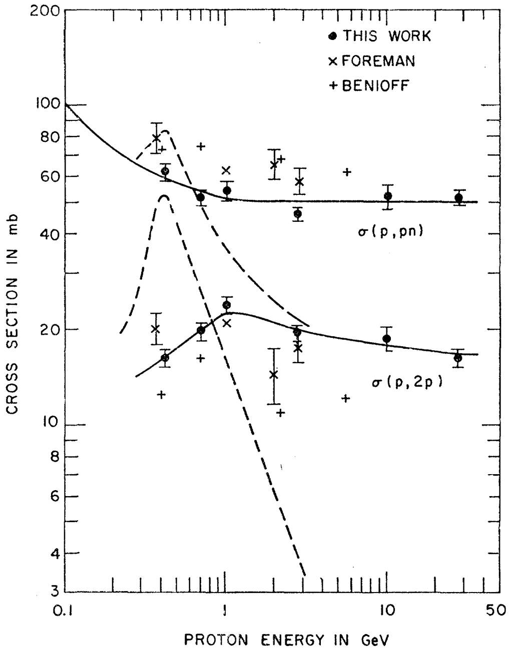

FIG. 2. Excitation functions for the Ce^{142}(p,pn)Ce^{141} and Ce^{142}(p,2p)La^{141} reactions. The solid curves have been drawn through the results of the present experiment. The dashed curves indicate the excitation functions obtained by Caretto and Friedlander (Ref. 11) and Strohal and Caretto (Ref. 12).

Our results and those of Foreman[14] and Benioff[15] are plotted in Fig. 2. The agreement between the results of different observers is by no means good. However, it should be noted that the errors shown in Fig. 2 do not include systematic effects. The solid curves in Fig. 2 have been drawn through the present data. The extension of the upper curve to $\approx$100 mb at 100 MeV is consistent with the results of Ware and Wiig.[13] Because of larger errors, their results have not been used to extend the (p,2p) curve. The (p,pn) cross section is seen to decrease to a value of $\approx$50 mb in the GeV region. The (p,2p) cross section shows a rise between 0.4 and 1 GeV and then a gradual decline. That the rise is significant is confirmed by the fact that both measured values of the (p,2p) cross section at 0.42 GeV are lower than any of the 7 values at 0.7, 1, and 2.8 GeV. The ratio of the mean cross section at 1 GeV to that at 0.42 GeV is 1.47 ± 0.13; the ratio of that at 0.7 GeV to that at 0.42 GeV is 1.22 ± 0.11; and that at 2.8 GeV to that at 0.42 GeV is 1.20 ± 0.10.

The dashed curves in Fig. 2 are based on the results of Caretto and Friedlander[11] and of Strohal and Caretto.[12] Such rapidly varying excitation functions are clearly inconsistent with the points plotted in Fig. 2. It is difficult to understand what sort of errors could lead to systematic discrepancies and yet give reasonable agreement between duplicate measurements at each energy. To investigate this further, we have obtained as much of the original data of Caretto and Friedlander[11] as was still available. On reanalysis with a least squares program, their beta counting data give Ce^{141} activities which differ in several cases by factors of two from those used in the original cross-section calculations. This does not account for the systematic discrepancy but does indicate a much poorer precision than quoted by the authors. Chemical yields had been obtained originally by weighing cerium or lanthanum oxalate precipitates on filter paper, or assumed in the case of the *P2P* cerium samples at energies of 2.2 and 3 GeV to be 100%. We have located one of these *P2P* cerium samples and found it to contain 3.2-mg Ce, 5.0-mg La, and 7.0-mg SiO$_2$, a cerium yield of 32%. We have also observed that the original authors made corrections (in three of the four measurements at 2.2 and 3 GeV and in one at 0.4 GeV) to the Ce^{141} activities of the *P2P* samples based on the assumption that all the observed Ce^{139} came from incomplete cerium, lanthanum separations. These corrections reduced the (p,2p) cross sections by as much as a factor of four. Since some Ce^{139} is expected from the decay of Pr^{139}, and since our reanalysis shows that the Ce^{139}/Ce^{141} ratios in these samples are not significantly higher than in the samples where no corrections were made, the corrections now appear unjustified. Based on these and other observations we conclude that the apparent precision of the original results and their agreement with smooth curves are highly fortuitous. The largest observed errors are in the direction to raise by large factors the (p,2p) cross sections at 2.2 and 3 GeV. We suggest that the results of Caretto and Friedlander[11] be disregarded; these authors concur in that conclusion. We note that the results of Strohal and Caretto[12] join smoothly the results of Ware and Wiig[13] to those of Caretto and Friedlander.[11]

DISCUSSION

In the vicinity of 0.4 GeV a major contribution to either (p,pn) or (p,2p) reactions is expected[7,23] to be from a "clean knockout" mechanism in which there is a single elastic collision between the incident proton and a target nucleon and then both escape. In particular, other mechanisms involving inelastic scattering followed by evaporation, or charge exchange scattering followed by evaporation, are not expected to contribute to the Ce^{142}(p,2p)La^{141} reaction. The cross section for a (p,2p) reaction based on a "clean knockout" mechanism will depend on the balance between two factors: first, the probability that the incoming proton interact with a not-too-tightly-bound proton in the nucleus (the absorption factor); and second, the probability that the incoming proton and both outgoing protons do not interact with other nucleons (the attenuation factor). As the proton energy increases from 0.4 to 1 GeV, the rise in σ_{pp} (see Fig. 1) is expected to be reflected by a rise in the absorption factor and the (p,2p) cross section. However, the rise in σ_{pp} is due to

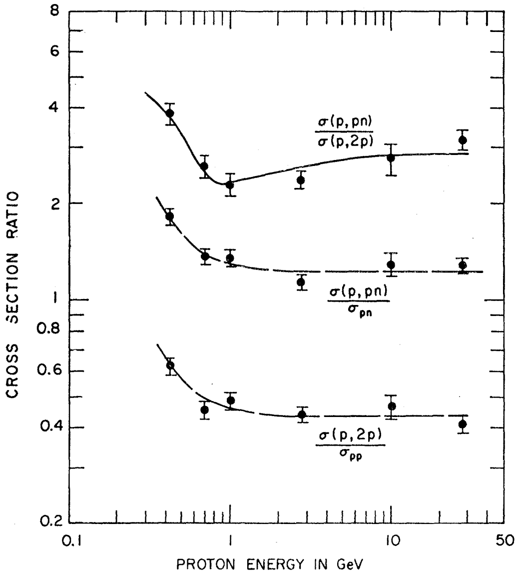

FIG. 3. Cross-section ratios. The center and lower curves (dashed) give the ratio of the $Ce^{142}(p,pn)Ce^{141}$ cross section to the *p-n* total cross section and of the $Ce^{142}(p,2p)La^{141}$ cross section to the *p-p* cross section, respectively. The upper set of points gives the ratio of $\sigma(p,pn)/\sigma(p,2p)$. The upper curve (solid) is the ratio σ_{pn}/σ_{pp} multiplied by 2.84.

inelastic interactions involving meson production. If a $(p,2p)$ reaction is to occur, the mesons produced must escape from the nucleus as well as both nucleons, i.e., an increased attenuation of the outgoing particles might also be expected which might more than compensate for the effect of σ_{pp} on the $(p,2p)$ cross section.

That a rise in the $Ce^{142}(p,2p)La^{141}$ cross section between 0.4 and 1 GeV is observed suggests that inelastic *p-p* collisions do indeed contribute to $(p,2p)$ reactions, and that attenuation of the outgoing particles is not the dominant factor in a nucleus as large as Ce^{142}. However, the rise in the $(p,2p)$ cross section is less pronounced than the rise in the *p-p* cross section. Furthermore, the (p,pn) cross section decreases between 0.4 and 1 GeV despite the fact that the *p-n* total cross section shows a slight rise. That the free-particle cross sections do not give exactly the shapes of the excitation functions for $(p,2p)$ and (p,pn) reactions is shown in Fig. 3, where the middle and lower curves give the ratios $\sigma(p,pn)/\sigma_{pn}$ and $\sigma(p,2p)/\sigma_{pp}$, respectively. Both curves drop between 0.4 and 1 GeV, indicating that inelastic collisions are less effective in producing $(p,2p)$ or (p,pn) reactions. The curves are surprisingly flat above 1 GeV. It might have been expected that the probability of a simple reaction would decrease as meson multiplicity increased, since the chance of at least one of the outgoing particles (nucleons or mesons) interacting again would increase. Experimentally, the attenuation of the outgoing particles appears remarkably independent of energy. Whether this is due to meson production via formation isobars,[25] which escape from the nucleus before decay, or whether changes in the energy spectrum or angular distribution of the mesons accidentally compensate for the increased numbers can not be decided from the present results.

A rather surprising result may be seen in the upper part of Fig. 3. The points here are the experimentally determined $\sigma(p,pn)/\sigma(p,2p)$ ratio. The solid curve gives the ratio of the free-particle total cross sections, σ_{pn}/σ_{pp}, multiplied by 2.84. The energy dependence of the $\sigma(p,pn)/\sigma(p,2p)$ ratio is predicted very well by the free-particle cross-section ratio although that of the individual $\sigma(p,pn)$ or $\sigma(p,2p)$ are not so well predicted by σ_{pn} or σ_{pp}, i.e., the two lower curves in Fig. 3 are not horizontal lines. Further discussion of our results is inappropriate since only one target system was investigated. (Nucleon, 2 nucleon) reactions in general are the subject of a forthcoming review.[7] We have shown, however, the presence of structure in the $(p,2p)$ cross section which correlates with the corresponding structure in the *p-p* free-particle total cross section.

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