(p,pxn) Reactions of Br^{79} and Br^{81} with 2.9-GeV Protons*

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Cross sections for the (p,pxn) reactions of Br^{79} and Br^{81} have been measured at 2.9 GeV. The cross sections decrease monotonically as x increases, and the decrease with increasing x is faster for Br^{79} than for Br^{81}. The results are compared with Monte Carlo cascade-evaporation calculations. The experimental values are larger than the calculated ones for $x \leq 3$ but are in good agreement for $x=4$–5. The systematics of (p,pxn) reactions at high energies are considered for a number of targets. A quantitative analysis of the $(p,p3n)$ and $(p,p4n)$ reactions indicates that the evaporation process determines the variation in cross section from target to target.

I. INTRODUCTION

THE investigation of (p,pxn) reactions at high energies has received considerable attention in recent years. Cross section measurements at GeV energies have been performed for Ga^{69},[1] Ga^{71},[1] As^{75},[2] I^{127},[3] and U^{238}.[4] The interest in the cross sections for these reactions stems from the fact that they may be used for a fairly direct comparison with the results of the Monte Carlo cascade calculations of Metropolis *et al.*[5] This comparison tests the adequacy of the cascade calculation for fairly simple cascades. It is well known that the cascade calculation grossly underestimates the cross sections of (p,pn) reactions. It has been shown that this is also the case for the $(p,p2n)$ and $(p,p3n)$ reactions of Ga^{69} and Ga^{71} as well as the (p,pxn) $(x=2$–$7)$ reactions of[3] I^{127} in the GeV region. On the other hand, the $(p,p4n)$, $(p,p5n)$, and $(p,p6n)$ reaction cross sections for the gallium isotopes are in agreement with the cascade calculation. In view of this situation it seemed worthwhile to measure additional (p,pxn) cross sections for targets between gallium and iodine and compare the results with cascade-evaporation calculations. We report the results of measurements on the (p,pxn) reactions of Br^{79} and Br^{81} at 2.9 GeV. The cross sections are compared with Monte Carlo cascade evaporation calculations and the situation is found to be similar to that for the gallium isotopes. A comparison with the corresponding cross sections for the previously studied targets reveals several interesting trends which demonstrate the effect of the evaporation process on the magnitude of the (p,pxn) cross sections.

II. EXPERIMENTAL

The experiments were performed in the course of a study of (p,pn) reactions and details of the experimental procedure have already been given.[6] Only a brief summary will, therefore, be presented in this paper.

The irradiations were performed in the circulating beam of the Cosmotron at an energy of 2.9 GeV. The beam intensity was monitored by means of the $Al^{27}(p,3pn)$ reaction whose cross section was taken as 9.1 mb.[7] The irradiation times ranged from 6 to 60 min. In the course of this study 15 irradiations were performed.

The targets consisted of NH_4Br deposited to a thickness of 2–4 mg/cm^2 onto filter paper by a previously described[6] sedimentation technique. The targets were prepared from highly enriched isotopes[8] (Br^{79}—95.1%, Br^{81}—96.3%). The effect of such factors as target nonuniformity, contribution of the backing material to the observed activities, and loss of radiobromine from the target due to hot-atom processes, was investigated. All these effects were found to be small and the results required no corrections because of them.

Following irradiation, the bromine targets were chemically purified from extraneous activities[6] and radioactivity measurements were performed. The γ-ray emission rate of the samples was assayed with a scintillation spectrometer consisting of a 3-in.$\times$3-in. NaI(Tl) detector connected to either a 100-channel or a 256-channel pulse-height analyzer. The detector had previously been calibrated with a number of standard sources. The positron emission rate was also assayed with this detector by measurement of the annihilation radiation. The disintegration rate of Br^{75} was determined by measuring the γ rays of the Se^{75} daughter, since the decay scheme of Br^{75} is poorly known. The branching ratios[9–12] for the particular radiations that

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TABLE I. Detection procedures and assumed branching ratios.

Nuclide	Radiation detected[a]	Branching ratio
6.5 min—Br^{78}	Gamma	β^+—93%[b]
58 h—Br^{77}	Gamma	0.25-MeV γ—31%, 0.30-MeV γ—6.9%,[c] 0.52-MeV γ—23%, 0.58-MeV γ—7.5%
16.1 h—Br^{76}	Gamma	β^+—65%, 0.56-MeV γ—33%, 0.65-MeV γ—10%[d]
1.6 h—Br^{75}	Radiations of Se^{75}	0.26-MeV γ+0.28-MeV γ—85%,[e] 0.40-MeV γ—11.6%

[a] The detectors are described in the text.
[b] From Ref. 9.
[c] From Ref. 10.
[d] From Ref. 11.
[e] From Ref. 12.

were used as a basis of cross-section determinations are listed in Table I.

3. RESULTS

The measured cross sections are presented in Table II and in Fig. 1. The number of separate determinations of each cross section is listed in parentheses. The errors for each cross section include both the standard deviation in the mean as well as an estimate of the systematic error ascribable to decay scheme or counting uncertainties. This estimate is based on the agreement between cross sections obtained from the detection of different γ radiations. The errors range from approximately 10 to 30%. The uncertainty in the cross section for the $Al^{27}(p,3pn)$ reaction is not included in this estimate. The relatively large errors reflect primarily the uncertainties in the assumed branching ratios of complex or poorly known decay schemes as well as the difficulties in the analysis of rather complex γ-ray spectra.

The product of the $Br^{81}(p,7n)$ reaction and of the $Br^{79}(p,5n)$ reaction decays to the product of the corresponding $(p, p(x-1)n)$ reactions prior to chemical separation. Recent measurements of (p,xn) reactions in this mass region[1] indicate that the (p,xn) cross sections in question should be smaller than the corresponding $(p, p(x-1)n)$ cross sections by at least a factor of 100. None of the other (p,xn) reaction products decays appreciably to the corresponding $(p, p(x-1)n)$ products prior to chemical separation.

Several of the (p,pxn) products can be formed from both Br^{79} and Br^{81}. Small corrections for this effect were applied to the measured cross sections on the basis of the known isotopic enrichments.

It is seen that the cross sections for the (p,pxn) reactions decrease as the number of emitted neutrons increases and that the decrease is faster for Br^{79} than for Br^{81}. Similar trends have been noted for the (p,pxn) reactions of Ga^{69} and Ga^{71}.[1] These trends may be attributed to the increasing probability of additional proton emission during both the cascade and evaporation phases of the reaction as the number of emitted neutrons increases. The faster decrease observed for Br^{79} is consistent with the fact that, other factors being equal, the proton evaporation probability increases as the evaporating nuclide becomes more neutron deficient.

TABLE II. Experimental cross sections at 2.9 GeV.

Target	Reaction	Cross section (mb)
Br^{81}	(p,pn)[a]	59 ±5
	$(p,p3n)$	14.5±2.4(4)[b]
	$(p,p4n)$	10.0±2.1(4)
	$(p,p5n)$	9.3±1.0(4)
	$(p,p6n)$	2.3±0.5(4)
Br^{79}	(p,pn)[a]	56 ±3
	$(p,p2n)$	25.8±7.0(4)
	$(p,p3n)$	12.3±1.3(4)
	$(p,p4n)$	6.2±0.6(2)

[a] From Ref. 6.
[b] The numbers in parentheses refer to the number of separate determinations of each cross section.

IV. DISCUSSION

The results may be compared with the predictions of Monte Carlo calculations based on a cascade-evaporation mechanism. Cascade calculations were available for Cu^{64} and Ru^{100} for an incident proton energy of 1.84 GeV.[13] In view of the small difference in the distributions

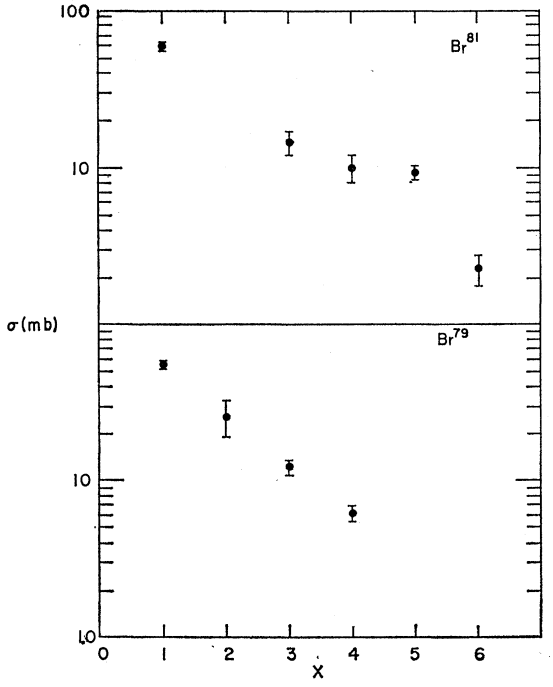

FIG. 1. Cross sections for the (p,pxn) reactions of Br^{81} and Br^{79} at 2.9 GeV.

[13] Data kindly made available to the authors by Dr. G. Friedlander.

of residual nuclei and excitation energy calculated for Cu^{64} and Ru^{100}, it seemed appropriate to use the results for Cu^{64}. Each residual nucleus was shifted in charge and mass number to correspond to the Br^{79} and Br^{81} target nuclei, and then used as the starting point for a Monte Carlo evaporation calculation. Cascades leading to a deposition energy of more than 100 MeV were not used for the evaporation calculation as it was established that none of the nuclides of interest could be formed at these high excitation energies. The evaporation calculation was performed by an adaptation of the Monte Carlo treatment due to Dostrovsky, Fraenkel, and Friedlander.[14] The level density parameter was taken as $a=A/20$ in a level density expression of the form $W(E) \propto \exp\{2[a(E-\delta)]^{1/2}\}$. Cameron's δ values[15] were used for the pairing energy correction. The nuclear radius parameter was taken to be 1.5 F. The branching ratios for the evaporation process were obtained on the basis of 20 evaporation runs for each of about 100 starting nuclei. It should be noted that the calculations have been performed at an incident proton energy of 1.84 GeV, while the experimental points were obtained at 2.9 GeV. Previous excitation function measurements for (p,pxn) reactions[1,3] indicate that the cross sections of these reactions have a negligibly small energy dependence between 1.8 and 2.9 GeV. A comparison between experiment and calculation thus is justifiable.

The ratios of experimental to calculated cross sections are given in Fig. 2. The error bars include the uncertainties of both experimental and calculated values. The uncertainty in the calculated value is due to the limited number of available cascades. It is seen that the ratios decrease with increasing number of emitted neutrons and indicate that experiment and calculation are in agreement for $x=4$–5. This result is quite similar to that previously noted for Ga^{69} and Ga^{71}. The discrepancy between experiment and calculation for $x \lesssim 3$ has been attributed to several approximations in the cascade calculation. These result in an underestimate of the relative number of cascades with low deposition energies involving the emission of only a few nucleons. These approximations are believed to include the lack of a diffuse nuclear surface and an overestimate of the importance of meson processes.

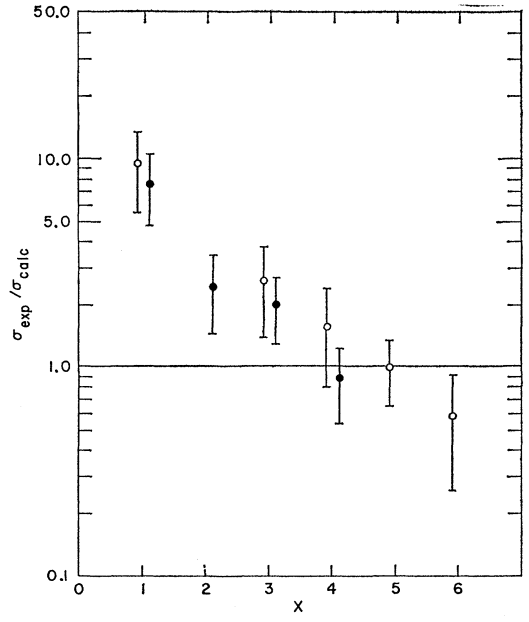

FIG. 2. Ratios of experimental to calculated cross sections for the (p,pxn) reactions of Br^{81} (open points) and Br^{79} (closed points).

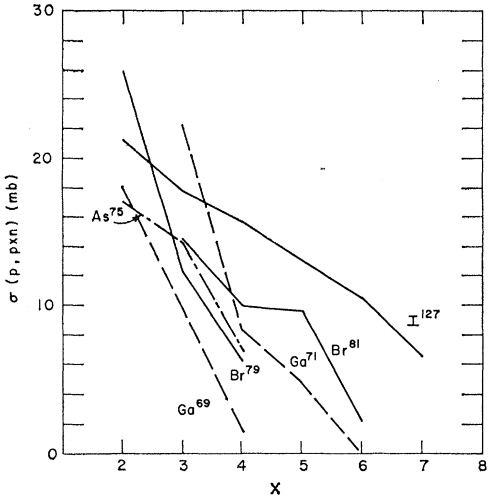

FIG. 3. Variation of (p,pxn) cross sections with x in the low GeV region for a number of targets. The sources of these results are given in the text.

A comparison of the (p,pxn) reaction cross sections for different targets reveals some interesting trends as shown in Fig. 3. The most notable feature is the difference in the cross sections of the (p,pxn) reactions with $x \gtrsim 4$, which is suggestive of the effects of the evaporation process. The (p,pxn) reactions with $x \gtrsim 4$ undoubtedly involve the evaporation of one or more neutrons following a ($p,px'n$) cascade. Proton evaporation competes at each stage of the evaporation process and depresses the cross sections of these reactions. This effect is more pronounced for the lighter targets where proton evaporation competes favorably and leads to the observed trend. The effect of proton evaporation following a (p,xn) cascade works in the opposite direction, but is much smaller in magnitude because of the low probability[5] of (p,xn) cascades. Differences in the distribution of residual nuclei following the cascade may also contribute to the observed trend but the cascade calculations indicate that this effect is very small.

A more quantitative interpretation of the observed trend may be made with the aid of evaporation calcula-

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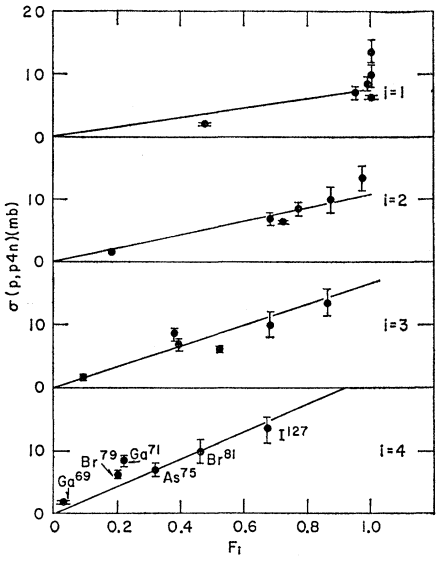

FIG. 4. Dependence of experimental $(p,p4n)$ reaction cross sections on the calculated neutron branching ratios F_i, for the consecutive evaporation of 1, 2, 3, or 4 neutrons. The targets are identified in the graph for $i=4$.

tions. If the very small contribution of (p,xn) cascades followed by proton evaporation is neglected the cross section for a (p,pxn) reaction is given by

$$\sigma(p,pxn)=\sum_{i=0}^{x}\int_{0}^{E_p}\sigma_{x-i}(E^*)f_i(E^*)dE^*, \qquad (1)$$

where $\sigma_{x-i}(E^*)$ is the differential cross section for a $(p, p(x-i)n)$ cascade with a residual excitation energy E^* and $f_i(E^*)$ is the branching ratio for the consecutive evaporation of i neutrons from the residual nucleus in question. The integration is performed over all possible excitation energies. In practice, $f_i(E^*)$ is a sharply peaked function while $\sigma_{x-i}(E^*)$ is expected to vary more gradually with E^*. Furthermore, $\sigma_{x-i}(E^*)$ may, according to the cascade calculations,[5] be taken as the same for all targets under consideration. Under these conditions Eq. (1) may be approximated by

$$\sigma(p,pxn)=\sum_{i=0}^{x}\sigma_{x-i}F_i, \qquad (2)$$

where F_i is the neutron branching ratio evaluated at the energy corresponding to the peak value of f_i. Let us consider the dependence of $\sigma(p,pxn)$ on each of the terms in this summation. It is seen that σ is directly proportional to F_i. A plot of the experimental $(p,p4n)$ cross sections in the low GeV region against the calculated values of F_i is shown in Fig. 4. The calculated values were obtained by means of the above-mentioned Monte Carlo evaporation program. The straight lines are drawn through the origin and the experimental points. It is seen that the cross sections show an approximately linear dependence on F_i for every value of i, i.e., $\sigma(p,p4n)=c_iF_i$. A possible solution of Eq. (2) may be obtained from the slopes of the lines in Fig. 4 to the extent that the linear approximation is valid. The following expression is obtained for the $(p,p4n)$ reaction cross section:

$$\sigma(p,p4n)=1.9F_1+3.0F_2+4.2F_3+5.5F_4 \text{ mb}. \qquad (3)$$

It should be emphasized that the numerical coefficients in Eq. (3) are not necessarily equal to the cross sections for forming the various residual nuclei in the cascade process. This is due to the fact that it is not possible to obtain a unique solution to Eq. (2) from the type of analysis under consideration. Furthermore, the analysis does not consider the direct formation of the product in the cascade and the contribution of this process is included in the other terms of Eq. (3). The above equation should, thus, be taken as a semiempirical expression based on the assumption that the difference in $(p,p4n)$ reaction cross sections for different targets is due to differences in the probability for neutron evaporation. This expression is expected to be valid for targets and bombarding energies such that the distribution of cascade products is similar to that for the cases under consideration. The shape of the excitation functions for (p,pxn) reactions[1,3] indicates that Eq. (3) is not valid below about 1.5 GeV. We estimate that Eq. (3) is accurate to within approximately 10% from the scatter of the points about the straight lines. The maximum observable $(p,p4n)$ cross section predicted by Eq. (3) is 14.6 ± 1.5 mb.

A similar analysis of the $(p,p3n)$ reaction indicates that the cross-sections for this reaction may be represented by the expression

$$\sigma(p,p3n)=5.3F_1+6.0F_2+7.3F_3 \text{ mb}, \qquad (4)$$

to within an average deviation of 20%. An analysis of this type would be of value for (p,pxn) reactions with $x>4$ but not enough data are as yet available on these reactions.

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