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SIMPLE NUCLEAR REACTIONS OF Ca^{48} *WITH HIGH-ENERGY PROTONS*

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The (p, pn), (p, 2n), and (p, n) reactions on Ca^{48} are measured for protons having energies from 120 to 660 MeV. The (p, pn) cross section is about 105 mb and is slightly dependent on the proton energy. The (p, 2n) and (p, n) cross sections decrease from ~ 20 and ~ 8 mb, respectively, at 120 MeV to ~ 6 and ~ 2 mb at 660 MeV. The dependences of the ratios $\sigma_{p,2n}/\sigma_{p,n}$ and $\sigma_{p,pn}/\sigma_{p,n}$ on the target-nucleus mass number and on proton energy are discussed.

1. INTRODUCTION

Among the diversified reactions between high-energy particles and complex nuclei the so-called simple reactions, accompanied by the emission of one or two nucleons, are of greatest interest, because they exhibit a considerable discrepancy between the experimental cross sections and calculations based on Serber's ideas.[1] Thus for (p, pn) reactions, which have been investigated more thoroughly than other reactions, the experimental cross sections exceed calculations by a factor of 3 or 4.[2] An attempt has been made to explain the disagreements by assuming that simple reactions of the types (p, pn), (p, 2p), (p, n) etc. involve mainly direct interactions with nucleons of the diffuse nuclear surface, and that the shell structure of the target nucleus exerts an important influence.[2] The available experimental information has been insufficient for a reliable observation of this effect. In addition, the published results from different laboratories obtained by different techniques are often in poor mutual agreement.

We have therefore undertaken a series of experiments investigating simple reactions on "magic" and "non-magic" nuclei with close values of A and Z. The present work concerns (p, pn), (p, 2n), and (p, n) reactions on $_{20}Ca^{48}$.

2. EXPERIMENTAL TECHNIQUE

A. Target and bombardment. A natural calcium target was used in the form of a pressed rectangular 15 × 4 × 1.5 mm calcium carbonate pellet. Since the irradiated target yielded no disintegration products of the possible heavy impurities, we concluded that it was of sufficiently high purity.

The target was bombarded 15—20 min in the internal beam of the synchrocyclotron of the Joint Institute for Nuclear Research. The proton beam was directed parallel to the 1.5-mm side of the target. The proton energy was varied by changing the radial position of the target in the accelerator.

The proton beam intensity was determined from the yield of the reaction $Al^{27}(p, 3pn)Na^{24}$. The target was wrapped in three layers of aluminum foil about 20 μ thick. To measure Na^{24} activity we used the middle foils in front of and behind the target, which were cut to exactly the same size as the latter. The activity differential between these two foils did not exceed 10% and averaged about 5%.

B. Chemical processing of the target. The irradiated target was dissolved in a small quantity of dilute HCl along with ~ 10 mg scandium carrier. Following the removal of CO_2 by boiling of the solution, NH_4OH was added to precipitate scandium hydroxide. The calcium and scandium fractions were then purified radiochemically.

The calcium fraction was purified by repeated precipitation of calcium oxalate in the presence of a magnesium holdback carrier and by the elimination of radioactive impurities using iron and scandium hydroxides. The calcium was finally deposited as an oxalate ($CaC_2O_4 \cdot H_2O$), filtered onto a filter-paper disk, washed with water and ethyl alcohol, dried at 110°C, and weighed. Transparent adhesive tape was used as a covering to avoid dispersion of the sample.

The scandium fraction was purified by a combination of three operations: precipitation of scandium fluoride using Na_2SiF_6, precipitation of scandium hydroxide in the presence of a calcium holdback carrier, and extraction of scandium by tributyl phosphate from a concentrated HCl solution. The scandium was finally deposited as a hydroxide, was heated at ~ 1000°C until its weight remained constant, was deposited on a filter disk, and was covered with transparent adhesive tape.

C. Activity measurements. Radioactivity was measured with a scintillation γ spectrometer including a 40×40 mm NaI(Tl) crystal and an AMA-3c 128-channel analyzer.[3] The ratio between the absolute activities of the reaction products and of Na^{24} was found by comparing the intensities of characteristic γ lines, taking the decay schemes and counting efficiency into account. The sensitivity of the spectrometer to γ rays of different energies was determined with the aid of Ce^{141}, Hg^{203}, Cs^{137}, Na^{22}, and Co^{60} sources, whose absolute activities were measured with a 4π gas flow counter. Table I shows the radioactive properties of the isotopes used in calculating the cross sections.

Table I

Nucleus	Half-life	γ line, keV	No. of γ quanta per decay, %
Na^{24} [3]	15.0 hrs	1368	100
Ca^{47} [3,4]	4,53days	1300	74
Sc^{47} [3]	3,4 days	160	67
Sc^{48} [3]	44 hrs	1315	100

In the case of Sc^{47}, in addition to the usual corrections for the isotopic composition of the target, chemical yield, bombarding period etc., we also took into account the accumulation of Sc^{47} through Ca^{47} decay.

D. Contributions of secondary processes. The presence of secondary neutrons in the accelerator chamber can lead to simulation of the (p, pn), (p, 2n), and (p, n) reactions by (n, 2n), $(n, 2n\pi^-)$, and $(n, n\pi^-)$ reactions, respectively. Since the reactions resulting in meson emission have very small cross sections, control runs were performed only to evaluate the contribution of (n, 2n) to the (p, pn) cross section. It was found that this contribution does not exceed a few percent and could be neglected in subsequent calculations.

3. EXPERIMENTAL RESULTS

Table II gives the cross sections for (p, pn), (p, 2n), and (p, n) at proton energies from 120 to 660 MeV, as well as the cross sections for the monitor reaction.[5] The rms errors are indicated; the given values are the averages of two or three determinations. The overall accuracy of the cross sections is estimated at about 15%. The cross sections also include errors associated with uncertainties in the decay schemes of the product nuclei and in the cross section for the monitor reaction.

The corresponding excitation functions are shown in Fig. 1. The cross section for (p, pn) appears to be somewhat enlarged by the contribution of $Ca^{48}(p, 2p)K^{47}$. The K^{47} nucleus is unknown; in all probability it is extremely unstable and can decay to Ca^{47}.

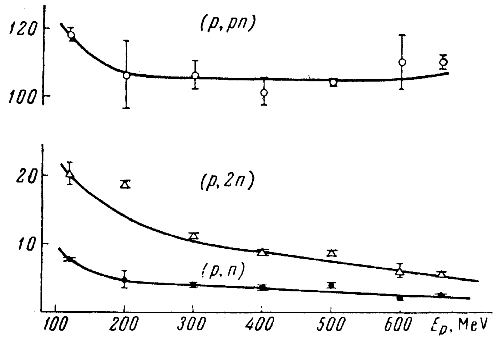

FIG. 1. Excitation functions of the (p, pn), (p, 2n), and (p, n) reactions on Ca^{48}.

4. DISCUSSION OF RESULTS

Figure 1 shows that the excitation functions of the given reactions behave differently. The (p, pn) cross section decreases in the proton-energy range 120–200 MeV, after which it remains practically constant with perhaps a slight tendency to increase. The (p, 2n) and (p, n) cross sections decrease monotonically with increasing energy. Similar behavior of the excitation functions of simple reactions has been observed for other nuclei.[6-8]

It can be assumed that the most important

Table II

Reaction	Cross section, mb						
	$E_p = 120$	200	300	400	500	600	660
(p, pn)	118±2	106±10	106±4	101±4	104±1	110±8	110±2
(p, 2n)	20.3±1.6	18.6±0.6	11.0±0.1	8,7±0,3	8,7±0.1	6.2±1.0	5.7±0,3
(p, n)	7.8±0.3	4.7±1.2	4.1±0.3	3,6±0.1	3.9±0.2	2,2±0.2	2.6±0.1
Al^{27}(p, 3pn)	10,2	9.1	11.0	11.3	11,1	11,0	10,9

mechanism in all the investigated reactions is a primary interaction between an incident proton and an intranuclear neutron. The character of this interaction determines the reaction channel. It is therefore of interest to consider the cross section ratios for simple reactions as functions of the bombarding energy.

Figure 2 shows the ratios of the (p, 2n) and (p, n) cross sections of Ca^{48}, Ga^{69},[8,9] and Y^{89}.[10]

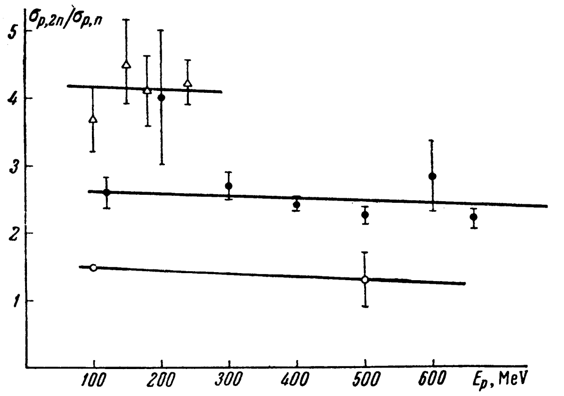

FIG. 2. $\sigma_{p,2n}/\sigma_{p,n}$ as a function of proton energy for $E_p \geq 100$ MeV. △ – Y^{89}, ● – Ca^{48}, ○ – Ga^{69}.

It is easily seen that in all cases $\sigma_{p,2n}/\sigma_{p,n}$ depends only very slightly on the bombarding-proton energy; for Ga^{69} the ratio remains practically constant to $E_p = 2.9$ BeV.

This constancy can serve as an indication that the (p, n) reaction and the first stage of the (p, 2n) reaction have identical mechanisms. Such a hypothesis to account for the constancy of $\sigma_{p,2n}/\sigma_{p,n}$ requires that the formation probability of a residual nucleus with excitation energy sufficient to evaporate only one neutron should depend slightly on the incident-proton energy. An indirect confirmation is furnished by the fact that the average excitation energy of residual nuclei following a (p, N) cascade depends slightly on E_p.[14]

The foregoing hypothesis also indicates that the p, 2n cascade makes only a small contribution to the (p, 2n) cross section. Indeed, the average excitation energy of the residual nucleus following a p, 2n cascade is about 85 MeV for $E_p \gtrsim 200$ MeV ($A = 64$–100); the formation probability of a residual nucleus having excitation $\lesssim 10$ MeV is close to zero.[11]

The absolute values of $\sigma_{p,2n}/\sigma_{p,n}$ depend strongly on the mass number of the target nucleus (Fig. 2). The same strong dependence on A is exhibited by $\sigma_{p,pn}/\sigma_{p,2n}$, accompanied by a different functional dependence on proton energy. The scantiness of experimental data hinders the interpretation of these results.

The cross section ratio of (p, pn) and (p, n) exhibits entirely different behavior. Figure 3 shows the values of $\sigma_{p,pn}/\sigma_{p,n}$ for Ca^{48}, Ga^{69},[8,9] Y^{89},[10] and Th^{232}.[12,13] Here strong dependence on the bombarding energy is observed with practically no dependence on the number of nucleons in the target nucleus. This latter independence can be understood as follows. According to a recent concept the (p, pn) and (p, n) reactions occur in the peripheral region of the nucleus, and each of these reactions should be sensitive to the details of nuclear structure.[14] It is reasonable to assume that an identical number of neutrons is available[1] for both reactions if we neglect the rearrangement energy of the nuclei. It follows that the ratio $\sigma_{p,pn}/\sigma_{p,n}$ should not depend on the number of available neutrons, i.e., on the properties of the target nucleus.

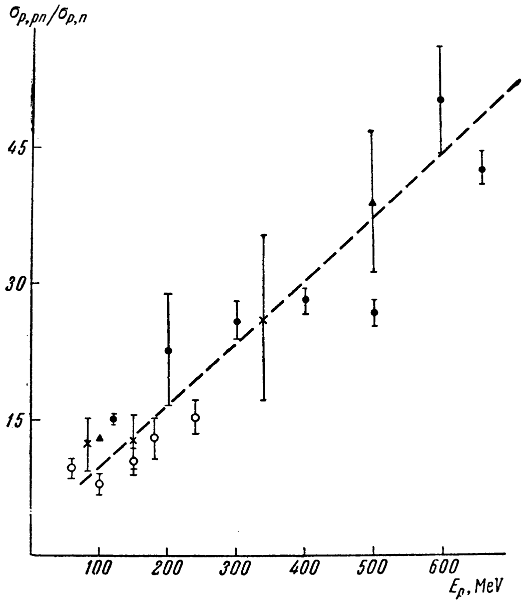

FIG. 3. Dependence of $\sigma_{p,pn}/\sigma_{p,n}$ on proton energy. ● – Ca^{48}, ○ – Y^{89}, ▲ – Ga^{69}, × – Th^{232}.

For a given target nucleus increasing proton energy enhances the relative probability that two colliding particles (the incident proton and a nuclear neutron) will be emitted. At the same time there will be a decrease in the relative probability that an incident proton will be scattered at a large angle or will be absorbed by the nucleus resulting in a (p, n) reaction. This produces a large increase of $\sigma_{p,pn}/\sigma_{p,n}$ with proton energy.

Benioff[14] has estimated that direct knocking-out of neutrons contributes not less than 95% to the

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[1] I.e., neutrons whose removal is not accompanied by transfer to the nucleus of excitation energy exceeding the neutron binding energy.

(p, pn) cross section for $E_p > 1$ BeV. The noted behavior of $\sigma_{p,pn}/\sigma_{p,n}$ suggests that this mechanism becomes predominant for protons of the order of a few hundred MeV.

Figure 3 does not include the corresponding values of the ratios for Cu^{65} (100 at $E_p = 340$ MeV),[15] and for U^{238} (185 at $E_p = 340$ MeV,[12] and 250 for $E_p = 680$ MeV.[16]). The large value of $\sigma_{p,pn}/\sigma_{p,n}$ for U^{238} must evidently be attributed to the fact that the absorption of a proton scattered at a large angle in most cases induces fission and thus a smaller (p, n) cross section. The cause of the discrepancy in the case of Cu^{65} is not clear and can possibly result from the relatively low accuracy of cross section determinations in the first experiments on interactions between fast particles and complex nuclei.

We note, finally, that the experimental cross sections include a contribution from a (p, 2p) reaction for both Ca^{48} and Th^{232}. Consideration of this contribution would most probably lead to a still closer grouping of the $\sigma_{p,pn}/\sigma_{p,n}$ ratios for different nuclei.

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