Multinucleon Removal Induced by High-Energy Protons

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Various light- and medium-mass nuclei have been bombarded with 150-, 230-, 600-, and 960-MeV protons. Prompt γ rays were measured with a Ge(Li) detector. A large number of lines in the γ-energy spectra correspond to the de-excitation of the first levels of $4n$ nuclei ($N=Z$ even). The dependence of this effect on the incident energy and the mass of the target is studied. The data are compared with recent pion-bombardment results.

Several experiments have recently been reported on the interaction of fast negative pions with nuclear matter, in which γ rays were measured by use of Ge(Li) detectors in coincidence with the incident beam.[1] Large cross sections were obtained for multinucleon removal compared to one-nucleon removal or inelastic scattering. If the target is a $4n$ nucleus, i.e., has an even and equal number of protons and neutrons, residual nuclei corresponding to single- and multiple-α (or $2p$-$2n$) removal from the target are produced with very large yields. Comparable results were also observed with low-energy and stopped pions,[2] stopped kaons,[3] and fast positive pions.[4] In these experiments, the reaction mechanism is nearly unknown. It appeared interesting to investigate whether similar results could be observed with other incident particles.

This Letter reports preliminary data of an experiment performed on the 3-GeV "Saturne" synchrotron at Centre d'Etudes Nucléaires de Saclay. A secondary beam of a few times 10^5 protons per burst bombarded 10–15-g/cm^2 thick targets of N, O, P, S, and V at 230 MeV and of Al, Si, Ca, and Fe at various energies up to 1 GeV.

The γ rays were measured by a carefully shielded Ge(Li) detector set at 90° to the beam direction close to the target. This detector was read in coincidence with a beam telescope and in anticoincidence with a scintillator detecting charged particles scattered by the target into the Ge crystal. A measurement of the time of flight of the incident particles allowed rejection of a 10% deuteron and 1% triton contamination of the beam.

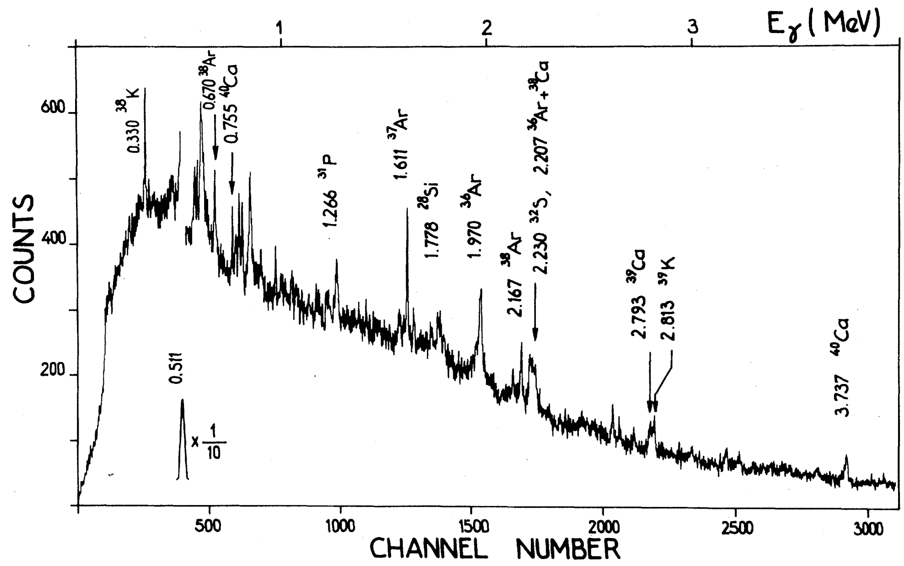

FIG. 1. Spectrum of γ rays from a Ca target bombarded by 210-MeV protons (average energy).

The energy resolution was 5 keV at 1 MeV. By a least-squares fit to the energies of the peaks, agreement was found with known energies of the assigned transitions to better than ± 1 keV. The detector efficiency and the absorption of γ rays in the target were measured in the experimental geometry to deduce cross sections accurate to within ± 20%.

Figure 1 shows the γ spectrum observed with 230-MeV protons striking a target of natural calcium (97% ^{40}Ca). The most energetic γ rays correspond to inelastic scattering on the ^{40}Ca (3^- state) and to one-nucleon pickup leading to the $\frac{1}{2}^+$ and $\frac{7}{2}^-$ levels of ^{39}K and ^{39}Ca. The most intense lines are found between 1.2 and 2.3 MeV and are attributed to ^{38}Ar and ^{38}K, ^{37}Ar, ^{36}Ar, ^{32}S, and ^{28}Si. 3^- and 2^+ levels are mainly excited in even nuclei; $\frac{7}{2}^-$ levels in odd nuclei. ^{28}Si and ^{32}S are only observed through a $2^+ \to$ g.s. line which is Doppler broadened.

Table I summarizes the cross sections calculated from the lowest γ transitions (the only ones observed) of residual nuclei, under the assumption of an isotropic angular distribution. In a first approximation, they are representative of the whole production of each nucleus (direct yield of ground states excepted). These first excited states indeed are populated either in a direct process or via γ-ray cascade from the decay of higher levels excited after successive evaporation of nucleons.

Fast- and stopped-pion data are also given to show the strong similarity between protons and fast pions in the prominent production of $4n$ nuclei. However, proton cross sections are weaker than π^- ones, on the average; the ^{37}Ar yield, which would correspond to the ejection of a ^{3}He particle, is large at low energy in better agreement with the π^--absorption data.

On the Ca the production of $4n$ nuclei appears enhanced when the proton energy increases. At 600 MeV, the production of ^{24}Mg is observed; however, because of the increased background, we did not find any conclusive evidence for ^{20}Ne

TABLE I. Cross sections for inelastic scattering and one-nucleon and multinucleon removal from ^{40}Ca, ^{28}Si, ^{27}Al, ^{32}S, ^{31}P, ^{51}V, and ^{56}Fe deduced from γ-ray yield.

Target Nucleus	Projectile a)	Cross Section Unit	Residual nuclei												
			^{40}Ca	^{39}Ca	^{39}K	^{38}K	^{38}Ar	^{37}Ar	^{36}Ar	^{32}S e)	^{28}Si	^{24}Mg	^{20}Ne		
^{40}Ca	p(110 MeV)	mb	20	20.7	15.2	12.7	12	21.3	29.6	18	19.5				
	p(210 MeV)	"	13.4	8.5	9.7	8.3	10.9	13.6	28.4	16.6	16.7				
	p(600 MeV)	"	5.2	2.9	3.2	4	3.4	5.4	14.1	7.6	6.9	3.6	<1		
	π^-(220 MeV)	"	45.9 c)	32.1				21.7	137.9	114.8	66.1	36.2	27.4		
	stopped π^-	arbit.	0.56 d)		0.22		1.07	2.19	1.34	0.47					
			^{28}Si	^{27}Si	^{27}Al	^{26}Al	^{26}Mg	^{25}Al	^{25}Mg	^{24}Mg	^{23}Na	^{22}Ne	^{21}Ne	^{20}Ne	^{16}O
^{28}Si	p(218 MeV)	mb	24.5	14	25	19.2	11	4.9	11 b)	32	9	6.7	6.7	19.3	
^{27}Al	p(190 MeV)	arbit.			25	18.2	15	0	7.5 b)	21.3	8.8	5.1	4.8	16.9	
^{28}Si	π^-(220 MeV)	mb	40.3 c)	13.7					23.4	38				21.6	5.9
			^{32}S	^{31}S e)	^{31}P e)	^{30}P	^{28}Si	^{27}Al	^{26}Al	^{24}Mg					
^{32}S	p(218 MeV)	arbit.	18.9	14.3	23	5.3	19.7	15	2.9	9					
^{31}P	p(220 MeV)	"			23	4.6	18.1	11.4	1.7	8.3					
			^{51}V	^{50}V	^{50}Ti	^{48}Ti	^{47}Ti	^{46}Ca	^{44}Ca	^{43}Ca	^{42}Ca				
^{51}V	p(224 MeV)	"	4.6	4.4	16.1	17.5	1.9	11.3	6.2	3	7.25				
			^{56}Fe	^{55}Fe	^{55}Mn e)	^{54}Fe	^{53}Mn	^{53}Cr	^{52}Cr	^{48}Ti	^{44}Ca e)				
^{56}Fe	p(960 MeV)	"	260	37.3	22.9	20	15.5	16.6	26.1	12.7	5.3				

[a] Average energy in the target.
[b] Ambiguous assignment.
[c] Ref. 1 for all this line.
[d] Ref. 2 for all this line.
[e] Uncertainty is larger for this column because of nearby lines.

(5α removal) at 960 MeV.

On Al and Si the production of $4n$ nuclei did not seem to be so strongly dependent on energy. Table I shows the similarity of Al and Si cross sections at 220 MeV. ^{27}Al, ^{26}Mg, ^{26}Al, ^{24}Mg, and ^{20}Ne are mainly produced in both cases, with ^{24}Mg comparatively more easily produced from ^{28}Si (1α removal). Other weakly observed nuclei are stable isobars down to ^{21}Ne.

The comparison of P and S shows the same effect as for Al and Si: t and $t+\alpha$ removal proceed on the odd target, and α and 2α removal on the even target, to lead to the same mass distribution.

On V, we observed that t is also more easily removed than α, and that $t+\alpha$ removal has a greater probability than 2α removal.

On Fe, residual nuclei equivalent to the target minus one, two, and three α particles are observed. Most of the residual nuclei show more levels than with other targets and the direct population of the first excited state seems to give only a small contribution to the cross section.

With 230-MeV protons striking a target of water, we observed two Doppler-broadened lines due to the $1_2^+ \rightarrow 0^+$ (1.632 MeV) and $0^+ \rightarrow 1^+$(g.s.) (2.312 MeV) transitions in ^{14}N as a result of a deuteron removal from ^{16}O. The widths of these lines are ≈ 20 and 28 keV, and thus proportional to the transition energies. This Doppler broadening strongly indicates the direct nature of the interaction in this case.

Finally, we report that a spectrum very similar to the 600-MeV proton one was recently measured with 600-MeV α particles on ^{40}Ca.

Qualitatively these results suggest a breaking of an excited system via the weakest bonds between groups of strongly bound nucleons.

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