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γ RAYS FROM PROTON BOMBARDMENT OF NUCLEI

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γ rays from nuclei bombarded by high energy protons (from 100 MeV to 1 GeV) lead to mass distributions of stable nuclei where 4n-nuclei are the most abundant. With calcium an energy dependence is found. A few evidence for direct or semi-direct processes are reported.

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We have measured the γ rays emitted by various light and medium-mass nuclei bombarded by high energy protons (from 100 MeV to 1 GeV). We used a 85 cc Ge(Li) detector in coincidence with protons of the beam and in anticoincidence with protons scattered by the target. Unfolding of the γ spectra gives transition energies to better than ± 1 keV and cross sections within ± 20% accuracy.

Large cross sections for 4n-nuclei (N and Z even) are observed suggesting single and multiple α (or 2p-2n) removal from the target. As shown by the table, in the case of a Ca target (97% ^{40}Ca), this process corresponds to nearly one half of the total cross-section. Increasing the incident energy seems to enhance the phenomenon (column 3 and 5).

Comparison of our 600 MeV data (column 5) with experiments performed with fast pions on the same target (column 6) shows a strong similarity between these data, except that proton cross-sections are much smaller than pion cross-sections. On the contrary, at lower energies, a large cross-section for ^{3}He removal is measured in analogy with stopped pions.

Experiments performed on Al, Si and Fe does not show a sensitive dependence of the relative cross-sections versus incident energy as on calcium. Large cross-sections are measured for production of ^{24}Mg and ^{20}Ne from Al and Si. This means that t and t + α removal from Al and α and α removal from Si proceeds to lead to the same 4n-nuclei. Other residual nuclei identified on Al and Si spectra are isobars of the valley of stability. From this, we infer that binding energy differences are a very important parameter of the process and that the reaction mechanism is most probably direct since a de-excitation of the nucleus by successive evaporation of nucleons would hardly reproduce the strong selectivity of residual nuclei which is observed in these experiments.

Another support for the assumption of a direct production of these nuclei is given by the Doppler-broadening of a few of the γ rays. As an exemple, with an O target, two lines coming from the de-excitation of the second level of ^{14}N were measured with widths of 20 keV and 28 keV proportionnal to the 1632 MeV and 2312 MeV transition energies.

Many of these results strongly suggest direct or semi-direct processes. Confirmation would give hopes of studying clustering in nuclei from the abundant α particle removal observed in these experiments.

Table

Final nucleus (1)	Equivalent removed particles (2)	Cross-section (mb) E_p=110 MeV (3)	E_p=210 MeV (4)	E_p=600 MeV (5)	E_{π^-}=220MeV (6) *
$^{40}Ca(3^-)$		20	13.4	5.2	45.9
^{39}Ca	-n	20.7	8.5	2.9	32.1
^{39}K	-p	15.2	9.7	3.2	
^{38}K	-(p+n)	12.7	8.3	4	
^{38}Ar	-2p	12	10.9	3.4	
^{37}Ar	-^{3}He	21.3	13.6	5.4	21.7
^{36}Ar	-α	29.6	28.4	14.1	137.9
^{32}S	-2α	18	16.6	7.6	114.8
^{28}Si	-3α	19.5	16.7	6.9	66.1
^{24}Mg	-4α			3.6	36.2
^{20}Ne	-5α			<1	27.4

* V.G.Lind et al., Phys. Rev. Lett., 1974, 32, p.479.