Photon-Induced Fragmentation in ^{27}Al and ^{32}S by 1-GeV Bremsstrahlung

V. di Napoli, F. Salvetti, and M. L. Terranova
Istituto di Chimica Generale e Inorganica, Università di Roma, Roma, Italy

H. G. de Carvalho and J. B. Martins
Centro Brasileiro de Pesquisas Fisicas, Rio de Janeiro, Brasil
(Received 12 December 1972)

Polyethylene, water, lithium fluoride, aluminium, and sulfur targets have been irradiated with 1-GeV bremsstrahlung beams at the Frascati electron synchrotron and the yields of some spallation products from ^{27}Al and ^{32}S and of ^{11}C and ^{7}Be from ^{12}C, ^{16}O, ^{19}F, ^{27}Al, and ^{32}S have been measured by the induced-activity and radiochemical methods. Evidence has been deduced for fragmentation from the mass-yield distribution of the photoproduced nuclides in ^{27}Al and ^{32}S.

I. INTRODUCTION

In the last few years most of the experimental work in the photonuclear research at energies higher than 0.1 GeV has been devoted to spallation and fission reactions in complex nuclei.[1-9] Moreover, the largest number of papers have dealt with photon- and electron-induced fission in medium-weight and heavy nuclei. Consequently, little quantitative information is available on fission in light nuclei and fragmentation. Only in some cases [1,6] has the fragmentation been investigated. Fulmer *et al.*[1] gave evidence for fragmentation induced by 16-GeV electrons in aluminum and Butement *et al.*[6] for fragmentation induced by 4-GeV electrons in cobalt, iodine, and tantalum. On the other hand, Kumbartzki *et al.*[5] did not find fragmentation with 1.5-GeV bremsstrahlung exposures of different nuclei ranging between vanadium and arsenic.

It is the purpose of this paper to present some data supporting a fragmentation-like mechanism in the photoproduction of some light nuclides from aluminum and sulphur by 1-GeV bremsstrahlung.

II. EXPERIMENTAL

Irradiations were made at the Frascati electron synchrotron. The targets were 0.2- and 0.05-cm-thick foils of polyethylene (85.7% ^{12}C) and aluminum (100% ^{27}Al), respectively, bidistilled water (88.8% ^{16}O) in 0.5-cm internal thickness lucite containers, and 0.1-cm-thick plates of compressed powder of natural sulphur (95% ^{32}S) and lithium fluoride (73% ^{19}F) in lucite containers. They were irradiated with an 1-GeV uncollimated bremsstrahlung beam, about 1 m (in air) from the beam exit window. A thin aluminum radiator (1.72×10^{-2} radiation length) has been used as bremsstrahlung source. The dose measurements, i.e., measurements of the number of equivalent quanta passed through the target samples during each irradiation, were carried out by means of monitors.[10]

Nuclide yields, expressed as cross sections per equivalent quantum σ_Q, have been measured by the induced-activity and radiochemical methods. Counting of the samples after irradiation has been performed on a conventional γ-ray spectrometry line with a 30-cm^3 Ge(Li) detector and 1024-channel pulse-height analyser. The identification of radionuclides was made from half-life measurements and γ-ray energy in the spectra; their yields were estimated from selected photopeak areas by converting peak intensities to source strengths using the experimentally measured detection efficiency and known data of the decay schemes[11] for each radionuclide.

For ^{32}S, some irradiated targets were dissolved in concentrated nitric acid. To the solution 20 mg of beryllium (II) carrier was added. Beryllium was precipitated as the hydroxide by adding dilute ammonia solution, dissolved in hydrochloric acid, and reprecipitated twice in the presence of sodium (I) hold-back carrier to remove ^{22}Na and ^{24}Na activities. The final precipitate was ignited to the oxide. To improve the statistics in the ^{7}Be activity measurements, counting was then carried out on the Be fractions with a 7.6-cm × 7.6-cm NaI(Tl) crystal.

III. RESULTS AND DISCUSSION

Figure 1 shows the results obtained for the ^{27}Al target. The data regarding the yields of ^{24}Na, ^{22}Na, and ^{18}F agree quite satisfactorily with those of previous measurements.[8,12] The slope K of the yield surface ridge (decrease of yield per unit ΔZ increase) has been calculated from the experimental values for the two nuclides ^{22}Na and ^{18}F.

The slope K can be expressed by the following formula[13]

$$K = (\sigma_{Q1}/\sigma_{Q2})^{1/\Delta Z} \qquad (1)$$

which relates K to the yields σ_{Q1} and σ_{Q2} of the two radionuclides 1 and 2, both on the neutron-deficient or proton-deficient side of the $N-Z$ plane and equally displaced from the center of the β-stability valley, and to the difference $\Delta Z = Z_1 - Z_2$ between their respective atomic numbers.

Figure 2 shows the results obtained for the ^{32}S target. Also in this case has the slope K been calculated from the yields of ^{22}Na and ^{18}F by means of Eq. (1).

The error in the yield measurement arose from a combination of errors in counting, back extrapolation of counting rates to obtain initial rates, evaluation of the detector efficiency, and dose measurements. In some cases (^{11}C and ^{7}Be from ^{27}Al and ^{24}Na, ^{11}C, and ^{7}Be from ^{32}S) more than one exposure has been made. The standard deviation for each yield was smaller than the error evaluated by the procedure above mentioned.

The yield data in Fig. 1 and in Fig. 2 have been treated following the procedure described in Refs. 1, 13. The curves through the experimental points at $Z = 11$, 9, and 6 in Fig. 1 and at $Z = 12$, 11, 9, and 6 in Fig. 2 account for the spallation processes, mainly due to the evaporation step in the deexcitation of the target nucleus after the cascade fast step having been accomplished.[1, 13-15]

The yields of ^{11}C and ^{7}Be from both aluminum and sulphur deviate from the spallation patterns by an extent well beyond the experimental error, thus indicating a mechanism being effective in their production quite different from the predicted one by the two-step cascade-evaporation theory. For aluminum, ^{11}C is likely a fission product, as has been suggested by Fulmer *et al.*[1] Assuming an ejection of three or more neutrons as the result of the nucleonic cascade step in the ^{27}Al nucleus, the yield of ^{11}C can be assumed to reach nearly the maximum of the mass-yield distribution of the fission of ^{27}Al, and this may explain the relatively high value of ^{11}C yield from aluminum.

The yields of ^{7}Be from aluminum and ^{11}C and ^{7}Be from sulphur, however, are too large and far from any reasonable mass-yield distribution of fission products, even though such a distribution is very broad. Moreover, very asymmetric fission at such energies and triple fission are to

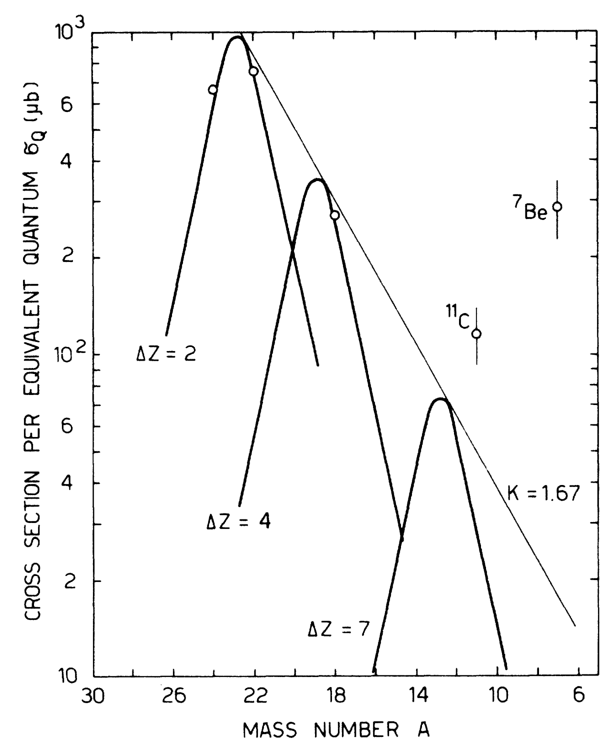

FIG. 1. Yields of radionuclides observed in a thin aluminium target irradiated with 1-GeV bremsstrahlung versus the mass number. ΔZ is the difference between the atomic number of the target nucleus ($Z = 13$) and the atomic number of the produced radionuclide.

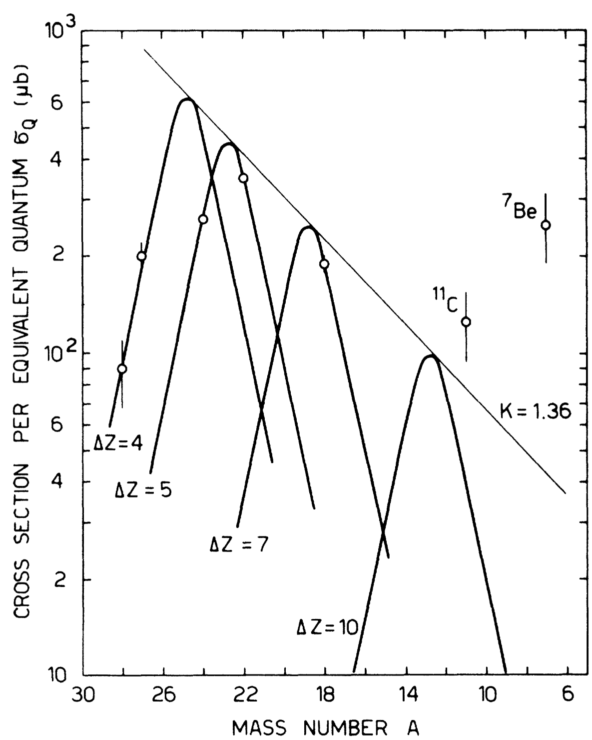

FIG. 2. Yields of radionuclides observed in a thin sulfur target irradiated with 1-GeV bremsstrahlung versus the mass number. ΔZ is the difference between the atomic number of the target nucleus ($Z = 16$) and the atomic number of the produced radionuclide.

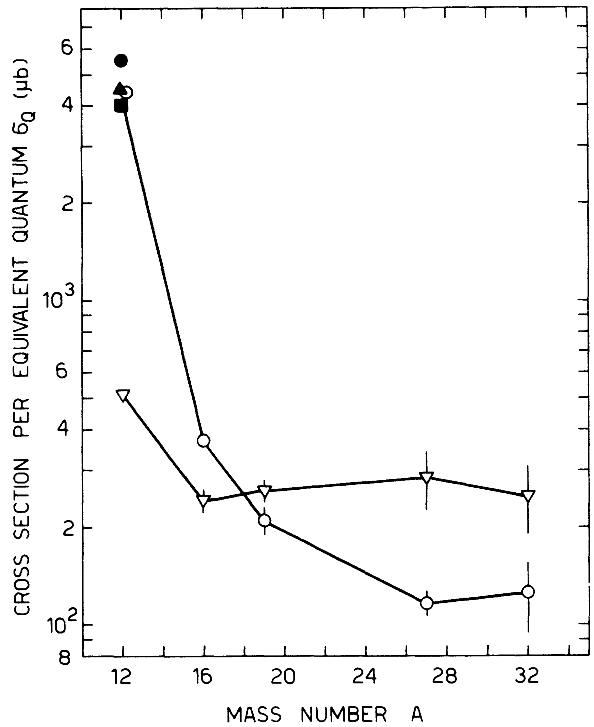

FIG. 3. Yields of ^{11}C and ^{7}Be versus the mass number of the target nucleus. Filled circle: ^{11}C, Ref. 16. Filled triangle: ^{11}C, Ref. 17. Filled square: ^{11}C, Ref. 8. Open circles: ^{11}C, present work. Reversed open triangles: ^{7}Be, present work.

such a degree rare processes, even for heavier nuclei, that they can be disregarded in the present case. The fact, then, that ^{7}Be yields are larger than ^{11}C yields suggests that at least ^{7}Be must originate by a process different from fission.

The only mechanism suitable in explaining the very large yield values of ^{7}Be from aluminum and of ^{11}C and ^{7}Be from sulphur is that of the fragmentation (i.e., the splitting off from the nucleus of clusters of nucleons in a fast process.)

It is of interest to examine in some detail the ratios between the experimental yield values of ^{7}Be and those calculated from the slopes in Fig. 1 and in Fig. 2. These ratios are 26 and 12 for ^{27}Al and ^{32}S targets, respectively. The much higher value of the ratio for ^{27}Al (about 2 times that of ^{32}S) may be explained by assuming a larger fissility in sulphur; as a consequence, lower probability for fragmentation would result in ^{32}S than in ^{27}Al. An alternative way to explain such a discrepancy is the following: ^{18}F may be produced from ^{32}S either by spallation or by fission, thus its yield is higher than the yield one might expect from the spallation only. Consequently, the slope K in Fig. 2 would be increased by a factor, which would correspond to a higher value of the ratio of the experimental and calculated yields of ^{7}Be.

In Fig. 3 the yields of ^{11}C and ^{7}Be from ^{12}C, ^{16}O, ^{19}F, ^{27}Al, and ^{32}S are plotted as a function of the target mass number. The rapid decrease of yield with increasing A undergoes a remarkable softening just as the difference between the target and produced nuclide mass numbers becomes always more consistent; when this difference is very large, the yields seem to remain constant or even to raise.

The general trend of the yields in the graph is very similar to that reported by different authors[18-21] to justify the assumption of a fragmentation-like mechanism in the production of several light nuclides from a number of target nuclei bombarded with protons, whose energy ranged between 0.7 and 30 GeV.

In summary we can conclude that the experimental evidence indicates the fragmentation process as being the effective one in the photoproduction of nuclides of mass around 7 in the aluminum targets. Any attempt to infer more quantitative conclusions (e.g. energy and target-mass-number dependence of the fragmentation yields as well as of the competition between fission and fragmentation) would bring about a considerable need for experimental data, much larger in number than at present available. Yield measurements of ^{11}C, ^{7}Be, and other fragments from a number of target nuclei in the energy range 0.3–1 GeV are presently being carried on in our laboratory. The results will be the argument of further papers.

ACKNOWLEDGMENTS

The authors wish to express their thanks to the members of the synchrotron staff of the Laboratori Nazionali di Frascati. The financial help of the Italian Consiglio Nazionale delle Ricerche and of the Brazilian Conselho Nacional de Pesquisas and Comissão Nacional de Energia Nuclear is also gratefully acknowledged.

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