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PHOTODISINTEGRATION OF LIGHT AND MEDIUM-WEIGHT NUCLEI AT INTERMEDIATE ENERGIES - IV

PHOTOPRODUCTION OF ^{7}Be AND ^{11}C FROM TARGETS WITH MASSES UP TO 40(*)

V. di Napoli, J.B. Martins(**), G. Rosa, F. Salvetti,
O.A.P. Tavares(**), M.L. Terranova

Istituto di Chimica Generale ed Inorganica dell'Università, Roma

and

H.G. de Carvalho

Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro

ABSTRACT

Mean cross sections for the photoproduction of ^{7}Be and ^{11}C from ^{19}F, ^{27}Al, ^{28}Si and ^{32}S targets, ^{7}Be from $^{10,11}B$, and ^{11}C from ^{14}N and ^{16}O targets have been measured using bremsstrahlung beams in the energy range 0.3-1.0 GeV. The results have been compared with previous measurements and an excellent agreement has been found. In most cases, the values obtained turned out to be much larger than those expected from a simple spallation mechanism. A fragmentation- and/or a fission-like process has been suggested in explaining the mechanism of such reactions.

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INTRODUCTION

In analysing data from intermediate-energy interaction of photons with nuclei having masses up to 40[1,2], some deviations from the expected patterns have been found as far as the production of some nuclides (e.g., ^{18}F) is concerned.

It has already been suggested that measurements of the yields of somewhat lighter fragments such as ^{11}C and ^{7}Be could explain to a certain degree the reported discrepancies. Being it possible, in some cases, to regard ^{11}C and ^{7}Be as fragments complementary to those measured in 1, their yields are likely to supply a valuable information about the interaction mechanism. On the other hand, ^{11}C and ^{7}Be are the lightest fragments easily detectable by means of the techniques customarily employed in nuclear- and radiochemistry.

Apart from the general interest in Nuclear Chemistry and in Nuclear Physics, the study of these cross sections can furnish contributions in Astrophysics and Geophysics. In fact, ^{7}Be and probably ^{11}C are generally believed to arise as secondary products from the interaction of heavier primary cosmic ray nuclides during their propagation in the interstellar medium[3].

The present paper deals with the ^{11}C photoproduction yields from ^{14}N, ^{16}O, ^{19}F, ^{27}Al, ^{28}Si, ^{32}S and $^{35,37}Cl$, and the ^{7}Be photoproduction yields from $^{10,11}B$, ^{19}F, ^{27}Al, ^{28}Si and ^{32}S, in the energy range 0.3-1.0 GeV.

EXPERIMENTAL

The experiment has been carried out at the Frascati

1-GeV Electron Synchrotron. The target samples were identical to those described in 1 , with the exception of $^{10,11}B$, ^{14}N and $^{35,37}Cl$ targets. These consisted in boron, lithium amide and lithium chloride powders, respectively, packed in thin walled lucite containers, with a density of about 10^{21} target nuclei *per* square centimetre. The purity of the samples was not less than 99.9%.

The experimental conditions, namely, exposure arrangements, bremsstrahlung intensities, monitoring procedures and counting techniques, were similar to those described in 1,2 . Irradiations were performed for each target at 10 end-point bremsstrahlung energies E_0, between 0.3 and 1.0 GeV. Exposure times lasting not more than one half-life of ^{11}C (20.34 min) were obviously chosen in studying the ^{11}C photoproduction, while the much larger half--life of ^{7}Be (53.6 d) allowed more lenghty exposures to be made. The ^{11}C and ^{7}Be activities were estimated from the 0.511 MeV annihilation peak (200 photons *per* 100 disintegrations) and the 0.477 MeV peak (10.3 photons *per* 100 disintegrations), respectively. In the case of ^{11}C photoproduction a certain number of exposures of samples packed in thin walled aluminium containers were carried out in order to ascertain the possibility of a contamination of the samples by ^{11}C activity produced in the lucite containers. It is to be noted that, within the limits of experimental errors, no relevant differences were found in ^{11}C yields obtained by the two different target arrangements.

EXPERIMENTAL RESULTS

The measured yields of the photoproduction of ^{11}C and ^{7}Be from nuclei, expressed as cross section *per* equivalent quantum, σ_Q, are listed in Tables 1 and 2 at the different bremsstrahlung energies. A discussion about the errors affecting the σ_Q's is reported in Ref. 4 .

Mean cross sections per photon, $\bar{\sigma}_k$, were deduced from the σ_Q values by assuming a pure 1/k-dependence of the bremsstrahlung spectra upon the photon energy k [5], in the region 0.3-1.0GeV. Along the present work results we report in Figs. 1 and 2 previous measurements, as well as a hitherto unpublished set of data regarding ^{11}C photoproduction from ^{16}O, ^{19}F, ^{27}Al, ^{28}Si and ^{32}S, and ^{7}Be photoproduction from $^{10,11}B$, ^{12}C, ^{16}O, ^{19}F, ^{27}Al, ^{28}Si and ^{32}S [6-14].

The general trend of ^{11}C photoproduction data enabled a treatment by means of the least squares method to be carried out. In this way, we obtained a straight line, whose equation is

$$\bar{\sigma}_k = \exp\left[(-0.028\pm0.03)A_t + (5.07\pm0.09)\right] , \qquad (1)$$

with a correlation coefficient of 0.8. From Eqn(1)the $\bar{\sigma}_k$ value for the photoproduction of ^{11}C from whatever target nucleus ($14 \leq A_t \leq 40$) may be obtained with an uncertainty estimated around 20%, corresponding thus to one standard deviation. In the case of ^{7}Be photoproduction (see Fig. 2), it was not possible to find any reasonable correlation between the resulting cross sections $\bar{\sigma}_k$, although there is a good agreement among different measurements.

From the σ_Q values listed in Tables 1 and 2, a general equation of the form

$$\sigma_Q = a \ln E_o + b \qquad (2)$$

can be deduced for the E_o-dependence of σ_Q, from which the threshold-energy for ^{11}C and ^{7}Be photoproduction from different target nuclei can be obtained as

$$E_{th} = \exp(-b/a) \quad . \tag{3}$$

Although the errors in evaluating E_{th} are quite large, a general trend of increasing the threshold-energy with increasing the reaction complexity can be deduced. The highest threshold-energy is found for the photoproduction of both ^{11}C and ^{7}Be from ^{40}Ca. However, high threshold values have also been met for ^{27}Al, ^{28}Si and $^{35,37}Cl$ targets.

A possible contribution to the yields of ^{11}C arising from ^{12}C impurities in the target material used has been taken into consideration. Due to the high value of the yield of ^{11}C from ^{12}C, the presence of 1% ^{12}C impurity would yield, in fact, a contribution of the same order of magnitude as the experimentally determined yields of the reaction under investigation. In the reality, the upper limit of impurities in the target materials was about 0.1%. Even if such impurities were only due to ^{12}C, the contributions of this nucleus to the total measured yields would be less than 10%, that is, within the limits of the experimental error. On the other hand, for ^{14}N, ^{16}O, ^{19}F, ^{27}Al and $^{35,37}Cl$ targets, the impurity content was considerably lower than 0.1%, and by considering the general trend observed in the photoproduction of ^{11}C from the different targets (see Fig. 1), one can conclude that the contribution of ^{12}C impurity can be safely neglected. By similar reasoning, the conclusion must also be drawn that for ^{7}Be photoproduction the contribution of impurities is a fortiori negligible. In addition, this conclusion is strongly supported by the fact that the observed thresholds for ^{7}Be and ^{11}C photoproduction from ^{19}F onward ($A_t \geq 19$) are considerably higher than would arise from the photoproduction on ^{12}C nuclei.

DISCUSSION AND CONCLUSIONS

Because of the lack of experimental data on the photoproduction of ^{7}Be and ^{11}C from light nuclei, a comparison has been made with cross sections calculated by using the five-parameter CDMD Rudstam's formula with suitable modifications of the parameters which account for the different type of incident particles[15]. Although this formula has been deduced for target nuclei with masses above about 30(*), we considered it worthwhile to use the formula for somewhat lighter nuclei, at least as a first approximation, with an expected uncertainty quite large, undoubtedly beyound the factor 2, as indicated in Ref. 15 .

Table 3 reports a number of data regarding the reactions we investigated. From the analysis of the table, it is easily seen that when the ratio between the nominal nucleon loss and the total number of target nucleons (4th column) is higher than about 40%, the ratio of the experimental cross sections to the calculated ones (7th column) is at least 7, which is considerably larger than the factor 2 above mentioned. In most cases this ratio is larger than 10, and for target mass number higher than or equal to 27 (Al) it reaches values ranging from a minimum of 14 to a maximum of 71. Correspondingly, the thresholds obtained by Eqn (3) turn out to be the highest found.

(*) Light nuclei with mass numbers $A < 27$ give rise to residual post-cascade nuclei having excitation energies which are, as a rule, too high to permit the application of the evaporation model.

The correlation which seem to exist among the large percentage of nucleon loss, the higher threshold values, and the very large difference between the experimental and calculated cross sections, strongly suggests the spallation mechanism being scarcely effective in yielding ^{11}C and ^{7}Be from nuclei having masses heavier than or equal to 27. Consequently, we assumed different reaction channels, namely those of fission and fragmentation, as the dominant ones.

A similar conclusion was drawn by Raisbeck and Yiou[3], who attributed to the mechanism of fragmentation the production of ^{7}Be by high-energy proton bombardment of Si and Mg. Moreover, they also found thresholds for these reactions of the order of magnitude of hundreds MeV.

A mechanism different from spallation effective in yielding ^{11}C and ^{7}Be could explain, as an example, the discrepancies met in the photoproduction of ^{22}Na and ^{18}F from $^{35,37}Cl$ and of ^{18}F from ^{32}S [1].

A recent Monte Carlo calculation on photonuclear reactions within the framework of a cascade-evaporation model[16] gives the following data regarding the interaction of 600-MeV photons with ^{27}Al: mean number of cascade neutrons ejected $\overline{n}_n = 1$, mean number of cascade protons ejected $\overline{n}_p = 1$, and mean excitation energy of the residual post-cascade nucleus $\overline{E^*} = 60$ MeV. This means that, after the cascade step, we have, as an average, the residual nucleus ^{25}Mg with an excitation energy of about 60 MeV. A rough estimate of the probability of ^{7}Be-cluster evaporation relative to the evaporation of a single nucleon gives a value not higher than 10^{-4}. Such a low probability makes it very unlikely the photoproduction of ^{7}Be and ^{11}C during the evaporation step. The same conclusion can be inferred for target nuclei with $27 < A_t \leq 40$. As far as lighter nuclei ($A_t < 27$) are concerned, it has already pointed out that the residual nuclei arising from the cascade step cannot be treated on the basis of an evaporation mechanism and, in this case also, the photoproduction of ^{7}Be and ^{11}C should be explained by means of other interaction mechanisms.

The induced radioactivity method used in the present experiment does not allow one to decide unambiguously about what kind of mechanism is the more suitable in describing the reactions studied. We believe that other detection techniques such as plastic detectors and solid state track recorders will clarify this problem.

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Table 1 - Cross Sections per Equivalent Quantum of ^{11}C Photoproduction

E_o (GeV)	Cross Section, σ_Q (μb) ^{14}N	^{16}O	^{19}F	^{27}Al	^{28}Si	^{32}S	$^{35,37}Cl$
0.30	520±30	200±20	110±20	28±10	35±10	45±10	30±10
0.32	520±30	210±20	120±20	30±10	42±10	50±10	30±10
0.35	530±30	230±20	125±20	38±10	45±10	60±10	40±10
0.40	530±30	230±20	130±20	42±10	52±10	65±10	50±10
0.48	550±30	255±20	150±20	60±10	70±10	80±10	60±10
0.55	570±30	260±20	160±20	60±10	78±10	85±10	60±10
0.65	600±30	290±20	180±20	70±10	85±10	98±10	75±10
0.75	620±30	300±20	180±20	79±10	95±10	110±10	85±10
0.90	650±30	320±20	190±20	90±10	110±10	120±10	95±10
1.00	680±30	330±20	210±20	100±10	115±10	125±10	100±10

Table 2 - Cross Sections per Equivalent Quantum of ^{7}Be Photoproduction

E_o (GeV)	Cross Section, σ_Q (μb) $^{10,11}B$	^{14}N	^{16}O	^{19}F	^{27}Al	^{28}Si	^{32}S
0.30	150±20	200±20	113±20	152±20	40±20	20±20	50±20
0.32	160±20	200±20	120±20	150±20	45±20	30±20	54±20
0.35	160±20	210±20	130±20	159±20	42±20	30±20	60±20
0.40	175±20	226±20	145±20	170±20	98±20	20±20	70±20
0.48	190±20	245±20	163±20	186±20	100±20	50±20	140±20
0.55	200±20	260±20	187±20	200±20	93±20	48±20	90±20
0.65	220±20	280±20	197±20	214±20	140±20	68±20	130±20
0.75	225±20	300±20	215±20	227±20	180±20	70±20	130±20
0.90	240±20	318±20	230±20	245±20	186±20	88±20	165±20
1.00	250±20	330±20	242±20	260±20	200±20	97±20	190±20

Table 3 - Comparison Between Experimentally Determined and Calculated Cross Sections of ^{7}Be and ^{11}C Photoproduction and Indication of the Dominant Reaction Channels.

Target Nucleus	Product Nucleus	Nominal Nucleon Loss, ΔA	$\Delta A/A_t$ (x100)	$\bar{\sigma}_{exp}$(*) (μb)	$\bar{\sigma}_{CDMD}$ (**) (μb)	$\frac{\bar{\sigma}_{exp}}{\bar{\sigma}_{CDMD}}$	Apparent Threshold (Exp.) E_{th}(MeV)	Possible Mechanism of Production
$^{10,11}B$	^{7}Be	(3), 4	(30),36	67	28	2	≤ 50	Spallation
^{12}C	^{7}Be	5	42	110	20	5	≤ 50	Spallation
^{14}N	^{7}Be	7	50	108	12	9	≤ 50	Fission Spallation
^{14}N	^{11}C	3	21	130	60	2	≤ 50	Spallation
^{16}O	^{7}Be	9	56	107	8	13	$50<E_{th}<200$	Fission Fragmentation
^{16}O	^{11}C	5	31	117	33	3	≤ 50	Spallation
^{19}F	^{7}Be	12	63	106	5	21	$50<E_{th}<200$	Fission Fragmentation
^{19}F	^{11}C	8	42	105	16	7	$50<E_{th}<200$	Fission Fragmentation Spallation
^{27}Al	^{7}Be	20	74	142	2	71	> 200	Fragmentation
^{27}Al	^{11}C	16	59	70	5	14	$50<E_{th}<200$	Fission Fragmentation
^{28}Si	^{7}Be	21	75	56	2	28	> 200	Fragmentation
^{28}Si	^{11}C	17	61	68	4	17	$50<E_{th}<200$	Fission Fragmentation
^{32}S	^{7}Be	25	78	114	2	57	≃ 200	Fragmentation
^{32}S	^{11}C	21	66	68	3	23	$50<E_{th}<200$	Fission Fragmentation
$^{35,37}Cl$	^{11}C	24,(26)	69,(70)	59	3	20	$50<E_{th}<200$	Fission Fragmentation
^{40}Ca	^{7}Be	33	83	70	1	70	> 200	Fragmentation
^{40}Ca	^{11}C	29	73	70	2	35	> 200	Fragmentation

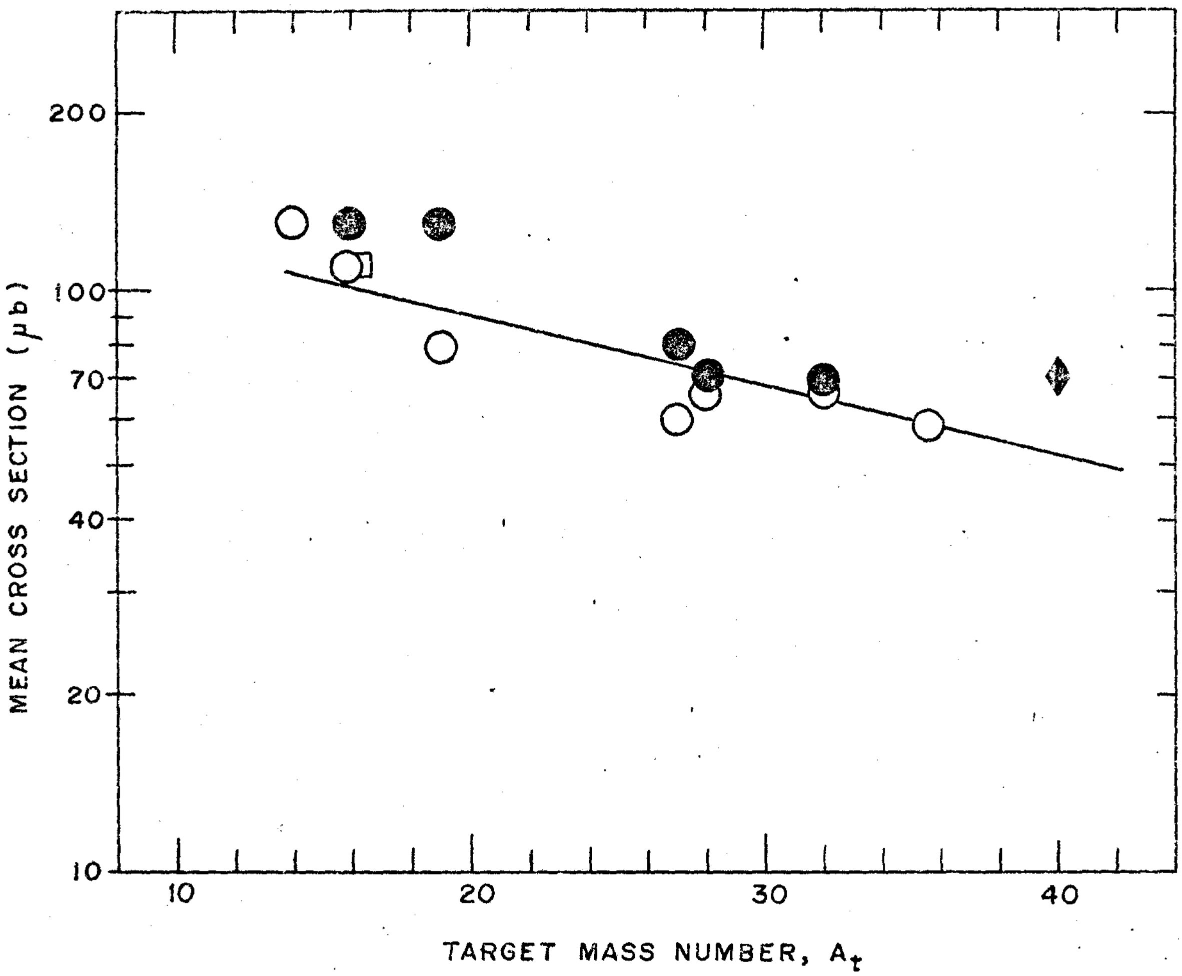
(*) Mean values of the different measurements (see Figs. 1 and 2).

(**) Calculated values according to Ref. 15 .

FIGURE CAPTIONS

Fig. 1 - Mean cross sections *per* photon, $\bar{\sigma}_k$, of ^{11}C photoproduction *versus* the target mass number A_t. Experimental data are taken from: filled circles, Ref. 9; open square, Ref. 13; filled rhomb, Ref. 2; open circles, present work. The straight line is a least squares fit of the experimental points.

Fig. 2 - The same as in Fig. 1 for ^{7}Be photoproduction. Experimental data are taken from: filled triangle, Refs. 6, 7; open reversed triangles, Ref. 8; filled circles, Ref. 9; open triangle, Ref. 10; filled rhomb, Ref. 11; filled reversed triangle, Ref. 12; open square, Ref. 13; filled square, Ref. 14; open rhomb, Ref. 2; open circles, present work.


200
100
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MEAN CROSS SECTION (μb)
10
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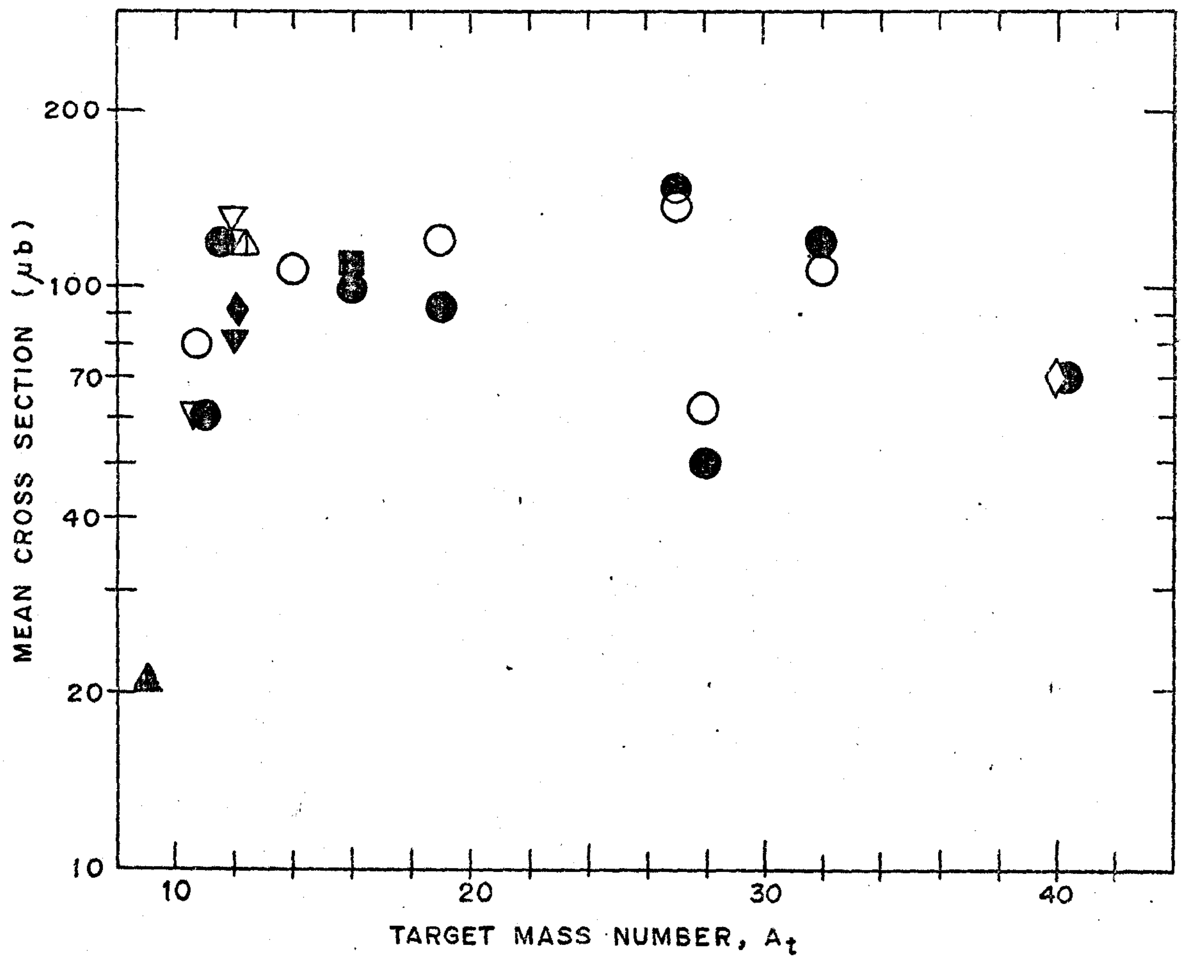
TARGET MASS NUMBER, A_t

Fig. 1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MEAN CROSS SECTION (μb)
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TARGET MASS NUMBER, A_t

Fig. 2