SOME REMARKS ON ^{13}N PHOTOPRODUCTION FROM ^{16}O AND ^{19}F AT INTERMEDIATE ENERGIES(*)(**)

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In the energy region above the meson photoproduction threshold ($E_\gamma > 0.15$ GeV), the interaction of bremsstrahlung beams with complex nuclei can yield different kinds of reactions, roughly classified as direct, fragmentation, fission and spallation reactions. Since a previous paper[1] has given a detailed discussion about the different mechanisms involved in these reactions, they will not be further described here.

This work, which deals with the photoproduction of ^{13}N from ^{16}O and ^{19}F via a (γ,p2n) and a (γ,2p4n) reaction respectively, is part of a systematic study of the spallation process which

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we are carrying out.

As has already been pointed out in previous papers[2,3,4], for nuclei of small mass number the experimental evidence strongly suggests that the two-step cascade-evaporation model[5,6,7] (which we refer to as "spallation mechanism") provides the proper description for reactions involving less than 40% of nucleons of the target nucleus. Owing to the low percentage of nucleons emitted (19% and 31% respectively) the two reactions under investigation may be designated as spallation reactions.

The experiment was carried out at the Frascati 1-GeV Electron-Synchrotron. Irradiations were performed at 12 end-point bremsstrahlung energies between 0.3 and 1.0 GeV. The targets consisted of bidistilled water (88.8% ^{16}O) in thin-walled lucite containers, and analytical grade lithium fluoride (73% ^{19}F) uniformly packed between two lucite discs. Experimental arrangements, irradiation condictions and monitoring procedures used in this experiment were similar to those used in other experiments carried out in our laboratory[8,9,10]. Exposure times ranged between 20 and 30 minutes and the related doses were, as an average, 3×10^{11} equivalent quanta per minute at 0.3 GeV and 1.0×10^{12} equivalent quanta per minute at 1 GeV. Counting of the irradiated samples started 6 minutes after the end of each irradiation and was performed on a 70cm^3 (nominal volume) Ge(Li) detector connected with a 1024 channel pulse-height analyser. The analysis of the 0.511 MeV annihilation photopeak in the gamma-ray spectra of both water and lithium fluoride targets revealed the presence of other emitting nuclides photoproduced by concurrent processes in the same target. They are reported in

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Table I, with some spectrometric data of interest[11]. The different half-lives of these nuclides made it possible to analyse the complex decay curves of the 0.511 MeV peak for each sample, in order to discriminate between the activities arising from ^{13}N and the others. The value of the ^{13}N disintegration rate at the end of each irradiation was then calculated by extrapolation and corrections for counting efficiency and decay during irradiation.

The yields of the reaction $^{16}O(\gamma,p2n)^{13}N$, expressed as cross sections per equivalent quantum, σ_Q, are listed in Table II. For a detailed discussion of the evaluation of experimental errors involved in cross section measurements the reader is referred to a previous paper[12]. To obtain the mean absolute cross section $\bar{\sigma}_k$ (per photon) from σ_Q values, the photon-difference method has been used with the assumption of a square shape for the bremsstrahlung spectra[12]. In this way a value of (24 ± 10)μb has been found for the reaction $^{16}O(\gamma,p2n)^{13}N$ in the energy range 0.3-1.0 GeV. As far as the production of ^{13}N from ^{19}F is concerned, very low and scattered values of σ_Q were obtained (for example, (23 ± 10)μb at 0.3 GeV and (48 ± 10)μb at 1.0 GeV). Consequently an upper limit of about 20μb only could be reasonably attributed to the mean cross section $\bar{\sigma}_k$ for this reaction.

According to the trend of mass distribution of spallation products[13,14,15,3] for both reactions under investigation, one would expect cross section values to be a factor of at least 8 above those obtained experimentally. We thought it would be useful in explaining such low yields, to compare the results of the present work with some data already accumulated on spallation reactions in light nuclei leading to radionuclides very close to the respective stable nucleus. Fig. 1 shows the mean absolute cross sections per nucleon σ_N in the energy range 0.3-1.0GeV reported as a function of the nominal nucleon loss for a number of target nuclei ranging between ^{16}O and ^{32}S. The straight line, the equation for which is

$$\sigma_N = 9.5 \exp(-0.1X) ,$$

with X standing for the nominal nucleon loss, has been drawn by means of the least-squares method. The value of σ_N in the case of ^{13}N production from ^{16}O and ^{19}F clearly deviate well beyond the experimental errors. It is to be noted that no activity resulting from ^{13}N photoproduction was detected in the course of previous experiments carried out on ^{27}Al and ^{32}S [15], although yields of a nuclide such as ^{11}C were easily measured. A deviation from the expected yield for the electro-production of ^{13}N from ^{27}Al and ^{56}Fe targets has already been found by Fülmer et al.[14]. Even if in this case, owing to the large number of nucleons emitted, ^{13}N yields can hardly be ascribed to a spallation process only, they are quite small compared with those of other produced nuclides.

It was also observed that very low values of cross sections, inconsistent with the experimental trend of (γ,n) reactions in complex nuclei[1] were obtained for the $^{14}N(\gamma,n)^{13}N$ reaction[17,18]. In this case it was suggested that such unexpectedly low yields of ^{13}N could be related to the instability of its excited states against particle emission. Results of the present work strongly support this suggestion. Let us consider the threshold energy for proton emission from ^{11}C, ^{13}N, ^{15}O, ^{18}F and ^{22}Na, which are residual nuclides of the spallation reactions we have been studying and which could decay to a stable nucleus by emitting a single proton. Owing to the decrease of the Coulomb barrier with mass decreasing a Coulomb barrier value of only 1.54 MeV results for ^{13}N. Moreover, among all the above listed nuclides, the lowest proton-separation energy is achieved in the case of ^{13}N (about 1.9 MeV). As a result, an overall energy of about 3.5 MeV is the threshold energy for proton emission from a ^{13}N nucleus. Thus, from all the experimental results we are led to conclude that in the case of reactions induced by photon beams in the energy range 0.3-1.0 GeV, the probability exists of finding a large amount of nuclides still having an excitation energy of at least 3.5 MeV at the end of the spallation process. As far as ^{13}N is concerned, it is possible to de-excite via a proton-emission to the stable ^{12}C. For the other nuclides of interest, the probability of a similar event is very small, since a residual energy of at least 7.5 MeV (for ^{18}F) would be required in order to emit a single proton, and indeed no difficulties have been found in the study of these nuclides.

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TABLE I - Produced radionuclides giving annihilation quanta of 0.511 MeV and related spectrometric data ([a]).

Target Material	Target Nucleus	Nominal Nucleon Loss	Produced Nuclide	Half-Life	Number of Photons per 100 disinte - grations ([b])
LiF	^{19}F	n	^{18}F	109.7m	194
		p,3n	^{15}O	123 s	200
		2p,4n	^{13}N	9.96m	200
		3p,5n	^{11}C	20.34m	200
H_2O	^{16}O	n	^{15}O	123 s	200
		p,2n	^{13}N	9.96m	200
		2p,3n	^{11}C	20.34m	200

([a]) Radionuclides with half-lives shorter than 2 minutes have been disregarded.

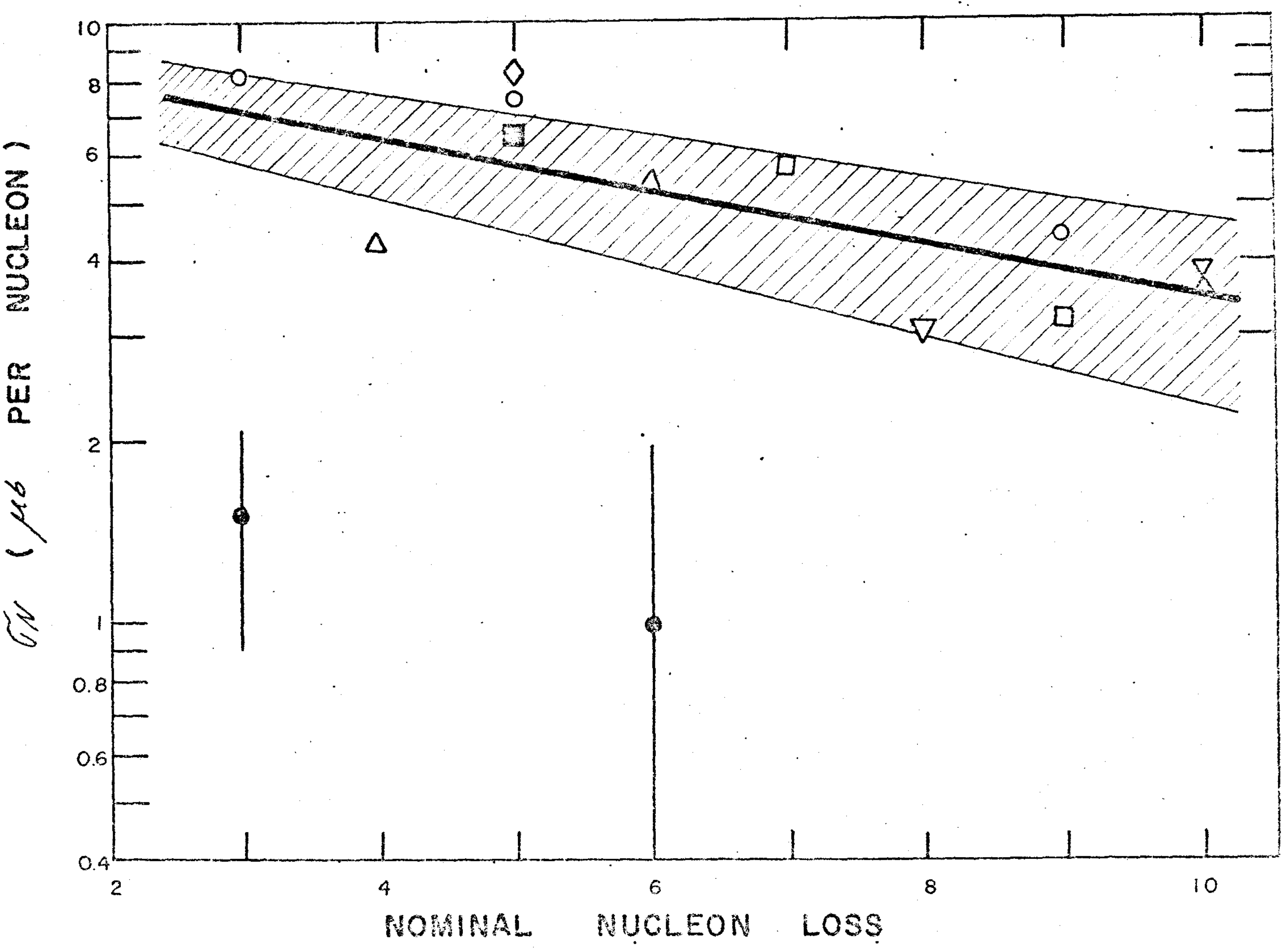
([b]) Values listed in this column are comprehensive of the branching ratios and the internal conversion factors.

TABLE II - Cross-Sections per Equivalent Quantum, σ_Q, for the reaction $^{16}O(\gamma,p2n)^{13}N$.

Bremsstrahlung Energy (GeV)	σ_Q(μb)
0.30	122 ± 10
0.35	125 ± 10
0.40	132 ± 10
0.45	132 ± 10
0.50	132 ± 10
0.55	143 ± 10
0.60	135 ± 10
0.70	145 ± 10
0.80	143 ± 10
0.85	147 ± 10
0.95	153 ± 10
1.00	151 ± 10

FIGURE CAPTION

Fig. 1 - Values of mean absolute cross section per nucleon σ_N as a function of the nominal nucleon loss (semilog plot). Open circles: ^{27}Al target, ref. 16,2,12; Open triangles: ^{28}Si target, ref. 3; Open rhomb: ^{23}Na target, ref. 2 ; Open reversed triangles: ^{32}S target, ref. 3; Open squares: ^{31}P target, ref. 3; filled square: ^{16}O target, ref. 2. The straight line is a least-squares fit of all the experimental points. The shaded area represents the standard deviation. Filled circles with error bars: present work results for ^{16}O and ^{19}F targets.



10
8
6
4
2
1
0.8
0.6
0.4
σN (μb PER NUCLEON)
2
4
6
8
10
NOMINAL NUCLEON LOSS

FIG. 1