A0014/76
MAI 1976

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(Received 23rd October, 1975)

ABSTRACT

Cross sections per equivalent quantum for $^{16}O(\gamma,4p5n)^{7}Be$ reaction have been measured in the energy range 0.3-1.0GeV. This reaction is proposed as a suitable and economic absolute monitor for intermediate-energy, high-intensity, bramsstrahlung beams.

The induced activity method for monitoring intermediate-energy bremsstrahlung beams[1,2] has been quite successfully applied in recent years. With the purpose of searching for other reactions, useful in the case of prolonged and intense exposure, we have undertaken the present work, which deals with the photoproduction of

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*This work has been supported by the Brazilian Conselho Nacional de Desenvolvimento Científico e Tecnológico and Comissão Nacional de Energia Nuclear, and by the Italian Consiglio Nazionale delle Ricerche.

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^{7}Be from ^{16}O in water targets, at energies between 0.3 and 1.0GeV. Along with our experimental results of yields of the $^{16}O(\gamma,4p5n)^{7}Be$ reaction*, we present a discussion about the properties and characteristics of such a reaction for monitoring purposes.

The experiment was performed at the Frascati 1 GeV electron-synchrotron by means of the uncollimated bremsstrahlung beam produced by electrons of different energies in a thin aluminium radiator (1.72×10^{-2}RL). The target samples, consisting of bidistilled water (about 10^{22} nuclei/cm^2 of ^{16}O) in thin-walled lucite containers of 5mm internal thickness and 5cm diameter, were positioned in air about 1.5m from the aluminium radiator, and at right angles to the beam outlet. They were irradiated at 9 end-point energies between 0.3 and 1.0 GeV and, depending on the maximum bremsstrahlung energy, the exposure times ranged between 3 and 6 hours. The time-dependent intensity fluctuations of the electron beam during each exposure were tested by means of electronic devices, and these fluctuations were found to be negligible. The dose passed through the samples, and measured by means of thin polyethylene monitors[1], was, as an average, 3×10^{11} equivalent quanta per minute at 0.3 GeV, and 1×10^{12} equivalent quanta per minute at 1 GeV.

In order to obtain the final nuclide yields, expressed as cross-sections per equivalent quantum, σ_Q, use has been made of the induced activity method. The irradiated water was quantitati-

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* Since it is not the purpose of this work to enter into a detailed discussion about the mechanism involved in such a reaction, for the sake of simplicity we shall denote henceforth the nominal nucleon loss, 4p5n, as x.

vely transferred into unirradiated containers. Absorption of the ^{7}Be hydrolysed ion into the lucite container surfaces has already been shown to be negligible[3]. The induced activities were detected by means of a conventional γ-spectrometry line with a 70 cm^3 (nominal volume) true coaxial Ge(Li) detector and a 1024 channel pulse-height analyser. The detector efficiency was experimentally checked with calibrated γ-rays sources (supplied by the New England Nuclear Corporation, Boston, Mass., USA), the effective standard deviation of which was less than 1%. According to the geometrical arrangement, corrections for non-point sources were taken into account[4].

In Table 1 are listed radionuclides produced by interaction of intermediate-energy γ-quanta with ^{16}O nuclei. Some spectrometric data[5], useful in calculating the cross-sections, are also reported.

The good energy resolution of the detector employed enabled us to discriminate between the 0.477 MeV peak of the ^{7}Be electron-capture decay and the 0.511 MeV anihilation peak arising from other nuclides photoproduced in the same target.

Fig. 1 reports cross sections per equivalent quantum, σ_Q, as a function of the bremsstrahlung maximum energy E_0 (semi log plot), for the reaction $^{16}O(\gamma,x)^{7}Be$. The experimental points have been fitted by means of the least-squares method, thus obtaining a straight line whose equation is

$$\sigma_{Q\ Be} = \left[(110 \pm 20) \log E_0 + (220 \pm 20)\right] \mu b \qquad (1)$$

with E_0 expressed in GeV. For a detailed discussion about experimental errors affecting cross section measurements, the reader referred to a previous paper[6]. Very good agreement is found between the present data at 1 GeV and a previous measurement at the same energy, as reported in ref.[7].

Dose measurement can easily be obtained (see next Section) from the above reported ^{7}Be production yield equation, provided that the amount of ^{7}Be produced in the irradiated water is carefully measured. Obviously no problem arises in this determination by using a Ge(Li) detector. In laboratory practice, however, it may be more convenient for monitoring purpose to use a less sophisticated detection technique such as a γ-spectrometer scintillator. In the latter case, the contribution from β^{+} radio-nuclides to the ^{7}Be activity must be taken into account.

As has been shown in previous experiments[8,9], within 1 hour after the end of irradiation, activities arising from ^{15}O and ^{13}N reach negligible values. Consequently, the main problem is to ascertain to what extend the ^{11}C activity interferes with our measurements. The ^{7}Be activity at the end of an irradiation at energy E_0 is given by

$$A_{o_{Be}} = \phi \left[1 - \exp(-t^{*}/\tau_{Be})\right] \varepsilon_{Be} \sigma_{Q_{Be}} \, AN/M \qquad (2)$$

where ϕ is the number of equivalent quanta per unit time, t^{*} the irradiation time, ε_{Be} the total counting efficiency for ^{7}Be (taking into account the branching ratios and the internal conversion factors), σ_Q the photoproduction cross section at the energy E_0, A the Avogadro's number, N the mass of oxigen per unit surface area, and M the molecular weight of the oxigen. An analogous expression may be written for ^{11}C activity arising from the concomitant reaction in the target:

$$A_{o_C} = \phi\left[1 - \exp(-t^*/\tau_C)\right]\varepsilon_C\sigma_{Q_C}\ NA/M \qquad (3)$$

Thus the ratio R_o of the ^{11}C activity to that of ^7Be at the end of the irradiation can be expressed as

$$R_o = \frac{\varepsilon_C}{\varepsilon_{Be}}\frac{\sigma_{Q_C}}{\sigma_{Q_{Be}}}\frac{\left[1-\exp(-t^*/\tau_C)\right]}{\left[1-\exp(-t^*/\tau_{Be})\right]} \qquad (4)$$

In a more general way, taking into account the exponential decay of both ^7Be and ^{11}C, at every time t after the end of irradiation, the ratio become:

$$R_t = R_o \exp(-2.04t) \qquad (5)$$

with t expressed in hours.

Let us now consider the case of an exposure lengthened by 3 hours at 1 GeV bremsstrahlung energy. The experimental values of the parameters in eq. (4) are found to be: $\sigma_{Q_{Be}} = 220\ \mu b$, $\sigma_{Q_C} = 330\ \mu b$[10]), $\varepsilon_C = 0.2394$ and $\varepsilon_{Be} = 0.0130$. By inserting these data in eq. (4) we obtain $R_o = 1.7 \times 10^4$, to be introduced in eq. (5).

Fig. 2 reports the trend of R_t as a function of the time t (in hours) elapsed after the end of irradiation. As one can see, if the time lapse between the end of irradiation and the counting of the sample is greater than 7 hours, the ratio reaches a negligible value, thus indicating that the detected activity may all be ascribed to ^7Be. In a similar way, the time at which activity of ^{11}C does not affect the counting may be estimated for any exposure whatever.

Knowledge of the amount of ^7Be photoproduced in the water target now enables us to monitor bremsstrahlung beams by subs tituting in eq. (2), the proper values of the parameters:

$$\phi = 2.66\times10^{7}\ A_t\ \exp(9\times10^{-6}t)/N\varepsilon\left[110\log E_0+220\right]\left[1-\exp(-9\times10^{-6}t^{*})\right] \quad (6)$$

with A_t expressed in count per minute, t and t^* in minutes, N in g/cm^2 and E_0 in GeV thus obtaining ϕ expressed in equivalent quanta per minute. If the counting of the irradiated target is carried out during the first 12 hours after termination of irradiations, we may assume $A_t \approx A_0$. By neglecting the exponential term in the numerator of eq. (6), the error is estimated to be about 1%. For irradiation lengthened up to 8 days, with constant flux, eq.(6) may be simplified by disregarding the correction for decay during the exposure. The error affecting dose measurement is, in this case, calculated to be less than 5%. With the above approximations, eq. (6) may be replaced by

$$Q = 2.39\times10^{14}\ A_t/N\varepsilon\left[110\log E_0+220\right] \quad (7)$$

which gives the number of equivalent quanta passed through the target exposed to the bremsstrahlung beam, without need of elaborate computation.

We are thus led to conclude that the reaction $^{16}O(\gamma,x)^{7}Be$ can be correctly used as a bremsstrahlung beam monitor over a large range of irradiation times (from 3 hours up to several days), even if the energy resolution of the detector employed is quite poor. Furthermore, if an approximate numerical calculation is undertaken (see eq. (7)) the resulting uncertainties are less than 10%, which is within the range of experimental error.

Although we have heretofore regarded our results from the point of view of nuclear physics research, it must not be forgotten, that knowledge about the kind and amount of different radionuclides photoproduced in water in the energy range considered, is of great importance in other research and application fields as well.

ACKNOWLEDGEMENTS

The authors wish to thank Prof. F. Salvetti for the useful discussion on this subject, and members of the Machine Group of the Laboratori Nazionali di Frascati for assistance given during irradiations.

M.L. Terranova wishes to express her appreciation of the very kind hospitality she received from the Centro Brasileiro de Pesquisas Físicas.

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TABLE 1

Produced Radionuclides and Related Spectrometric Data[a]

Nominal Nucleon Loss	Residual Nucleus	Half-Life	E_γ (MeV)	Number of Photons per 100 disintegrations[c]
n	^{15}O	123 sec	0.511	200
p,2n	^{13}N	9.96 m	0.511	200
2p,3n	^{11}C	20.3 m	0.511	200
4p,5n	^{7}Be	53.6 d	0.477	10.3

a Radionuclides having half-lives shorter than 2 min have been disregarded.

b The nucleon loss refers to ^{16}O. The composition of Oxigen (% isotopic abundance) in natural water is the following: 99.759% ^{16}O; 0.037% ^{17}O; 0.204% ^{18}O.

c Values listed in this column are comprehensive of the branching ratios and the internal conversion factors.

FIGURE CAPTIONS

Fig. 1 - Cross sections per equivalent quantum of the reaction $^{16}O(\gamma,4p5n)^{7}Be$ versus the natural logarithm of bremss trahlung energy E_o. The straight line is a least-squa res fit of the experimental points.

Fig. 2 - Ratio, R_t, of the ^{11}C activity to the ^{7}Be activity in a water target irradiated for 3 hours at 1 GeV bremss trahlung maximum energy (semilog plot) versus the ti- me elapsed after the end of irradiation. For the equa tion of the straight line see text.

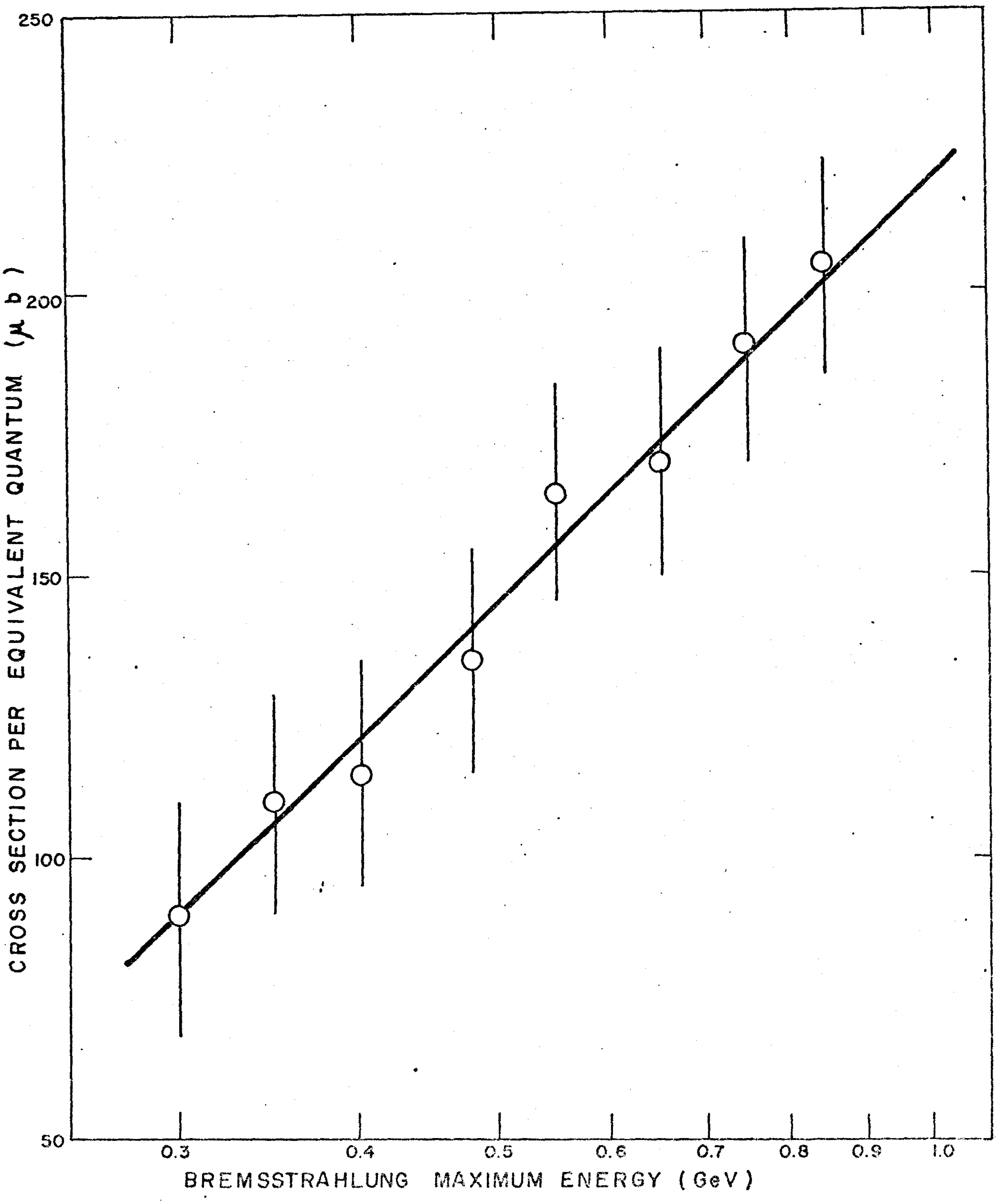
250
200
150
100
50
CROSS SECTION PER EQUIVALENT QUANTUM (μb)
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
BREMSSTRAHLUNG MAXIMUM ENERGY (GeV)

FIG. 1

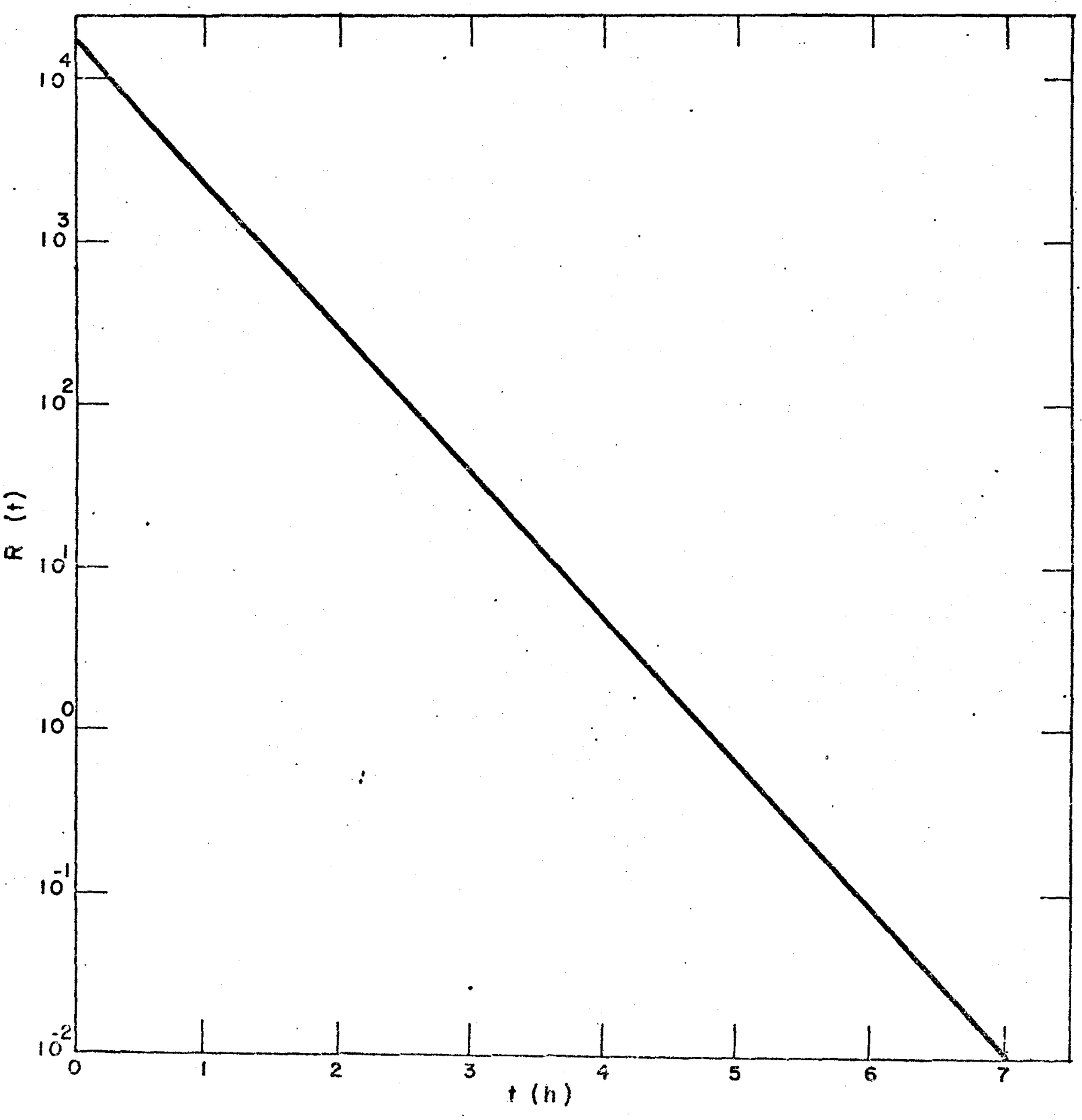

FIG. 2