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SUMMARY

The photofission yields of Bi induced by the quasi-monochromatic photon beam from in flight annihilation of positrons of the Frascati linac have been measured. The experiment has been performed at sixteen different positron energies, from 120 MeV up to 280 MeV, by collecting the annihilation photons at angles  $0.5^\circ < \theta_\gamma < 1^\circ$ . The fission fragments have been detected with glass sandwiches.

The behaviour of the photofission cross-section was deduced by means of an appropriate unfolding method.

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The photofission of heavy and medium-heavy nuclei at photon energies  $k > 100$  MeV has been extensively studied in several laboratories<sup>(1)</sup> only by bremsstrahlung photon beams, because of the lack of suitable powerful monochromatic gamma sources with variable energy.

The fission cross-sections  $f(k)$ , as deduced from the experimental yields, show some discrepancies, as reported in the literature. This may be partially ascribed to the known difficulties found in solving the Volterra linear equation:

$$G(k_{m_j}) = \int_{k_T}^{k_{m_j}} N(k, k_{m_j}) f(k) dk, \quad (1)$$

where  $N(k, k_{m_j})$  is the number of photons in the energy interval from  $k$  to  $k+dk$ ;  $k_{m_j}$  is the maximum photon energy in the  $j$ -th spectrum;  $k_T$  is the fission threshold energy. This equation is particularly "unstable", especially if the dependence of the kernel  $N(k, k_{m_j})$  on the energy<sup>(2)</sup> is very weak, as in the case of measurements made with a bremsstrahlung photon beam.

An improvement in fission measurements was obtained by some of us<sup>(3-5)</sup> by using the quasi-monochromatic photons from the Frascati electron synchrotron, obtained by coherent bremsstrahlung of 1000 MeV electrons striking a diamond single crystal. This photon beam was characterized by a "quasi-monoenergetic" main peak lying above a continuous spectrum<sup>(6)</sup>. The accurate knowledge of the photon spectra used and the application of an appropriate unfolding method to the experimental data made it possible to deduce the photofission cross-section in the 220-500 MeV photon energy range with greater reliability compared to the bremsstrahlung results of other authors. The cross-sections obtained - referring to 7 elements with  $73 \leq Z \leq 92$  - showed a clear resonance at a photon energy of  $\sim 340$  MeV. The resonant behaviour of the photofission cross-section was adequately explained<sup>(7)</sup> by assuming a photomesonic model of the process and adopting a nuclear fissility increasing with photon energy at least up to 500 MeV.

Accurate knowledge of the photofission cross-section for energies below 220 MeV can enable information to be deduced on the photon-nucleus interaction in a region where the absorptions by a correlated neutron-proton pair (quasi-deuteron model) and by a single nucleon (photomesonic model) are both relevant.

The opportunity to extend the previous photofission measurements to energies near the photomesonic threshold was provided by the LEALE quasi-monochromatic photon facility at Frascati<sup>(8)</sup>. This photon beam, obtained from in flight positron annihilation on a liquid hydrogen target, exhibits a monoenergetic peak at the correct annihilation energy, together with an unavoidable bremsstrahlung continuous tail. The peak energy can be continuously varied from 100 MeV up to 300 MeV by changing the positron energy. Moreover, it is possible to increase the annihilation/bremsstrahlung,  $N_A/N_B$ , ratio at the expense of the intensity and peak resolution, by increasing the photon collection angle,  $\theta_\gamma$ . We therefore sought a compromise between a large value of the  $N_A/N_B$  ratio and a suitable photon beam intensity, in order to get a reasonable exposure time for fission experiments. The best experimental conditions for performing photofission measurements are reported in our previous paper<sup>(9)</sup>.

In this paper we report the results of photofission measurements performed on Bi at Frascati, taking into account the suggestions given in ref. (8). The Bi fission fragment yields have been measured at 16 positron energies, ranging from 120 up to 280 MeV, with  $\Delta E_{e^+} \approx 10$  MeV steps and collecting the annihilation photons at angles  $0.5^\circ < \theta_\gamma < 1^\circ$ . The fission fragments have been detected by means of the glass sandwich technique<sup>(3)</sup>. We used a metal target of natural Bi, with a surface area of  $(50 \times 50)$  mm<sup>2</sup> and a thickness of 0.1 mm, sandwiched between two plates of glass which covered all the sample surface.

We were mainly interested in the photofission cross-section behaviour, and thus we used a thick target in order to get a sufficient number of fission events in a reasonable exposure time. However, the sandwiches were

thin enough to degrade the photon spectrum to a negligibly extent only. The photon dose was measured by a Komar, Kruglov and Lopatin quantameter<sup>(10)</sup>. An exact knowledge of the photon energy spectrum was required in order to evaluate the fission cross section with a good degree of reliability. Therefore, all the photon spectra were measured on-line with the exposure of the fissionable sample by a magnetic pair spectrometer inserted on the beam channel immediately before the target. The electronic detection apparatus and the real-time data acquisition system are described in refs. (9,11). A typical measured photon spectrum is shown in Fig. 1. The dots represent the experimental data, and the solid curve is a least-square fit. For the best fit of the spectra we used the theoretical formulae of the cross-sections, reported in ref. (12). The experimental effects such as energy spread of the incident positrons and finiteness of the photon collection solid angle are also taken into account.

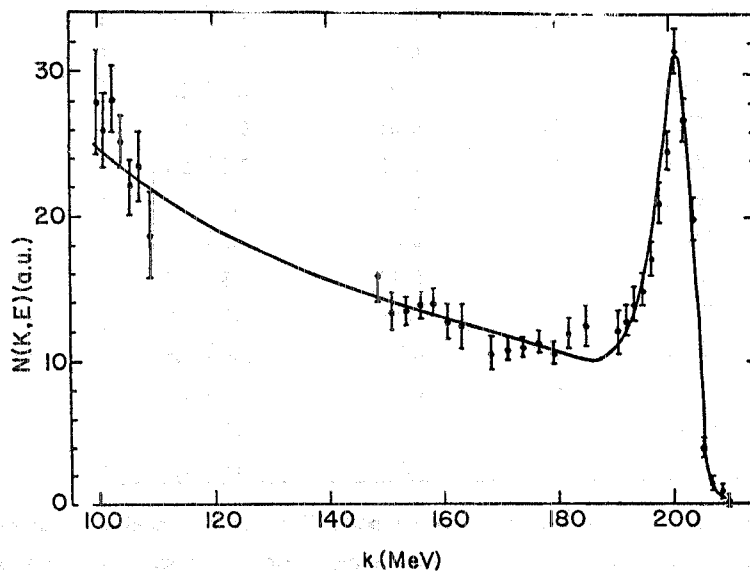


FIG. 1 Photon energy spectrum measured with a pair-spectrometer at positron energy  $E=200$  MeV and photon collection angle  $\langle \theta_{\gamma} \rangle = 0.65^\circ$ . The continuous curve represents a least-square fit.

The collimated photon beam struck the glass sandwiches at right angles and had a cross sectional diameters of  $\sim 4$  cm. After the exposure, the glass plates were submitted to the usual chemical etching and optical-microscope scanning procedure<sup>(4)</sup>. In order to test the center and the actual cross-sectional area of the photon beam on the glass plates, we periodically irradiated some glass sandwiches with a metal target of natural Uranium. By scanning the entire surface of these plates we observed that the fission events had a distribution which could be approximated by a two-dimensional Gaussian distribution, centred on the photon beam axis, and reproducing the space distribution of the photons. The results were in good agreement with the data deduced by a multiwire chamber profile monitor<sup>(13)</sup>.

For all the glass plates we scanned two rectangular strips with a surface area of  $(50 \times 15) \text{ mm}^2$  at right angles to each other and centred with respect to the photon beam. We also scanned the surface of the plates not in contact with the target and we estimated the background contribution due to spurious events in the glass plates.

The cross-section per equivalent quantum were obtained by counting the number of fission tracks in the scanned surface and measuring the exposure dose with the quantameter. The values obtained are given in Table I

TABLE I - Experimental yields  $g(k_A)$  of Bi as a function of the energy  $k_A$  of the annihilation photon peak.  $\Delta k/k_A$  is the peak resolution (FWHM).  $\langle \theta_\gamma \rangle$  represents the actual photon collection angle.

$k_A$ (MeV)	$\Delta k/k_A$ (%)	$\langle \theta_\gamma \rangle$ (°)	$g(k_A)$ (a.u.)
121.7	2.5	0.63	$1.6 \pm 0.1$
130.2	2.4	0.51	$3.2 \pm 0.3$
139.6	4.3	0.92	$3.8 \pm 0.4$
149.8	3.5	0.78	$4.5 \pm 0.5$
160.3	5.0	0.89	$7.1 \pm 1.0$
170.4	5.0	0.96	$10.8 \pm 0.7$
182.1	3.3	0.68	$10.1 \pm 0.5$
188.6	4.1	0.73	$13.0 \pm 1.6$
199.5	6.1	0.91	$17.2 \pm 1.7$
201.8	3.3	0.65	$16.6 \pm 1.0$
209.1	5.9	0.88	$17.8 \pm 1.7$
231.7	6.0	0.89	$21.7 \pm 1.9$
237.8	5.2	0.79	$23.6 \pm 1.9$
246.3	6.7	0.87	$26.2 \pm 2.2$
264.5	6.5	0.81	$34.3 \pm 1.4$
275.6	7.1	0.81	$33.9 \pm 2.2$

as a function of the energy  $k_A$  of the annihilation photon peak. The experimental error takes statistical errors into account as well as the accidental errors due to the scanning method and was evaluated in the same way as in previous experiments<sup>(4)</sup>. The Table also gives the annihilation peak resolution (FWHM) and the photon collection angle  $\theta$ .

In order to solve eq. (1), we assumed  $k_{m_1}$  to be equal to the incident positron energy and we used the unfolding method described in ref. (4). In the present measurements, we assumed that the contribution of the trial solution was exactly equal to zero in eq. (10) of ref. (4). With this additional condition the method is similar to the numerical one proposed by Cook<sup>(14)</sup>, with an improved accuracy in the representation of the  $f(k)$  solution, which now is approximated by a natural spline function, instead of a step-wise function, as in ref. (14). To date we have evaluated the fission cross-section for 10 photon energies, at intervals of 20 MeV, in the 100 to 280 MeV range. We assumed the photofission cross-section of Bi to be negligible below 80 MeV. The  $f_1$  values obtained and the continuous solution calculated by means of natural spline functions (solid curve) are reported in Fig. 2. The errors were calculated by the usual propagation rule and they account for both the experimental errors in the yields and the auxiliary conditions imposed upon the solution. Fig. 2 also reports the cross-section values measured in the previous experiment using coherent bremsstrahlung. The results of both measurements are in good agreement within the experimental errors: nevertheless the  $f(k)$  behaviour now obtained with more detail clearly shows a change of slope at photon energies  $k > 140$  MeV.

This fact seems to indicate that in the photofission reaction at these energies the photo-mesonic mechanism is dominant.

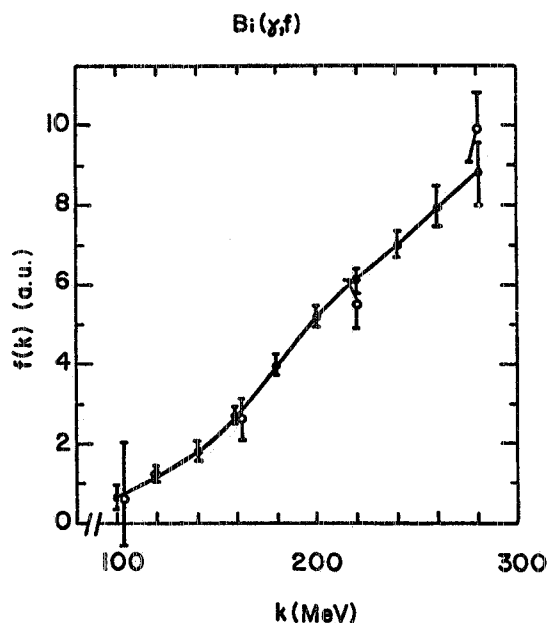


FIG. 2 Photofission cross-section of Bi versus the photon energy  $k$ . Parameters of the estimated solution:  $\gamma = 3 \cdot 10^{-2}$  (smoothing parameter),  $\chi^2 = 15.4$ .

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