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Integrated Cross Sections for ^{209}Bi$(\gamma,xnyp)$ Reactions

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Integrated cross sections for the photoproduction of $^{200-206}$Bi and $^{200-204}$Pb from ^{209}Bi have been measured. A single sample was activated during a 10-minute 137-MeV bremsstrahlung bombardment by the NBS Linac, and γ rays from the daughter products was measured with a Ge(Li) spectrometer over a two-month period to obtain relative yields. The yield data were used along with the established $(\gamma,2n)$ integrated cross section and a calculated thick-target bremsstrahlung spectrum to derive integrated cross sections as follows: ^{206}Bi (168±25), ^{205}Bi (88±22), ^{204}Bi (55±16), ^{203}Bi (66±23), ^{202}Bi (31±12), ^{201}Bi (10.7±5.9), ^{200}Bi (5.7±3.4), ^{204}Pb (8.0±2.4), ^{203}Pb (3.8±1.3), ^{202}Pb (3.4±1.3), ^{201}Pb (15.3±8.4), and ^{200}Pb (1.62±.97) MeV mb. Evidence is also presented for an 11.5-h isomeric state in ^{200}Pb.

THE experiments which have measured photospallation are numerous but in most cases the end result of such work has been relative yield data. In a few cases integrated $(\gamma,3n)$ cross sections have been measured[1–3] and in one case some information has been gleaned about the $(\gamma,4n)$ and $(\gamma,5n)$ cross sections for Tl.[4] A few other isolated spallation cross sections have been measured.

In this report integrated cross sections for bismuth for the complete system of processes $(\gamma,3n)$ to $(\gamma,9n)$ and $(\gamma,5np)$ to $(\gamma,8np)$ are presented. Two recent developments have made this type of systematic study possible. The first is the production of very intense bremsstrahlung beams at 137 MeV by the NBS Linac[5] and the second is the development of high-resolution Ge(Li) γ-ray spectrometers[6] with the associated data-handling system.[7] With this equipment it has been possible to produce and measure in one ^{209}Bi sample daughter products with half-lives between 30 minutes and 30 years. The relative yield in atoms for each nuclide was determined by γ rays measured over a two-month period. For each nuclide at least one and in some cases as many as twenty γ rays could be followed to establish a decay curve.[7] Relying on published values for transitions per disintegration, half-lives[8]; and using measured efficiency data[7] the counts per minute at time zero were converted to the relative yield data of Fig. 1 and Table I. The uncertainty in these results can best be evaluated from the scatter of points, each representing yield deduced from one γ ray, plotted on Fig. 1. These lead to an uncertainty of up to 30%. A portion of the scatter may be attributed to uncertainties in the published transitions per disintegration and the electron conversion coefficients used in calculating the disintegrations per measured γ ray. These will tend to cancel each other in those cases where several γ rays are measured.

From these data it was possible to calculate relative integrated cross sections by the use of a calculated thick target bremsstrahlung spectrum. For this rough calculation several approximations were used. First, the total cross section for each interaction was assumed to fall at one peak energy. Second, the peak energy selected was assumed to increase in regular steps of 7.4 MeV from the published (γ,n) cross section peak.[9] The step size used was equivalent to an average binding energy taken from values calculated for the (γ,n), $(\gamma,2n)$, $(\gamma,3n)$, and $(\gamma,4n)$ threshold values.[10] These assumptions are quite plausible in the light of the cross sections, differential in energy, measured for the nearby thallium nuclides.[4] To the extent that high-energy tails on the cross sections exist for production of the nuclides measured, the integrated cross sections given here for large numbers of nucleons emitted are underestimates of the true value. The integrated (γ,n) and $(\gamma,2n)$ cross sections of Fig. 1 were taken from the data of Harvey *et al.*[9] The calculated ratio of these integrated cross

TABLE I. Integrated cross sections and mean yield for production of $^{200-206}$Bi and $^{200-204}$Pb.

Process	Nuclide produced	Mean yield	$\int\sigma\,dE$ MeV-mb
(γ,n)	^{208}Bi	...	2170
$(\gamma,2n)$	^{207}Bi	2.08×10^{11}	760 ±38
$(\gamma,3n)$	^{206}Bi	3.09×10^{10}	168 ±25
$(\gamma,4n)$	^{205}Bi	1.19×10^{10}	88 ±22
$(\gamma,5n)$	^{204}Bi	5.63×10^{10}	55 ±16
$(\gamma,6n)$	^{203}Bi	5.43×10^{9}	66 ±23
$(\gamma,7n)$	^{202}Bi	2.10×10^{9}	31 ±12
$(\gamma,8n)$	^{201}Bi	6.01×10^{8}	10.7 ± 5.9
$(\gamma,9n)$	^{200}Bi	2.76×10^{8}	5.7 ± 3.4
$(\gamma,4np)$	^{204}Pb	8.25×10^{8}	8.0 ± 2.4
$(\gamma,5np)$	^{203}Pb	3.12×10^{8}	3.8 ± 1.3
$(\gamma,6np)$	^{202}Pb	2.28×10^{8}	3.4 ± 1.3
$(\gamma,7np)$	^{201}Pb	8.57×10^{8}	15.3 ± 8.4
$(\gamma,8np)$	^{200}Pb	7.8×10^{7}	1.62± 0.97

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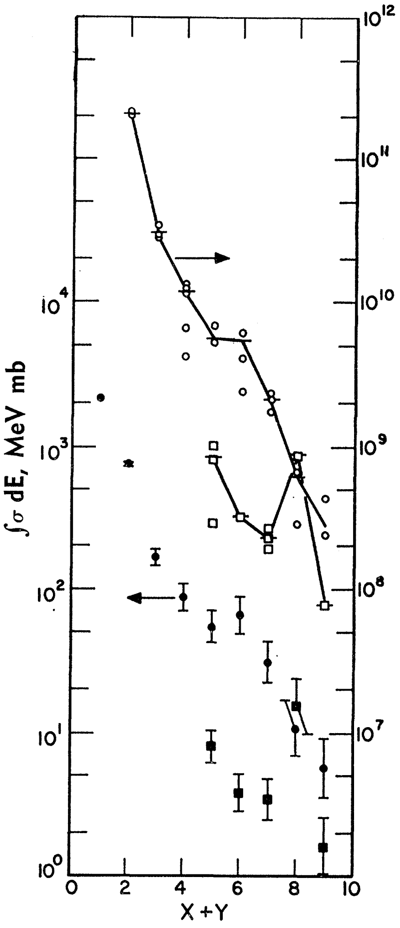

FIG. 1. The plotted points in the upper portion of this graph represent the relative yield in atoms of each nuclide plotted against the sum of the neutrons x and protons y emitted. Circles are for bismuth and squares for lead nuclides with $y=1$. The points in the lower portion of the graph are cross sections integrated to 137-MeV photon energy. Uncertainties indicated are deduced from the scatter of the yield points and thick target bremsstrahlung shape uncertainty.

sections[11] also fits their data. The relative cross sections of our experiment were normalized to the $(\gamma,2n)$ value of 760 MeV mb and may be corrected when better integrated $(\gamma,2n)$ cross section values are determined. The integrated cross sections for the production of $^{200-206}$Bi and $^{200-204}$Pb given in Fig. 2 and Table I were obtained in this fashion. The thick-target bremsstrahlung shape calculation is estimated to have introduced an additional systematic uncertainty not exceeding 30% in the calculated cross sections.

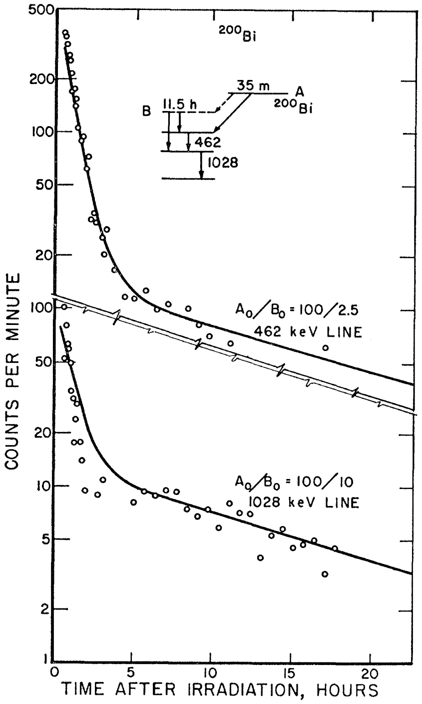

FIG. 2. Decay curves for the 462- and 1028-keV γ-rays from ^{200}Bi. Note the divided counts per minute ordinate. These data have been corrected for analyzer deadtime. The shapes of the solid curves were calculated for a combination of 35-min and 11.5-h isomers with initial decay rates of A_0 and B_0.

The decay curves for the two γ rays from ^{200}Bi shown in Fig. 2 indicate the presence of not only the 35-minute half-life component expected but also a longer half-life component. This is tentatively ascribed to a new isomeric state of ^{200}Pb having a half-life of about 11.5 hours.

The yield of ^{204}Pb was evaluated by measuring the decay of the 67-minute isomer. The initial population of the 1.4×10^{17}-year isomer could not be measured. Walters and Hummel[12] have shown that longer life isomers such as this can account for from 20 to 50% of the initial production so the value listed in Table I and plotted in Fig. 1 must be considered to be a lower limit in this case.

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