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Excitation Functions for (α, n), (α, $2n$), and (α, $3n$) Reactions on Indium*

GEORGES M. TEMMER**
Department of Physics, University of California, Berkeley, California

WHEN In^{115}, whose isotopic abundance is 95.5 percent, is bombarded with α-particles, the capture process followed by the emission of one, two, or three neutrons leads to antimony isotopes of mass numbers 118, 117, and 116, respectively. Activities in the first two mentioned Sb isotopes have been reported by Coleman and Pool,[1] who obtained them by an (α, n) reaction on indium and deuteron bombardment of tin. Because of the ten stable tin isotopes, the isotopic assignment could only be made tentatively.

The α-particles of the Berkeley 60-inch cyclotron (37 Mev) produce sufficient excitation in the compound nucleus to permit the evaporation of one, two, and three neutrons. Hence, activities in the (α, n), (α, $2n$), and (α, $3n$) products were found and identified chemically as antimony, and by Calutron analysis as being mass numbers 116, 117, and 118. The periods found for Sb^{118} and Sb^{117} (5.1 hours and 2.8 hours) agree with those reported by Coleman and Pool. Sb^{116} decays with a 60-minute half-life. Reactions on In^{113} were not detected because of its low abundance.

These three periods are too close together to permit their satisfactory resolution from composite decay curves for the establishment of excitation curves. In order to separate the periods more effectively, use was made of a magnetic lens β-ray spectrometer of the Siegbahn type[2] constructed by Mr. R. W. Hayward. The momentum spectra of β-rays emitted by indium foils activated by 36-Mev and 22-Mev α-particles were scanned in an effort to locate salient features of the radiations of the three Sb isotopes (Fig. 1). The peak in the solid curve decay with the 2.8-hour period belonging to Sb^{117} and is produced by the conversion of a 156-kev γ-ray in the K-shell of Sn. The conversion peak

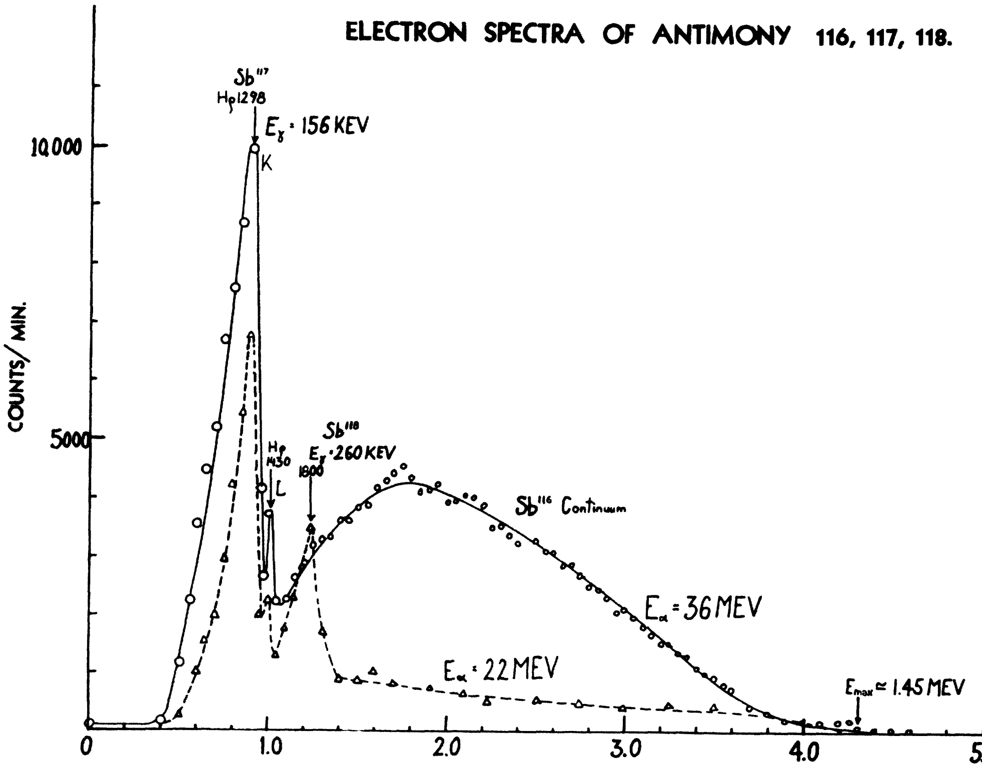

FIG. 1. β-spectra of α-induced Sb activities. Abscissa is proportional to momentum, ordinate is in arbitrary units of activity. Solid curve is for 36-Mev alphas, dashed curve for 22-Mev alphas.

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[1] K. D. Coleman and M. L. Pool, Phys. Rev. **72**, 1070 (1947).

[2] J. K. Siegbahn, Phil. Mag. **37**, 162 (1946).

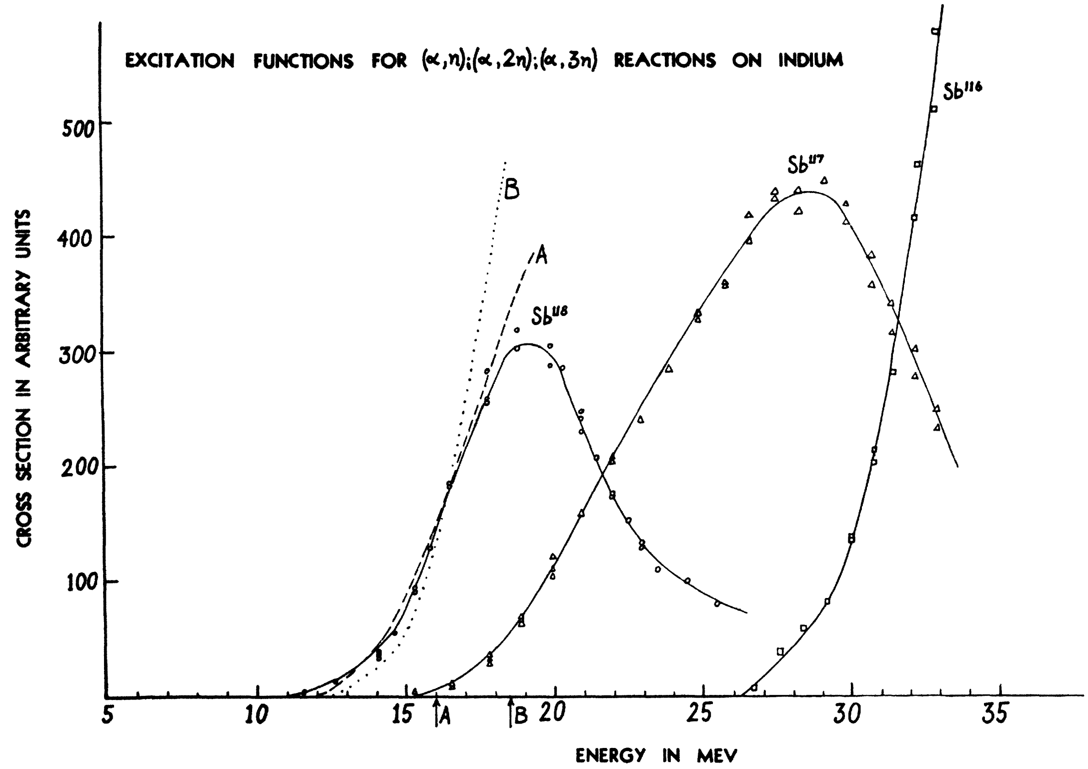

FIG. 2. Excitation curves for α-particle reactions on indium. The cross sections in arbitrary units (also arbitrary in relation to each other) are plotted against the α-particle energy in Mev. Circles indicate $In^{115}(\alpha, n)Sb^{118}$, triangles indicate $In^{115}(\alpha, 2n)Sb^{117}$, squares indicate the Coulomb barrier heights for $r_0=1.5$ and $r_0=1.3(R=r_0A^{\frac{1}{3}}\times 10^{-13}$ cm), and curves A and B are the corresponding theoretical capture cross sections.

of $H\rho=1800$ in the dashed curve corresponds to a 260-kev γ-ray decaying with the half-life of Sb^{118}. Sb^{116} was identified with the positron continuum with an upper energy limit of about 1.45 Mev. By means of an electron-positron discriminator (helical baffle), it was found that no continuous β^--spectrum is present, as is to be expected for neutron-deficient isotopes. Hence, the two other isotopes (Sb^{118} and Sb^{117}) must decay primarily by K-capture.

To obtain the excitation functions, the stacked-foil technique was used, bombarding foils of indium evaporated to a thickness of about 5 mg/cm² upon quarter-mil foil. This was necessitated by the low melting point of metallic indium (155°C). In this way, steps of about 1 Mev in α-particle energy were obtained. Ten foils at a time were mounted in the spectrometer with a special wheel assembly permitting any one of the foils to be rotated internally to the source position, while at the same time shielding all others behind a Pb baffle. This device proved to be essential for the performance of the experiment because of the short periods involved.

A magnetic field in the spectrometer corresponding to 1-Mev electrons was selected to follow the positron activity. The procedure used to obtain the excitation curves was to set the field on the conversion peaks (or point of the continuum) and then to sweep through the ten foils, thus getting counting rates proportional to the cross sections at the various foil energies. The usual procedure would have been to follow the decay of these points in time and to extrapolate back to time zero. This, however, would have entailed greater uncertainties due to lack of reproducibility of current settings, and was unnecessary because of the almost pure decay of the points selected on the spectrum. In this manner the curves shown in Fig. 2 were obtained. They were compounded from several overlapping bombardments, as well as from data from the same run taken at various times, and normalized. The alpha-particle energy was obtained from semi-empirical range-energy curves for α-particles in aluminum and silver which is close enough to indium for the purpose ($Z=47$ *vs.* $Z=49$). The vertical scales of the three excitation curves bear no relation to each other since decay schemes and conversion coefficients are not known.

The energy values are uncertain because of the inherent spread of about 1 Mev of the uncollimated cyclotron beam (uncollimated because of need for high intensity). An additional uncertainty is introduced by non-uniformity of the foils and straggling, estimated at 0.5 Mev.

The errors along the ordinate are mostly due to slight variations in magnet current from the peak positions, as well as variations in geometry for the various foils at the source, accounting for about 5 percent, plus counting statistics, usually below 5 percent. The overall error is thus about 10 percent, which is borne out by the spread of the experimental points from various runs.

Results of a possible (α, p) reaction could not be observed since the product tin isotope is stable. At any rate, for an atomic number $Z=50$ and near the threshold it is reasonable to expect that the contribution of protons will be quite small compared to that of neutrons because of the Coulomb barrier penetration factor. The rising portion of the (α, n) cross section should thus be mainly governed by the behavior of the capture cross section for the bombarding α-particles, which in turn is mainly determined by the penetration factor as long as the excitation of the compound nucleus lies above about 10 Mev and the levels overlap. The curves labeled A and B are theoretical values of the capture cross section as calculated by Weisskopf.[3] A nuclear radius

$$R=r_0A^{\frac{1}{3}}\times 10^{-13}\text{ cm}$$

was used, with $r_0=1.5$ leading to Coulomb barrier A at 16 Mev and curve A, while $r_0=1.3$ leads to barrier B at 18.5 Mev and curve B (Fig. 2). While one cannot select one or the other of these curves on the basis of this experiment, their general behavior is in general agreement with theory over the portion of the (α, n) curve up to the point of inflection at about 16 Mev where the competition of the $(\alpha, 2n)$ process sets in. Because of the unknown ratio of these two processes, it is not possible to add the two contributions constituting the modes of decay of the compound nucleus. The $(\alpha, 2n)$ mode is brought down in turn by the $(\alpha, 3n)$ process, beginning at about 26 Mev and still rising at the highest energy investigated.

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[3] V. F. Weisskopf, MDDC 1175, p. 105 (Los Alamos Notes).