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K-shell ionization of heavy atoms produced in (α,xn) nuclear reactions

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K-shell ionization cross sections are measured for Dy atoms produced in (α,xn) reactions induced by α particles in the energy range of 47–130 MeV on several separated Gd isotopes. The ratios of these cross sections to those of the corresponding (α,xn) nuclear reactions are found to be practically independent of the α-particle bombarding energy and to vary strongly from one final nucleus to another. A recently proposed general relationship between the nuclear reaction and K-x-ray production must be considered only a crude order-of-magnitude estimate.

The recent progress in acceleration of heavy ions and developments in the in-beam spectrometric techniques have brought about an increased interest in the inner-shell ionization phenomena accompanying collisions of energetic nuclear projectiles with heavy target atoms. The primary technique used to study these phenomena is measuring the characteristic x-ray spectra following the ionization. At bombarding energies appropriate for nuclear fusion reactions with subsequent neutron evaporation (e.g., in the α and heavy-ion induced reactions), these x-ray spectra correspond in general to the Z_t and Z_t+Z_{proj} elements if Z_t and Z_{proj} are the atomic numbers of the target and the bombarding ion, respectively. If Z_{proj} is sufficiently large, x-rays from the projectile may also be observed. The target atoms are ionized mainly by the impact, at least for not-too-heavy projectiles at sufficiently high energies. The atoms of the nuclear reaction products are left with ionized inner shells mainly as a result of internal conversion of γ rays deexciting the residual nuclei. In the following, we shall restrict the discussion to light projectiles for which the Z_{proj} x-rays are not observed.

An investigation of the K x-rays of elements Z_t and Z_t+2 following the bombardment of high and medium Z elements with α particles has recently been reported by Deconninck and Longrée.[1] The cross sections for K-shell ionization of the (α, xn) reaction product atoms, σ_{Z+2}^{K}, have been found to be of similar order of magnitude as those of the (α, xn) nuclear reactions themselves. In one particular case, namely, that of ^{165}Ho+ 50 MeV α particles, the authors have carried out an analysis of the discrete γ-ray spectrum corresponding to the $^{165}\text{Ho}(\alpha,4n)\,^{165}\text{Tm}$ reaction which is the main exit channel at this energy. By assigning a proper multipolarity to each of the γ transitions and with the use of experimental or theoretical K-shell internal conversion coefficients they could sum the expected contributions to the K-shell ionization per one $(\alpha, 4n)$ reaction. They obtained the value $\sigma_{Z+2}^{K}(\alpha,4n;\text{ derived}) = 1.98$ b. Next, they assumed that the ratio of this cross section to that of the $(\alpha, 4n)$ reaction is similar also for other (α, xn) reactions with the same target. The reaction cross-section weighted result for the total ionization cross section was $\sigma_{Z+2}^{K\,\text{tot}}(\alpha, xn;\text{derived}) = 3.69$ b to be compared with the measured value of 3.38 b. The authors considered the agreement between these two values as justifying their adopted procedure and proposed a general relationship between the nuclear reaction and the K-x-ray production cross sections for residual nuclei of similar structures.

The subject of this comment is to present experimental data which complement the analysis of Deconninck and Longrée and show the limits of applicability of their generalized relationship for the σ_{Z+2}^{K} ionization cross sections. Moreover, it is shown that haphazard fluctuations in these cross sections may easily occur even for adjacent final nuclei. In particular, a large even-odd staggering of the σ_{Z+2}^{K} value as a function of the neutron number of an even Z element seems to be characteristic of the deformed residual nuclei. This assessment is based on a large body of data on the ionization of the $Z_t+2=66$ (Dy) atoms produced in ^{154,155,158,160}Gd targets bombarded with α particles in the energy range 47–130 MeV. The data have been accumulated as a by-product in the course of a systematic study[2] of nuclear cross sections for α-induced reactions. These cross sections have been measured by in-beam γ-ray spectrometric techniques, with normalization to the yields of the x-rays characteristic of the target atoms and with the use of the corresponding ionization cross sections $\sigma_{Z_t}^{K}$ taken from literature. The K x rays were measured with a high-resolution hyperpure Ge detector. The x rays of Dy were well resolved from those of Gd and were observed in all the cases studied. Details of this work will be the subject of a forthcoming publication.[3]

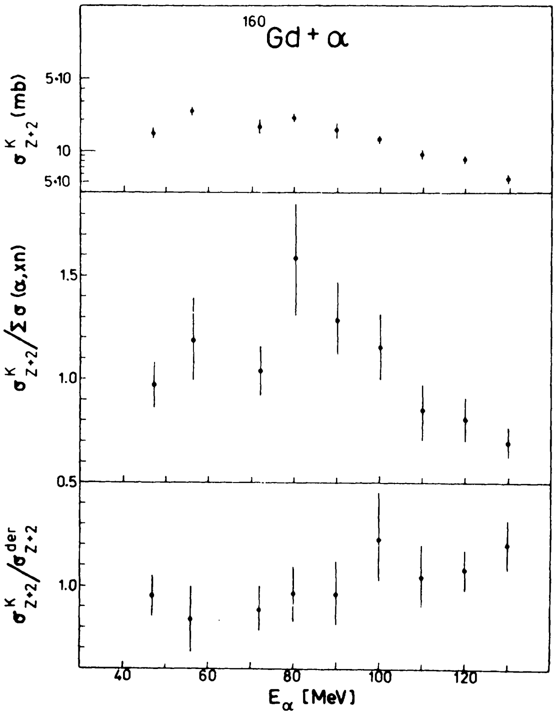

FIG. 1. Measured ionization cross sections for Dy atoms produced in (α,xn) reactions, average numbers of ionizations per nuclear reaction, and ratios of measured and derived ionization cross sections as functions of α-particle bombarding energy for ^{160}Gd target.

Figure 1 shows the measured σ^K_{Z+2} values as a function of bombarding energy for the ^{160}Gd target and the ratios of these values to the summed (α, xn) cross sections determined in the same experiment for each bombarding energy, $\sigma^K_{Z+2}/\sum_x \sigma(\alpha,xn)$. The corresponding ratios of the measured and "derived" ionization cross sections are given at the bottom of Fig. 1. The "derived" values are those obtained as a sum $\sum_i \sigma_{\gamma_i}\alpha^i_K$ of products of cross sections of all the Dy γ rays observed, σ_{γ_i}, and their corresponding K-shell internal conversion coefficients α^i_K. The $\sigma^K_{Z+2}/\sigma^K_{Z+2}$ (derived) ratios have values very close to unity which gives confidence to our analysis of the γ-ray spectra and signifies that very few relevant γ transitions have been omitted. Similar results have been obtained for other Gd targets. In view of this, we can proceed to analyze the partial ionization cross-section values, derived separately for each (α, xn) reaction channel at every bombarding energy and for every target.

It is found that the ratios of the σ^K_{Z+2} $(\alpha, xn;$ derived) values to their corresponding nuclear reaction cross sections are remarkably constant over the whole range of the α-particle energy and are characteristic for the final nuclei. Figure 2 shows

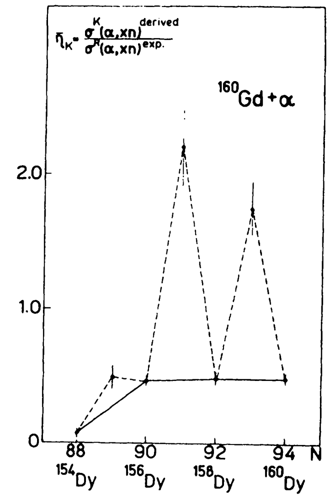

FIG. 2. Partial numbers of ionization per nuclear reaction, characteristic for a given final isotope as a function of the neutron number for Dy isotopes. The entries are obtained as averages for several bombarding energies (see text).

the average values of these ratios as a function of the neutron number of the final Dy nuclei. The values vary quite smoothly for even nuclei, with a sharp increase at the transition from $N = 88$ to $N = 90$. This apparently is a manifestation of a sudden decrease of the energy spacing between collective excited states at the onset of nuclear deformation (and hence enhancement of the internal conversion leading to ionization). The odd-A final nuclei, however, are characterized by the ionization-per-reaction yields being several times higher than those for the adjacent even nuclei and showing much larger straggling from one nucleus to another.

The even-odd difference and the straggling among the values for odd-A nuclei are not surprising in view of the fact that in most cases the dominating contributions to the ionization are due to only a few low-energy γ transitions. Two other reasons for the even-odd difference and the straggling are the following. (i) The level spacing in odd-A nuclei is generally much smaller than in the even ones, making the low-energy transitions more probable. (ii) There is no obvious regularity for odd-A nuclei in the spacing between band heads of various collective bands populated in the reactions. The odd-odd nuclei are likely to show even larger fluctuations.

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[1]G. Deconninck and M. Longrée, Phys. Rev. A 16, 1390 (1977).
[2]D. Chmielewska, Z. Sujkowski, J. F. W. Jansen, W. J. Ockels, and M. J. A. de Voigt, Nukleonika 23, 333 (1978) and unpublished.
[3]D. Chmielewska, Z. Sujkowski, J. F. W. Jansen, W. J. Ockels and M. J. A. de Voigt, presented at the XIth Masurian Summer School, Mikolajki, Poland, 1978; Nucleonika 24, 395 (1979).