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## K X-RAY MULTIPLICITIES FOR RARE EARTH ATOMS PRODUCED IN (H.I., xn) NUCLEAR REACTIONS

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K X-ray multiplicities are determined for a number of nuclear reaction products in the rare earth region. It is shown that if certain conditions are fulfilled the values of these multiplicities can be considered as characteristic for the reaction residues independently of the reaction used. They can thus be used for the quantitative determination of cross sections.

Heavy evaporation residues produced in H.I. induced reactions are ionized with high probability in the inner electron shells. The main contributing effect is the internal conversion of the  $\gamma$ -rays deexciting the reaction residues [1]. The high average angular momentum of the residues results in  $\gamma$ -ray multiplicities of typically 10 to 30 per cascade. The life-time of a K shell vacancy is much shorter than those of the nuclear states involved. A cascade of the converted  $\gamma$ -rays may therefore result in an X-ray multiplicity per reaction,  $M_K$ , well in excess of one. Since the internal conversion probability decreases rapidly with the transition energy (roughly  $\sim E_\gamma^{-3}$ ) and since it varies appreciably with multipolarity, the  $M_K$  values can in general be expected to depend strongly both on the nuclear structure and on the population pattern of the excited states of the residue. They thus depend both on the properties of the final nucleus and of the reaction used.

There exists, however, a class of nuclei for which the  $M_K$  values are practically independent of the angular momentum input,  $l$  and of the initial excitation energy. The nuclei in question are those that are well deformed and have no high spin isomers. The independence of  $M_K$  on  $l$  for such nuclei is a simple result [2, 3] of the monotonic increase of the level spacings of the yrast states with spin and of the property of the  $\gamma$ -ray flow in residual nuclei to concentrate along the

yrast line. As a consequence, the main contribution to the ionization in deformed nuclei is due to transitions between yrast or near-yrast states of rather low spin, whose population only weakly depends on the reaction. A possible contribution from the quasicontinuum  $\gamma$ -transitions deexciting medium-high spin states ( $l \leq 40 \hbar$ ) is expected [4] to be small.

There are a number of applications where a knowledge of the K X-ray multiplicities is important. In ref. [5], the total cross sections for ( ${}^6, {}^7\text{Li}$ , xn) reactions on nuclei in the lead region were deduced from the observed K X-ray yields. The effective multiplicity values,  $\bar{M}_K$ , were determined from the measured X-ray-X-ray coincidence to X-ray singles counting rates. The measurement of particle-X-ray coincidences has proved to be of particular value for the investigation of incomplete fusion reactions [6], where the identification of the nuclear charge of the reaction residues is essential. In this case, however, the requirements on the statistical accuracy needed for determining the  $\bar{M}_K$  values from the triple particle-X-ray-X-ray coincidence counting rates impose rather severe restrictions on the use of this method for a quantitative determination of the cross sections.

The purpose of the present letter is to report on the first results of a systematic study initiated in order to obtain a comprehensive set of X-ray multiplicity values for as large as possible a number of residual nuclei in the rare earth region. The technique used is essentially the same as that of refs. [2,3] and consists in compar-

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ing the X-ray and  $\gamma$ -ray yields from targets of high  $Z$  bombarded with  $\alpha$ - and medium-heavy ions. Special attention is devoted to specifying the conditions under which the measured values could be considered as reaction independent quantities.

The measured K X-ray multiplicity,  $\bar{M}_K$ , is a weighted average of the multiplicities,  $M_K(x)$ , corresponding to the various isotopes produced. For an ensemble of residues with atomic number  $Z_r = Z_t + Z_p$  we can write

$$\bar{M}_K = \frac{\sum_x \sigma(xn) M_K(x)}{\sum_x \sigma(xn)} = \frac{\sigma_K(Z_r) \omega_K(Z_r)}{\sum_x \sigma(xn)}, \quad (1)$$

where  $\sigma_K(Z)$  is the K shell ionization cross section,  $\omega_K(Z)$  is the fluorescence yield and the subscripts  $r$ ,  $t$ ,  $p$  refer to the residue, target and projectile, respectively. The  $\sigma_K(Z_r)$  value is directly proportional to the observed K X-ray yield. The nuclear cross sections,  $\sigma(xn)$ , can be obtained from the yields of the characteristic  $\gamma$ -rays measured simultaneously.

About 20 metallic, self-supporting targets 1–2 mg/cm<sup>2</sup> thick were bombarded with  $\alpha$ , <sup>12</sup>C and <sup>14</sup>N beams of several energies. Singles X-ray (cf. fig. 1) and  $\gamma$ -ray spectra were recorded with a thin hyperpure Ge X-ray detector (FWHM  $\sim 0.5$  keV in the X-ray region) and with a 10%  $\gamma$ -X Ge-detector placed at 55° and 125° with respect to the beam direction, correspondingly. The target-detector distances were kept rather large (15–25 cm) in order to avoid corrections for the coincidence summing [7].

Deduction of reaction cross sections from the characteristic  $\gamma$ -ray spectra is straightforward only in the case of the even–even residual nuclei, for which the cross section for the  $2^+ \rightarrow 0^+$  ground state transition is a good measure of the respective  $\sigma(xn)$  value. Reliable recipes for obtaining the  $\sigma(xn)$  values for odd- $A$  and odd–odd final nuclei are more difficult or impossible to construct, respectively, mainly because of the lack of the relevant spectroscopic information. We have therefore resorted to indirect ways of obtaining the denominator in formula (1), or a fraction thereof, whenever the published data on a given product did not warrant a reliable recipe. In particular, use was made of the set of measured [8] cross section values for the  $(\alpha, xn)$  reactions on several Gd targets in the  $\alpha$ -energy range 47–130 MeV. Corrections for relative changes of these cross sections with  $Z$ ,  $A$  and  $Q$ -values of the targets were calculated with the evaporation code PACE

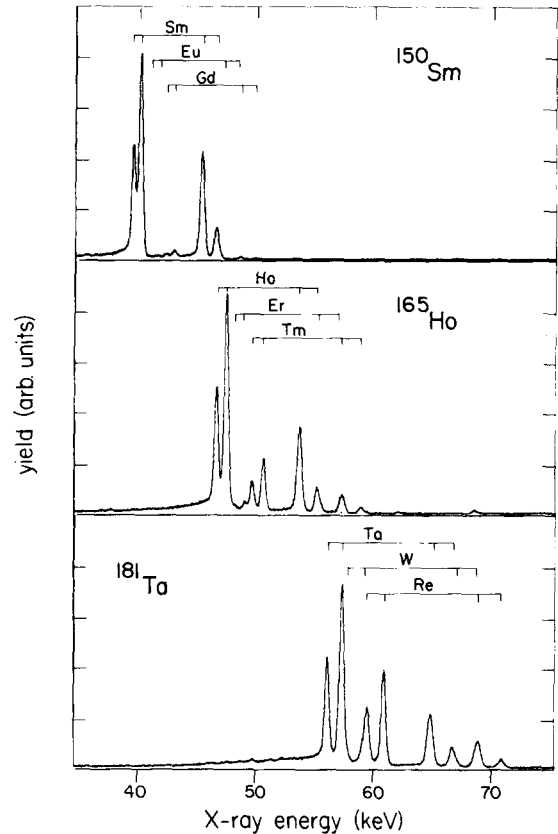


Fig. 1. Examples of the K X-ray spectra from <sup>150</sup>Sm, <sup>165</sup>Ho and <sup>181</sup>Ta targets bombarded with 50 MeV  $\alpha$ -particles.

[9]. They were typically of the order of 10% of the corresponding  $\sum_x \sigma(xn)$  values for Gd. The normalizations were attained by comparing the observed  $\gamma$ - and X-ray yields to those of the characteristic target X-rays and by using the theoretical  $Z$ -dependence of the  $\alpha$ -induced ionization cross sections (cf. ref. [3] for details). In the case of <sup>12</sup>C and <sup>14</sup>N induced reactions we have used only those results where the  $\gamma$ -ray spectra were yielding unambiguous information.

The measured  $\bar{M}_K$  values (figs. 2,3) depend on the cross section distribution with neutron number of the residual isotopes [cf. eq. (1)]. Strictly speaking, they therefore can be used to interpret data from reactions for which such distributions are sufficiently similar. In fig. 2 (bottom) we present the  $\bar{M}_K$  values for Dy isotopes plotted as a function of the average neutron

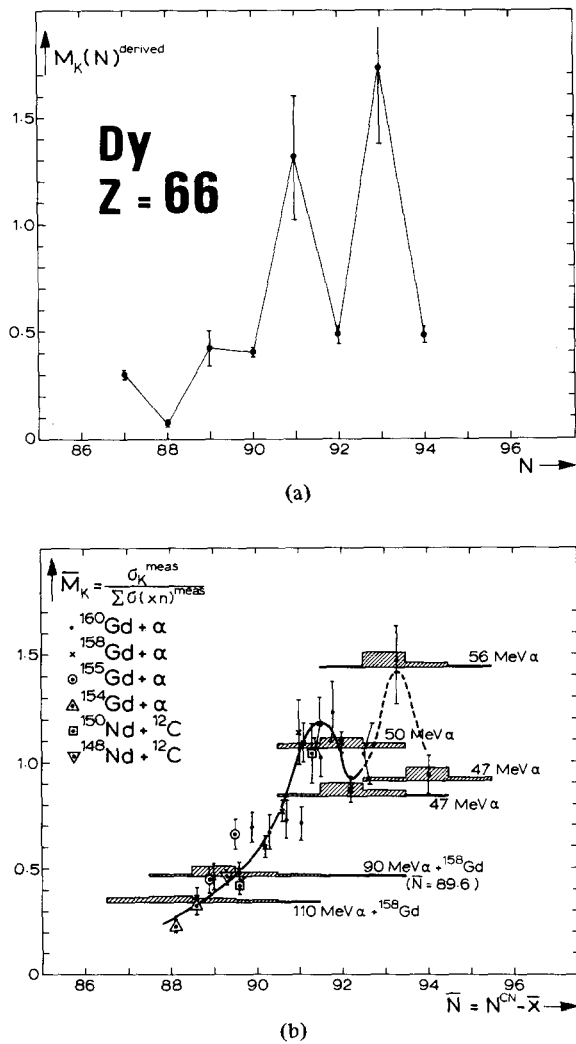


Fig. 2. Bottom: The average K X-ray multiplicity,  $\bar{M}_K$ , as a function of the average neutron number,  $\bar{N}$ , of the Dy residues. The shaded histograms represent the measured cross section distribution with neutron number for a few selected reactions. Top: The corresponding (unfolded) multiplicity values for zero neutron dispersion,  $M_K$  versus  $N$ .

number of the residues,  $\bar{N} = \sum_x N \sigma(xn) / \sum_x \sigma(xn)$ . Fig. 2 (top) shows the corresponding dependence of the individual  $M_K$  values on the neutron number of the residue.

Two features are apparent upon the inspection of fig. 2: (a) the strong even-odd staggering of the  $M_K$  values with  $N$ , and (b) the gradual increase of the  $\bar{M}_K$  values with  $\bar{N}$  in the region of increasing deformation ( $88 \leq N \leq 91$ ). Similar figures, though with fewer data

points, have been constructed for other even  $Z$  final nuclei. Both the even-odd staggering and the deformation dependence were found to be present in all these cases.

Determining the individual  $M_K$  values for all the rotational nuclei is impractical and approximate methods of obtaining applicable average quantities have to be used. A closer inspection of the  $\bar{M}_K$  versus  $\bar{N}$  and  $M_K$  versus  $N$  dependences (cf. fig. 2) shows that it is possible to deduce average K X-ray multiplicity values characteristic for a given element provided that (a) the variation of the deformation parameter among the isotopes produced is small, and (b) the dispersion in the neutron number is large enough to smooth out the saw-tooth curve of the  $M_K$  versus  $N$  dependence. In fig. 3a we present the  $\bar{M}_K$  values measured for each final element with varying composition of the isotopes produced. Fig. 3b shows the average values,  $\langle \bar{M}_K \rangle$ , obtained with the restriction that  $\bar{N} > 91$ . The condition of large neutron dispersion (i.e. sufficiently high excitation energy) is only partly fulfilled for our data, which may contribute to the scatter of the points. Certain systematic trends can nevertheless be seen. The  $\langle \bar{M}_K \rangle$  values for even  $Z$  elements scatter around 0.95 and those for odd  $Z$  around 1.7. Aside of this odd-even staggering no systematic variation with  $Z$  is observed.

Average K X-ray multiplicity values of  $\sim 3$  and  $\sim 2$  have been reported [5] for odd- and even- $Z$  residues, respectively, in the  $110 \leq \bar{N} \leq 120$  region. We find a similar systematic even- $Z$ -odd- $Z$  difference for the elements studied presently. The values reported in ref. [5] for deformed residues (light Os and Re isotopes) fit well the present systematics ( $\bar{M}_K(\text{Os}) \sim 1.1$ ,  $\bar{M}_K(\text{Re}) \sim 1.6$ ).

The K X-ray production cross sections for residual light Dy isotopes have recently been studied [11] for  $^{32}\text{S}$  induced reactions on several Sn targets ( $112 \leq A \leq 124$ ). An elegant technique of detecting the recoil nuclei in coincidence with the K X-rays was used. The  $\bar{M}_K$  values determined in ref. [11] cannot, however, be included in the present systematics. The final Dy nuclei produced range between  $A \sim 140$  and  $A = 152$ , i.e. they do not correspond to the criterium of sizeable stable deformation. Strong angular momentum effects on the  $M_K$  values have in fact been observed [3] for  $^{151}\text{Dy}$  and  $^{152}\text{Dy}$ . Similar effects should be present also for the lighter Dy isotopes. No regular even-odd staggering is expected among these nuclei, in contrast to the rotational ones, while large fluctua-

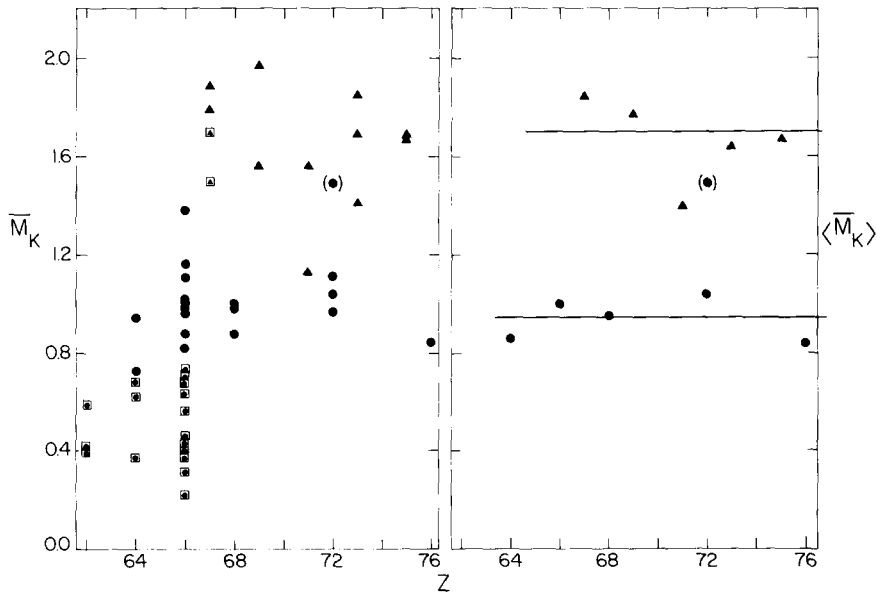


Fig. 3. Left: The measured multiplicity values,  $\bar{M}_K$ , as functions of  $Z$ . Errors are typically about 10–15%. Squares indicate that the final nuclei are not well deformed ( $\bar{N} < 91$ ) and thus should not be considered in the averaging procedures. Right: The K X-ray multiplicity values,  $\langle \bar{M}_K \rangle$ , obtained as averages of the experimental  $\bar{M}_K$  values for  $\bar{N} \geq 91$ . To guide the eye, lines are drawn through triangles for odd- $Z$  and dots for even  $Z$  elements, respectively. The dot in parentheses at  $Z = 72$  corresponds to the main product  $^{176}\text{Hf}$ , and illustrates the importance of high spin isomerism [10] for fluctuations in the  $\bar{M}_K$  values.

tions in  $M_K$  can easily occur, depending on the nucleus and the reaction.

We conclude that it is possible to deduce average, characteristic values of K X-ray multiplicities for selected groups of isotopes of some elements. We have determined such values for several rare earth elements. These values can be used e.g. to deduce nuclear reaction cross sections from the observed X-ray spectra for a variety of reactions. There are, however, certain necessary conditions which must be fulfilled:

(i) With respect to the type of reaction: sizeable excitation energy and angular momentum have to be transferred to the residue (this is typically the case for H.I. induced complete and incomplete fusion reactions at energies well above the Coulomb barrier),

(ii) With respect to the residual nuclei: they have to be strongly deformed and should have no high spin isomers populated in the reaction.

For nuclei at the onset of deformation and/or for reactions leading to residues with small neutron dispersion the variation in individual X-ray multiplicity values for adjacent isotopes should be taken into account explicitly in constructing the average quantities. For non-deformed nuclei as well as for the deformed

ones with high spin isomers (e.g. K-isomers) one can expect large variations of the X-ray multiplicity with the angular momentum transfer. Thus for such nuclei a great caution should be exercised in using  $\bar{M}_K$  values determined under different experimental conditions.

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