Coulomb Excitation of Nuclei by Heavy Ions

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THE cross section of Coulomb excitation of the nucleus in the case of quadrupole excitation is expressed by the formula

$$\sigma = (m^2 v_f^2 / z_2^2 e^2 \hbar^2)\, B_e(2)\, f_2(\xi), \qquad (1)$$

where

$$\xi = (z_1 z_2 e^2 / \hbar)(1/v_f - 1/v_i), \qquad (2)$$

m is the reduced mass of the bombarding particle, z_1 is the number of protons in its nucleus, v_i and v_f are its relative velocity before and after the collision, z_2 is the number of protons in the nucleus of the target atom, $B_e(2)$ is the reduced probability of electric quadrupole transition of this nucleus from the ground state to a given excited state, $f_2(\xi)$ is the Coulomb excitation function[1-3]. The graph of the function $(25/2\pi^2) \times f_2(\xi)$ is drawn in Ref. 2. This function increases rapidly with decreasing ξ.

In cases in which the cross section σ is small, experimenters have attempted to step up the energy of the bombarding particle. However, this can lead to the appearance of nuclear reactions (especially in research with protons and for small z_2), which make very difficult the possibility of correctly calculating the quantity σ from the experimental data. One can step up the energy of the particles significantly without risking the excitation of nuclear reactions if accelerated heavy ions are used instead of protons or α-particles for Coulomb excitation of the nucleus.

Let us estimate the value of the cross section σ_T of Coulomb excitation of the nucleus by heavy ions. It is appropriate to replace the calculation of σ_T with the calculation of the relative value (σ_T/σ_P) in its dependence on ξ_P (the subscript p refers to the proton). The parameter ξ_P can be represented in the form

$$\xi_P = 0.1575 z_1 z_2 \sqrt{\mu_P}\left((E_P - \Delta E)^{-1/2} - E_P^{-1/2}\right). \qquad (3)$$

In Eq. (3) and later, the collision energy E and the excitation energy ΔE are expressed in mev; μ is the reduced mass of the particle, expressed in nuclear mass units. As follows from Eq. (1),

$$\frac{\sigma_T}{\sigma_P} = \frac{\mu_T (E_T - \Delta E)}{\mu_P (E_P - \Delta E)} \frac{f_2(\xi_T)}{f_2(\xi_P)}. \qquad (4)$$

In the calculation of the values of σ_T/σ it is assumed that $E_T = Z_T E_P$. The parameter ξ_T is computed by a formula analogous to Eq. (3). The results of the calculations, relative to the use of nitrogen ions, are plotted in Fig. 1 in the form of graphs computed for tantalum ($z = 73$, $A = 181$) and manganese ($z = 25$, $A = 55$) for different values of the parameter $k = \Delta E / E_P$. For convenience in estimating the energy of the particles from the graph, we have also provided the values of E_P which correspond to the given ξ_P for different values of the parameter k. Consideration of the graphs permits us to draw the following conclusions:

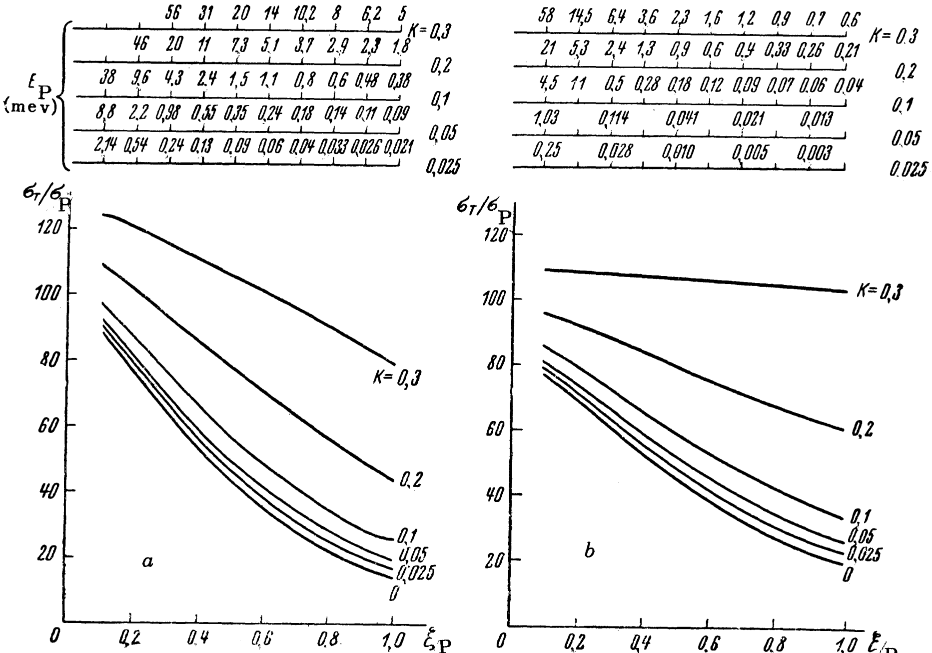
1) With decrease in E_P, the ratio σ_T/σ_P decreases. The maximum value of σ_T/σ_P for a given k occurs for $\xi_P \to 0$, i.e., for large E_P;

2) For ξ_P in the region from 0 to 1, the values of σ_T/σ_P are much greater than unity;

3) The values of σ_T/σ_P increase with increase in k, especially for $\xi_P \to 1$.

In cyclotrons of average size, one can accelerate triply ionized nitrogen ions up to energies of 10-30 mev. In Ref. 4, which pertains to the investigation of Coulomb excitation nitrogen ions were investigated with energies of 15.6 mev. For ions with such energy we find the value of σ_T/σ_P for the excitation of the first and second levels of Ta^{181} ($\Delta E_1 = 0.137$ mev and $\Delta E_2 = 0.303$ mev). In this case $E = 14.5$ mev, $E_P = 14.5/7 \approx 2.1$ mev*, $k_1 = 0.065$, $k_2 = 0.15$. Interpolating the data shown in Fig. 1, we get for the first and second excited levels of Ta^{181} the valuse of σ_T/σ_P equal to 75 and 50, respectively.

Calculation shows that for nuclei close to the A and z for Ta^{181} in the excitation of the level with $\Delta E = 0.5$ mev, the equality $\sigma_P = \sigma_T$ (14.5 mev) will hold for $E_P = 5.3$ mev; similarly, if $\Delta E = 0.2$ mev, then $\sigma_P = \sigma_T$ only for $E_P \gg 7$ mev. For nuclei of the type Mn_{25}^{55}, for all values of ΔE lower than 0.7 mev, $\sigma_T > \sigma_P$ if $E_P < 7$ mev.



The dependence of the ratio σ_T/σ_P on E_P for different values of $k = \Delta E/E_P$. The curve 0 was computed according to the formula of semiclassical theory[1,2] which holds as $k \to 0$; a -- $z_2 = 73$; $A = 181$; b -- $z_2 = 25$, $A = 55$.

To increase the yield of γ-photons, the experimental investigations of the c oulomb excitation are frequently carried out with thick targets. The ratio of the yield of γ-rays due to the Coulomb excitation of some state is given by the formula

$$\frac{Q_T}{Q_P} = \int_{E_T}^{0} \sigma_T(E) \frac{dE}{(dE/dx)_T} \Bigg/ \int_{E_P}^{0} \sigma_P(E) \frac{dE}{(dE/dx)_P} \quad (5)$$

Equation (5) assumes an equal number of protons and heavy ions falling on the target per second.

In application to the excitation of the first level of the nucleus Ta^{181} by nitrogen ions with $E_T = 14.5$ mev, calculation from Eq. (5) gives $Q_T/Q_p = 12$. The value of $(dE/dx)_T$ which is necessary for the calculation for the retardation of nitrogen ions in Ta is obtained by the method of recalculation of the range-energy curve for α-particles and tantalum according to the method set up by Longchamp.

Then, the ratio Q_Y/Q_p for a thick target is still greater than 1 although it is appreciably smaller than σ_T/σ_p (12 instead of 75).

In the passage of charged particles through matter, there arises characteristic x-radiation. In some cases, the energy of the x-ray K-quanta is close to the energy of γ-photons which are emitted as a result of Coulomb excitation. In such cases, the K-radiation forms an interfering noise. It was shown by Henneberg[7] that the cross section for the formation of x-ray K-quanta in the ionization of atoms by slow charged particles is approximately proportional to $z_1^2 (E_1/A_1)^4$. Making use of this relation and the data given above, it is possible to calcluate that in the case of a thick Ta target, the ratio of the number of x-ray K-quanta, arising as a result of the ionization of the atoms of Ta by the incident particles, to the number of K-quanta with energies to 137 kev, in the use of nitrogen ions with energies of 15.6 mev, is 15 times smaller than in the use of protons with energies of 2.1 mev.

We thank G. N. Flerov for calling our attention to the possibility of the use of heavy ions for the investigation of Coulomb excitation and also give thanks to K. A. Ter-Martirosian who put at our disposal tables and graphs of the function $f_2(\xi)$, kindly sent him by Alder and Winther.

* We note that the protons used for Coulomb excitations of Ta^{181} in Ref. 5 have almost the same energy.

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Experimental Study of Coulomb Excitation of Nuclei by Nitrogen Ions

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THEORETICAL estimates[1] indicate some advantage can be gained if heavy ions are used as bombarding particles in the study of Coulomb excitation of nuclei. We have carried out an experimental investigation of Coulomb excitation of the nuclei of 21 elements by nitrogen ions. The purpose of the measurements was the determination of the lowest excited levels of the nuclei under investigation and the value of the reduced probabilities $B_e(2)$ for the corresponding transitions.

A beam of triply ionized nitrogen ions, accelerated in a cyclotron to 15.6 mev, was brought into a vacuum tube by means of the usual deflector and passed through a system of two magnetic quadrupole lenses, which focussed the beam on the target. To rid the beam of singly charged ions, the beam was passed through a plane condenser with horizontal plates, located at the exit of the deflector unit. A constant voltage of $\sim$ 14 kv was applied across the plates.

The target was pressed into the bottom of an isolated metallic vessel which served as a Faraday cylinder. The beam spot on the target had a height of $\sim$ 5, and a depth of $\sim$ 14 mm. Use of the magnetic lenses permitted an increase in the intensity of the ion beam falling on the target (by a factor of about 5) and also separated the deflecting arrangement by 1.8 m. The quantity of electricity in the incident beam was measured by integration of the current.

The γ-radiation of the target was investigated with the help of a scintillator γ-spectrometer. The latter consisted of a crystal of NaJ(Tl), a photomultiplier, a linear amplifier and a 50 channel pulse-amplitude analyzer*.

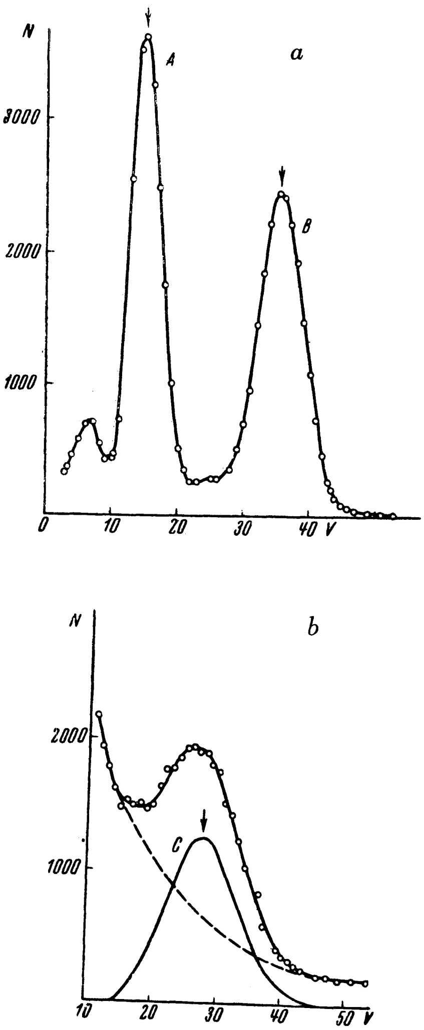

FIG. 1. Amplitude spectrum of pulses in the Coulomb excitation of Ta^{181}: a = x-ray K-line of Ta; B = γ-line corresponding to the decay of the second excited level of Ta^{181} with E = 301 kev (the curve was obtained after subtraction of the noise, indicated by the broken curve).

The form of the spectrum of Coulomb excitation obtained for radiation of tantalum foil (of 100 μ thickness) by nitrogen ions is shown in Fig. 1. The peak A corresponds to the x-ray K-radiation of the atoms Ta with E = 57.2 kev. According to