COULOMB EXCITATION OF NUCLEI BY HEAVY IONS, ACCOMPANIED BY EMISSION OF GAMMA QUANTA

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We consider Coulomb excitation of high single-nucleon levels in the nucleus, due to bombardment of the latter with heavy ions of energies lower than the Coulomb barrier. The value of the cross sections thus obtained indicates that an experimental proof of the existence of such levels may be feasible.

In reactions due to Coulomb excitation of nuclei, one observes most frequently collective excitations corresponding to rotational and vibrational degrees of freedom. Most experiments pertain to a study of the lower levels (lower than 1 Mev). This circumstance is explained by the fact that the accelerated ions employed are protons, deuterons, and low-energy α particles. As the ion energy is increased, one can hope to obtain higher excited states of nuclei. In this case, however, the energy is found to be considerably higher than the Coulomb barrier, and other reactions due to nuclear interaction become possible and make the investigations difficult.

In view of modern advances in technique, it becomes feasible to accelerate heavy ions (up to iron ions[1]). Naturally, the use of such ions will make it possible to raise considerably the region of investigated levels of the Coulomb-excited nuclei (approximately 6 or 7 Mev). From this point of view it is interesting to investigate the Coulomb excitation of a nucleus by a heavy ion, followed by emission of a relatively high-energy photon (6 or 7 Mev).

This process can be analyzed using the shell model, i.e., within the framework of single-nucleon excitations. It is well known that earlier calculations for this process, in the region of low excitations, could not yield satisfactory results because the experimental probabilities of radiative nuclear transitions deviated greatly from the probabilities calculated theoretically on the basis of the independent-particle model. This is understandable, for the collective aspects of the nucleus play an important role at low excitations. However, as shown by the author in a paper on resonance scattering of γ quanta by nuclei,[2] in the energy interval of interest to us a decisive role is played by single-nucleon transitions. The theory developed in reference 2 agrees satisfactorily with experiment. This circumstance gives some grounds for using the shell model to estimate the cross sections for the process indicated above.

By way of a specific example, we consider the Coulomb excitation of Pb^{208} by the Ne^{20} ion. The Coulomb barrier has in this case an approximate order of magnitude of 130 Mev. Let the kinetic energy of the ion be approximately 100 to 120 Mev. The nucleus can go into the ground state, emitting a 6-Mev γ quantum, if, for example, a neutron electric-dipole transition $2f_{7/2} \rightarrow 2g_{9/2}$ is realized in the excitation. The energy lost by the ion to excitation of the nucleus is nearly $1/20$. Under these conditions, the excitation process can be considered from the classical point of view.

Using the theory of the Coulomb excitation of nuclei in this approximation,[3,4] we can calculate the total cross section. The reduced probability B(E1) (with allowance for the filling of the corresponding shell), has the following form

$$B(E1) = \frac{3\varepsilon^2}{4\pi}\left|\int \varphi_f^* r \varphi_i r^2 dr\right|^2 (2L_i+1) \times (2L_f+1)\,|\,(L_i 100\,|\,L_f 0)\,|^2 W^2 (L_i J_i L_f J_f, {}^1/_2 1).$$

Here ϵ is the effective charge of the nucleon (in our case $\epsilon \approx 0.4$), $(L_i 100 \mid L_f 0)$ is the Clebsch-Gordan coefficient, W is the Racah function, while φ_i and φ_f are the radial parts of the nucleon wave functions in the initial (ground) and final (excited) states, respectively. We borrow the expressions for φ_i and φ_f from reference 2. They are exact solutions of the approximate Schrödinger equation, with allowance for the smearing of the nuclear boundaries, and have the form

$$\varphi_i = r^{-1} N_i 2\alpha_i (r - r_0^i) \exp[-\alpha_i^2 (r - r_0^i)^2/2],$$

$$\varphi_f = r^{-1} N_f 2\alpha_f (r - r_0^f) \exp[-\alpha_f^2 (r - r_0^f)^2/2],$$

where N is a normalization factor; α and r_0 are parameters determined when solving the equation.

The matrix element in B(E1) can be determined numerically. It is found to be approximately 5.6×10^{-13} cm. The total cross section for Coulomb excitation of the single-nucleon level $2g_{9/2}$ in the Pb^{208} nucleus by the Ne^{20} ion (100 to 120 Mev) is approximately 2×10^{-2} mb.

As the ion energy is decreased, the cross section diminishes practically exponentially.

If Pb^{208} nuclei are bombarded with much heavier ions, for example, Fe^{56} (Coulomb barrier ~ 360 Mev), then at an approximate energy of 300 Mev (direct contact between the nuclei becomes possible at higher energy), the cross section is $\sigma = 0.01$ mb.

Assuming that the reverse transition is also pure electric-dipole, and using the general theory of angular correlation (see reference 5 and also 3), we can calculate the angular distribution of the γ quanta for the case $Ne^{20} + Pb^{208}$.

Its form is

$$W(\vartheta) = 1 - 0.064\, P_2(\cos\vartheta_\gamma).$$

Analogously we can obtain the cross section for the Coulomb excitation for the case of single-nucleon transitions of the electric-quadrupole type. A specific example is the transition $1h_{11/2} \rightarrow 2f_{7/2}$ in Pb^{208} (transition energy 3.5 Mev).

Using the method indicated above to determine the wave functions, we can calculate the matrix element $\langle r^2 \rangle_{if}$ to be approximately 20.2×10^{-26} cm^2. We then obtain for Ne^{20} ions with approximate energy 120 Mev, $\sigma = 0.24$ mb. For ions with approximate energy 200 Mev, the cross section is found to be 0.67 mb.

The calculated cross sections appear to be sufficiently large. It is therefore advantageous to set up experiments for the purpose of analyzing the high excited levels of nuclei.

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