A METHOD FOR INVESTIGATING OPTICAL ANISOTROPY AND SURFACE SHAPE OF ATOMIC NUCLEI

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We discuss a method for investigating the optical anisotropy and the shape of the surface of atomic nuclei based on the study of the angular distributions of charged sub-barrier particles emitted by deformed nuclei in photonuclear reactions.

AT the present there are many papers devoted to the optical anisotropy of atomic nuclei [1-5]. According to present notions concerning the mechanism of interaction between γ quanta and nuclei, in the region of giant resonance the elastic scattering and absorption amplitudes (or cross sections) of the γ quanta depend essentially on the orientation of the wave vector of the photon relative to the nuclear spin **I** or the unit vector **n** in the direction of the principal deformation axis of the nucleus (we are considering axially-deformed nuclei).

Indispensable to a rigorous experimental proof of the existence of optical anisotropy of the nuclei are experiments with oriented nuclei, yielding the dependence of the cross section on the angle between the electric vector (or momentum) of the photon and the preferred direction connected with the nucleus (**I** or **n**). This method, however, entails great experimental difficulties and is applicable only to nuclei with large spins.

The proposed method of investigating optical anisotropy is based on fixing the direction of **n** by means of the sub-barrier charged particles (p, d, t, α) emitted from the nucleus as a result of photonuclear reactions.

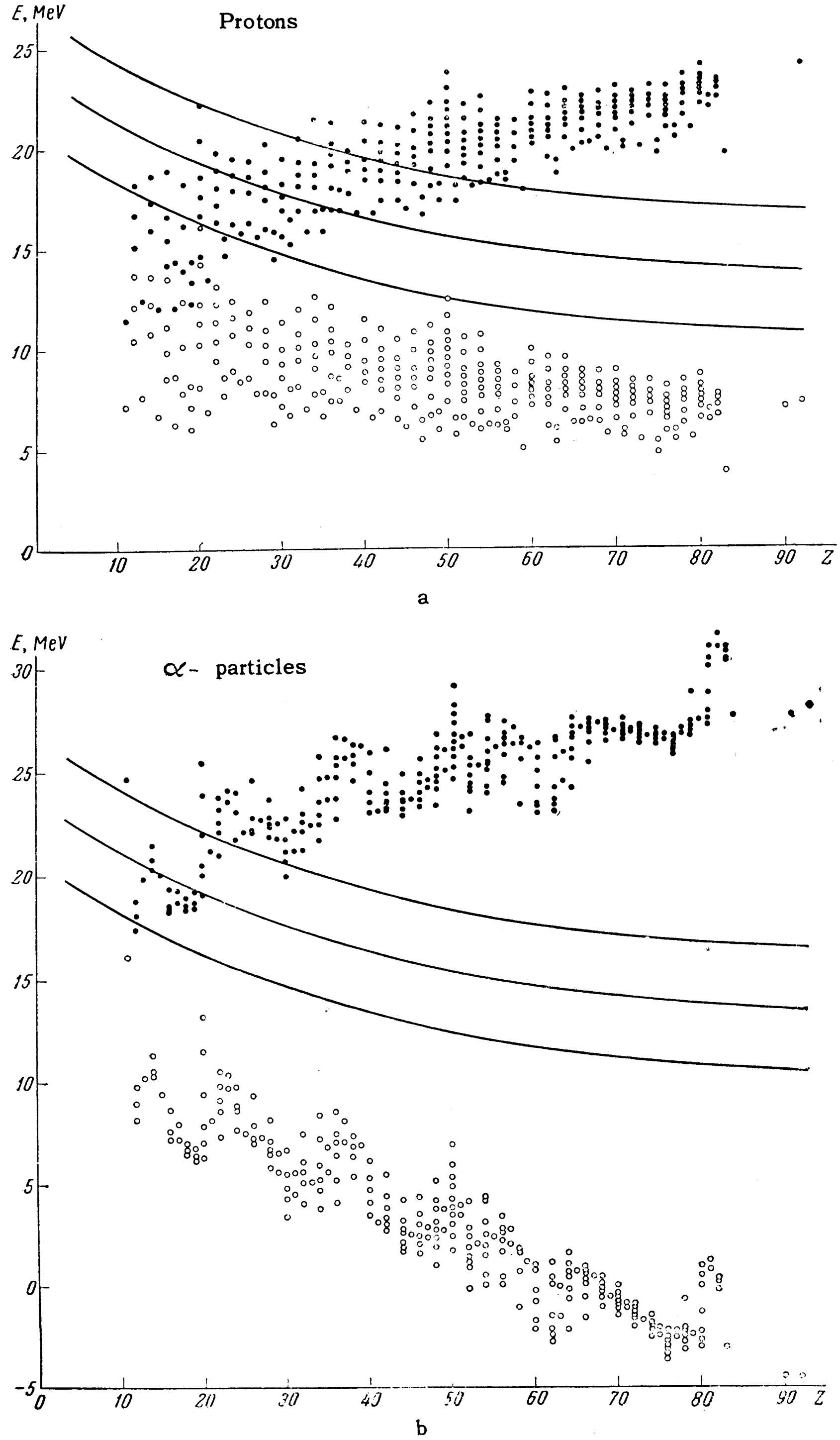
In photodisintegration of deformed nuclei it is necessary to consider two types of transitions: the group of transitions connected with the direction of **n** (transitions concentrated in the frequency region $\omega \approx \omega_{\parallel}$), and the transition group connected with the other axes of the nucleus, perpendicular to **n** (transitions in the frequency region $\omega \approx \omega_{\perp}$).

For the first group of transitions ($\omega \approx \omega_{\parallel}$), in the case of prolate nuclei, the summary effect of the penetrance of the Coulomb barrier and of the logarithmic derivative on the surface of the nucleus, which is determined by the dynamics of the γ-quantum absorption, causes the emission amplitude of a charged subbarrier particle F(**p**, **n**) (where **p** is the wave vector of the emitted particle) to have, in the coordinate frame fixed in the residual nucleus, sharp maxima at angles zero and 180° between **p** and **n**. (As shown by the theory of α decay of deformed nuclei [6,7], the penetrance of the Coulomb barrier of prolate nuclei in the direction of **n** is more than one order of magnitude larger than the penetrance in a direction perpendicular to **n**. In addition, in transitions in the vicinity of $\omega \approx \omega_{\parallel}$ we can expect the logarithmic derivative on the surface of the nucleus in the vicinity of the poles to be at least not smaller than in the equatorial region [8].) If the condition $\Delta E/E \ll 1$ is satisfied (ΔE is the energy of the rotational levels of the residual nucleus and E is the energy of the emitted particle) and the rotational state of the product nucleus is not fixed in the experiment, then the angular distribution of the emitted particles (provided the photons are not polarized and the nuclei not oriented) has in the laboratory frame the form

$$d\sigma/d\Omega \sim \sin^2\vartheta + \Delta \tag{1}$$

(ϑ is the angle between the momenta of the photon and the emitted particle). The quantity $\Delta \approx \theta_{1/2}^2/2$, where $\theta_{1/2}$ is the half-width of the angular distribution of the particles in the coordinate system fixed in the residual nucleus. Estimates show that $\Delta \approx 0.05 - 0.1$. A particular case of (1) is the result obtained by Gustafson in an analysis of the angular distribution of photoprotons from Mg^{24} [8].

For transitions in the frequency region $\omega \approx \omega_{\perp}$ we cannot obtain a general relation similar to (1), for in this case the penetrance of the Coulomb barrier and the logarithmic derivative on the surface of the nucleus have maxima at different angles. In this case a special calculation is necessary for each specific nucleus, analogous to that made in [8]. The results obtained in that paper lead us to expect the angular distributions of the subbarrier charged



Binding energies and Coulomb barriers of protons (a) and α particles (b) for different isotopes with $Z > 10$. Central curve – position of the maximum of giant resonance (E_{res}) as a function of Z. The lower and upper curves, corresponding to ($E_{res} \pm 3$ MeV), limit the principal region of giant resonance. o – binding energy (taken from the tables of Cameron[10]); ● – binding energy plus the height of the Coulomb barrier (calculated for the average radius $\bar{R} = 1.3 \times 10^{-13} A^{1/3}$).

photoparticles to be smoother functions of the angle ϑ in the transition region $\omega \approx \omega_\perp$, with

$$\sigma(0)/\sigma(\pi/2) \approx 1. \qquad (2)$$

An experimental verification of relations (1) and (2) proves the existence of optical anisotropy in the nuclei.

For oblate axially-deformed nuclei in the frequency region $\omega \approx \omega_\perp$, we can also obtain in analogy with (1) a general form of the angular distribution of the subbarrier charged photoparticles. It has the form

$$d\sigma/d\Omega \sim 2 + \sin^2\vartheta + \Delta'. \qquad (3)$$

The value of Δ' is determined by the half-width of the angular distribution of the particles in the coordinate system fixed in the nucleus, with $\Delta' \approx 0.05 - 0.1$.

For prolate nuclei $\omega_\parallel < \omega_\perp$, and for oblate ones $\omega_\parallel > \omega_\perp$. Thus, by investigating the form of the angular distribution of the subbarrier charged photoparticles in the region of the first maximum of the giant-resonance cross section for deformed nuclei, we can establish the sign of the quadrupole moment of the nucleus.

All the regularities noted above are not limited to photonuclear reactions. For example, the angular correlation of a high-energy proton inelastically scattered through a small angle and a subbarrier charged particle emitted by an excited nucleus should be determined by relations of the type (1)—(3) inasmuch, as shown in [9], the states excited in such reactions correspond to photonuclear giant resonance. Analogous conclusions are valid also for the case of electrodisintegration of nuclei [1)].

The main advantage of the proposed method is that it can be used to investigate nuclei with arbitrary values of the spin, including I = 0. The applicability of the method is limited by the condition that the sum of the binding energy of the particle and the height of the Coulomb barrier exceed the energy corresponding to the region of giant resonance. As shown by crude estimates (see the figure) this corresponds to $Z > 44$ for protons and $Z > 34$ for α-particles, i.e., to practically the entire most interesting region of nuclei. It must be borne in mind, however, that in the case of a large difference between the kinetic energy of the particle and the height of the barrier, the cross sections of interest to us will be small. In addition, when the energies of the emitted particles are very low, the widths of the corresponding reactions become comparable with the distances between the rotational levels [in the derivation of relations (1) and (3) we used the concept of a deformed excited nucleus]. This circumstance can lead to a change in the expected angular distributions. Indeed, an account of this effect in the quasiclassical approximation yields in lieu of (1) the expression

$$\frac{d\sigma}{d\Omega} \sim \frac{2 + [(\gamma/\delta)^2 + 1] \sin^2 \vartheta}{(\gamma/\delta)^2 + 4}. \qquad (4)$$

Here γ is the width of the corresponding reaction and the distance between the rotational levels. Thus, for a reliable interpretation of the experimental results it is necessary to use that region of emitted-particle energy, which is appreciably lower than the height of the barrier and for which the relation $\gamma/\delta \gg 1$ is satisfied.

A development of this method, as can be readily seen, will yield a very effective means for investigating the form of the nuclear surface. This method has all the advantages of the investigation of the nuclear form on the basis of a study of the α decay, and the following additional advantages: a) it is possible to investigate not only α-active nuclei, b) it is possible to vary the energy of the charged particle, c) there is an additional preferred direction (the electric vector). The latter circumstance, in conjunction with the possibility of investigating the discussed reactions on oriented nuclei with the aid of polarized photons, offers particularly much promise.

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[1)]One can expect the angular distributions of photoneutrons with large angular momenta also to have an anisotropy similar to (1)–(3). In this case, however, the anisotropy will be much weaker than in the case of subbarrier charged particles.

[1] A. M. Baldin, Tr. Konferentsii po yadernym reaktsiyam pri malykh i srednikh énergiyakh (Trans. Conf. on Nuc. Reactions at Low and Medium Energies), AN SSSR, 1958, p. 479; Nucl. Phys. **9**, 237 (1958); JETP **37**, 202 (1959), Soviet Phys. JETP **10**, 142 (1960).

[2] K. Okamoto, Progr. Theor. Phys. **15**, 75 (1956); Phys. Rev. **110**, 143 (1958).

[3] M. Danos, Bull. Am. Phys. Soc. II, **1**, 135 (1956); Nucl. Phys. **5**, 23 (1958).

[4] E. G. Fuller and E. Hayward, Phys. Rev. Lett. **1**, 465 (1958); Proc. of the Int. Conf. on Nuclear Structure, Kingston, Canada (1960), p. 763.

[5] S. F. Semenko and B. A. Tulupov, JETP **41**, 1996 (1961). Soviet Phys. JETP **14**, 1417 (1962).

[6] D. L. Hill and J. A. Wheeler, Phys. Rev. **89**, 1102 (1953).

[7] V. G. Nosov, Doctoral Dissertation, Phys. Inst. Acad. Sci. and the literature cited therein.

[8] T. Gustafson, Nucl. Phys. **28**, 665 (1961).

[9] M. Kawai and T. Terasawa, Progr. Theor. Phys. **22**, 513 (1959). Y. Sakamoto, Progr. Theor. Phys. **24**, 81 (1960).

[10] A. G. Cameron, Chalk River, Ontario, AECL No. 433, (1958).

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