Concerning the mechanism of ternary nuclear fission

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A new mechanism of ternary fission is proposed, with removal of a long-range charged particle. This mechanism is connected with the emergence of the corresponding single-particle energy levels to the continuous-spectrum band. The charged-particle spectrum is calculated, and its dependence on the energy of the internal excitation of the fissioning nucleus, on the mass of the third particle, and on its emission direction is analyzed. Many known experimental facts find a natural explanation within the framework of the proposed mechanism.

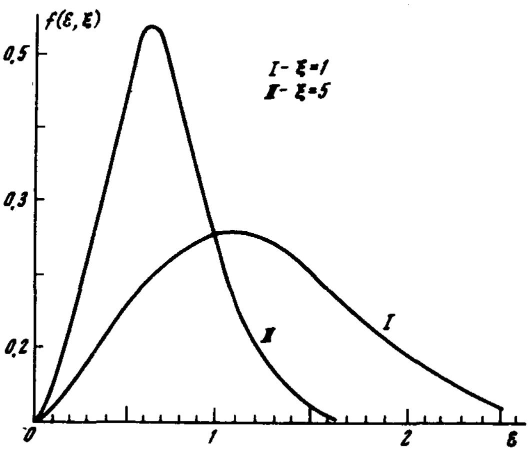
1. The fission of an atomic nucleus is accompanied, as is well known, by an appreciable fragment excitation that relaxes by neutron evaporation and γ-quantum emission. The fragment-emission spectrum is a valuable source of data on the fission products, but as a rule yields no information on the properties of the

fissioning nucleus itself. Unique information on the properties of nuclear matter under conditions of critical deformations, during the stage of the separation and acceleration of the fragments, is contained in the spectra of the particles that are released in the fission act itself, within a time $t_f \sim 10^{-20}$ sec.

The emission of "prompt" nucleons is traditionally regarded as a particular case of ternary fission, which is satisfactorily described within the framework of the liquid-drop model and trajectory calculations in the case of sufficiently heavy particles (He^3, He^4, Li^6). However, this approach is less consistent the smaller the mass of the third particle. For example, the calculated angular and energy distributions of the protons accompanying the fission of the Cf^{252} nucleus do not agree with the measured ones.[1] On the other hand, the single-particle model of non-adiabatic ejection of a particle at the instant of scission,[2] while it does permit a calculation of the ternary-fission probability, is based on the assumption of almost instantaneous scission. Even for the case of fission nuclei, t_{sc} should be close to 2×10^{-22} sec. For heavier particles, the corresponding values should be even smaller.

The purpose of the present communication is to call attention to the possible role of a new dynamic mechanism of release of nucleons and light nuclei in fission, a mechanism connected with the removal of the corresponding single-particle states to the continuous spectrum. This mechanism is perfectly universal, for its relative effectiveness depends significantly on the concrete properties of the system (the level scheme of the single-particle states, the presence of pseudocrossings, the rates of change of the deformation parameters η, etc.). Its role can be decisive in those cases when scission causes only excitation of single-particle states (for example, if $t_{sc} > 2\times 10^{-22}$ sec), the decay of which occurs during subsequent stages of the fission. This apparently takes place in the case of spontaneous fission of Cf^{252}, for which both the possibility of high values of the excitation energy at the instant of the appearance of the third particle (up to 7–10 MeV)[3] and an appreciable probability of the appearance of neutrons from not fully accelerated fragments (already after the fission)[4] were recently demonstrated.

2. The very fact that neutrons are emitted by the fission fragments indicates that with increasing nuclear deformation the many-particle levels of the system rise, cross the boundary of the continuous spectrum, and are transformed into narrow resonances. The neutron widths of these states are so small, that the fragments always move apart before the neutron manages to be emitted ($\Gamma_n \ll h/t_f \sim 5\times 10^{-2}$ MeV).



The possibility of removal of single-particle levels to the continuous spectrum is clear from general considerations (one broad potential well has more levels than two wells having the same total volume). The calculations of the states in deformed potentials of finite depth also demonstrate clearly this possibility (see, e.g.,[7,8]), namely, there are many states in which the nucleon binding energy decreases monotonically with increasing η and vanishes at a certain value η_0.

At $\eta > \eta_0$, such states should go over into potential resonances, the decay widths of which depend mainly on the projection of the angular momentum Ω and on the energy level E^0. Recent calculations have shown that single-neutron widths of deformed nuclei amount to $\Gamma_n \sim 3\times 10^{-3}$ MeV[9] already at $E^0 \sim 1$ MeV and $\Omega = 9/2$, and consequently the probability of their decay within a time t_f is not small ($w \sim \Gamma_n t_f \sim 0.1$). For states with smaller Ω and large E^0 (the experimentally established characteristic energy of prompt neutrons is ~5 MeV), the corresponding values should be even larger. For single-proton states, even at $Z = 92$, widths $\Gamma_p \sim 10^{-3}$ MeV are reached at $\Omega = 3/2$ and $E^0 \sim 10$ MeV, the widths increasing rapidly with increasing E^0 and with decreasing Z_{eff}.

The energy spectrum $N(E)$ of the particles released upon decay of the quasistationary states is given by[1)]

$$N(E) = \sum_i a_i \frac{\Gamma_i(E)}{h\left(\frac{dE_i^0}{dt}\right)} \exp\left[-\frac{2}{h}\int_0^E \Gamma_i(E)\frac{dt}{dE_i^0}\,dE\right] \quad (E>0) \tag{1}$$

The spectrum (1) corresponds to adiabatic motion of the system over the term of the decaying state $[E_i(t) = E_i^0(t) - i\Gamma_i(t)]$. The dependence on t is determined by the relation $E(t) = E[\eta(t)]$. The summation in (1) is over all the levels that go to the continuous spectrum and are populated during the course of the deformation of the nucleus with partial probabilities $a_i (\sum_i a_i = 1)$. For neutrons with $\Omega = 1/2$ and $3/2$, the spectrum (1) is analytically similar to the statistical spectrum customarily used in the interpretation of experiments.[4] For the case of charge particles we have $\Gamma(E) \approx C\sqrt{E}\exp(-a/\sqrt{E})$ and the spectrum takes the form

$$\begin{aligned} N(E) &= \sqrt{\epsilon}\exp\left[-\frac{1}{\sqrt{\epsilon}} - \frac{\xi}{3}\sqrt{\epsilon}\left(\epsilon - \frac{\sqrt{\epsilon}}{2} + \frac{1}{2}\right)\right. \\ &\quad \left.\times \exp\left(-\frac{1}{\sqrt{\epsilon}}\right) + \frac{1}{6}E_i\left(-\frac{1}{\sqrt{\epsilon}}\right)\right] \\ &\approx \sqrt{\epsilon}\exp\left[-\frac{1}{\sqrt{\epsilon}} - \xi\epsilon^2 e^{-\frac{1}{\sqrt{\epsilon}}}\right], \quad (\epsilon \ll 1,\ \xi \gg 1). \end{aligned} \tag{2}$$

Here $\epsilon = E/a^2$ is the energy in dimensionless units and $\xi = 2ca^3/(dE/dt)h$ is the dynamic parameter of the model. The charge-particle spectra are thus determined by two dimensionless parameters that can be found from the experimental data. Plots of $N(E)$ at $\xi=1$ and $\xi=5$ are shown in the figure. With increasing parameter ξ, i.e., with decreasing rate of change of the deformation coordinate η at the point η_0 $[\xi \sim dt/dE \sim (d\eta/dE_0)/(d\eta/dt)]$, the maximum in the energy distribution shifts towards lower energies, and the spectrum becomes narrower. It was apparently this effect which was observed in[3], where the correlation of ternary-fission α particles and of the γ quanta emitted by the fragments ($E_\gamma=1-5$ MeV) was measured, namely, the increase of the energy of the internal excitation (which correlates with the γ-quantum energy) should be accompanied by a decrease in the rate of passage through the point η_0 with increasing parameter ξ.

The "nonstationary α decay" mechanism proposed in the present paper explains also other experimental facts. Thus, for example, the shift of the maximum of the energy distribution of charged particles as a function of their mass and emission angle can be related to the dependence of the penetrability of the potential barrier that separates the region of most probable localization of the third particle (in the vicinity of the neck and the "stubs") from the region of classically accessible motion.

1) A similar situation is well known in the physics of atomic collisions. See, e.g., [5,6] and the literature cited there.

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