Low-density nuclear isomer and a possible explanation for the anomaly in the free path of nuclear fragments in photoemulsions

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An explanation is proposed for the anomalous behavior of the free path of nuclear fragments in photoemulsions.

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Several recent papers[1,2] based on experiments performed on the Bevalac accelerator report the observation of an unusual phenomenon, apparently observed previously for cosmic rays.[3,4] Studying the distribution of free paths λ of nuclear fragments with constant charge $Z \gtrsim 4$, formed with irradiation of a stack of photographic plates by a relativistic beam of heavy Fe and O ions with energies of about 2 GeV/nucleon, the experimenters discovered that the mean free path λ of fragments depends on the distance R traversed by a fragment in the photoemulsion. For small values $R \lesssim 2.5$ cm, λ is much small than the normal value λ_0 [for $Z \simeq 6-8$, $\lambda_0 \simeq 14$ cm, $\lambda \sim 10$ cm (Ref. 2)]. The length $\lambda(R)$ approaches λ_0 with increasing R. It was asserted in Refs. 1 and 2 that this behavior of $\lambda(R)$ can be explained by assuming that about 5% of the fragments formed have a free path length an order of magnitude shorter than the usual value. The phenomenon has one more important property: anomalous fragments are formed preferentially in "white stars," events with a relatively small number of thick tracks, which indicates the comparatively small energy transfer in nuclear-nuclear collisions.[2]

A possible explanation of the phenomenon observed is that it is related to the excitation of a nuclear isomer with anomalously large dimensions. Such an isomer must correspond to one more minimum on the curve of the energy $E = Nf(\rho)$ as a function of the nuclear density [pressure $P = \rho^2(df/d\rho)$, chemical potential $\mu = d/d\rho(\rho f)$]. We shall try to clarify the values of ρ for which such an isomer can arise. It is well known that the equation of state for nuclear matter with a local NN interaction amplitude $F(\mathbf{r}, \mathbf{r}') = [a + b\,\rho(r)]\delta(\mathbf{r} - \mathbf{r}')$, which is widely used in nuclear calculations, does not have additional minima for small ρ.[5,6] Taking into account the well-known Landau relation $F(\mathbf{r}, \mathbf{r}') = \dfrac{\delta^2 E}{\delta\rho(\mathbf{r})\delta\rho(\mathbf{r}')}$, it is easy to obtain

$$f(\rho) = \frac{3}{10}\frac{p_F^2(\rho)}{M} + \frac{a\rho}{2} + \frac{b\rho^2}{6}, \qquad p_F(\rho) = (3\pi^2\rho)^{1/3}; \quad p_F(\rho_0) =: p_0, \tag{1}$$

where the subscript 0 corresponds to the equilibrium state.

It is not difficult to see that the form (1) of the function $f(\rho)$ excludes the existence of a second minimum. However, at small densities ρ, when the distance between particles increases, the nonlocal part, which stems from the existence of a deuteron pole in the vacuum amplitude of the interaction of two nucleons, begins to play an increasing role in the NN scattering amplitude. This characteristic appears when the chemical potential $\mu(\rho)$, which determines the limiting energy of the quasiparticles, approaches the deuteron binding energy ϵ_d. Using the value ($a p_0 M/\pi^2 \simeq -5$[6]) found from an analysis of the nuclear experiment and with the help of (1), it is not difficult to establish that this occurs for nuclear densities ρ at which the radius of the nucleus $R \sim 3R_0$. Estimates show that the critical density ρ_c, at which a quasideuteron bound state first appears in the nuclear medium, which leads to a phase transition similar to the Mott metal-insulator transition, is of the same order of magnitude. Calculation of the equation of state in this region is rather complicated due to the inapplicability of the standard-gas approximation, because of the resonant nature of the NN interaction at low energies, and will be examined separately. Here we shall restrict ourselves to a discussion of the experimental consequences of assuming the existence of long-lived ($\tau \gtrsim 10^{-11}$ s) quasideuteron nuclear isomers with radius $R_i \sim 3R_0$ (their free path is presumably an order of magnitude smaller than the usual value) and binding energies per particle of the order of ϵ_d. It follows from these assumptions that the excitation energy of the isomeric state constitutes about 5–6 MeV/nucleon, i.e., approximately 100–150 MeV for light nuclei with mass number $A \sim 20$. Quasideuteron isomers with $A > 60$ are apparently not formed, since they are absolutely unstable with respect to fission. We recall that this instability is determined by the competition between Coulomb repulsion E_Q and surface tension E_S and corresponds to vanishing of the drop fission barrier. This occurs when the parameter $\xi = Z^2/A$ reaches a magnitude ξ_c, such that the reaction $x = E_Q/2E_S$ becomes equal to unity. For ordinary nuclei, $\xi_c^0 \simeq 48$–50. The Coulomb energy of the isomer, is apparently lower than the usual value $E_Q^i = E_Q^0 r_0/r_i$, but the surface energy $E_S^i = 4\pi r_i^2 \sigma_i A^{2/3}$ (σ_i is the coefficient of surface tension, r_i is the average distance between particles) decreases with increasing r_i even more rapidly. From dimensional considerations, $\sigma_i \sim \epsilon_F^i/r_i^2 \sim 1/Mr_i^4$ (the numerical factor is obtained in Refs. 7 and 8). For this reason, when the distance r_i between particles increases, $E_S^i \simeq E_S^0 r_0^2/r_i^2$ and therefore the ratio ξ_c^i decreases for isomers: $\xi_c^i \simeq \xi_c^0 r_0/r_i \simeq 16$, i.e., $Z_c^i \simeq 30$–40 and $A_c^i \sim 70$–90. The boundary of mass numbers, beginning with which isomers in the ground state are unstable relative to fission, is estimated analogously, although the fission barrier does exist. For normal nuclei, this process is possible for $A > 60$ and for isomeric nuclei for $A > 20$. Thus, beginning approximately with $Z_f \sim 10$, quasideuteron isomers are capable of fissioning and this process can in principle be observed in a photoemulsion. [For the isomer with $Z \sim 20$, the magnitude of the drop barrier (see Ref. 9) $\Delta \sim 1$ MeV.] In addition, as the atomic number decreases, the barrier between the ground and isomeric states decreases; for example; for ^{4}He isomers it should no longer exist. For this reason, the study of the free path λ of particles with charges $Z = 2.2$, just as for high $Z > 40$, is decisive for checking the hypothesis being discussed.

In nuclear reactions induced by pions, nucleons and electrons, even with favorable kinematics (and it imposes rigid restrictions on the conditions under which isomeric states can be observed), the isomeric state is apparently strongly suppressed, analogously to the manner in which fission of heavy nuclei by thermal neutrons is suppressed by the competition between many degrees of freedom.[10] Accordingly, isomeric states should not be excited with inelastic scattering of nuclei by target protons. A simple experiment can be performed by placing a hydrogen target in front of a stack of photographic plates. If this hypothesis is valid, then the anomalous behavior of the free path in the photoemulsion will remain unchanged, irrespective of the thickness of the hydrogen target.

Nuclear–nuclear relativistic collisions are preferable for exciting isomeric states, since it is highly probable that the interaction has a collective nature in such processes. The collective process leading to the formation of an isomer can be viewed as an expansion of the nucleus under the action of a sudden external pressure $P = \Delta p_\perp / R^2 \Delta t$, where $\Delta p_\perp$ is the characteristic momentum transfer in the collision, and $\Delta t \sim c/R$ is the collision time.

The final state of the process is determined by the excitation energy of the nucleus: if it exceeds 8 MeV/nucleon, the nucleus breaks up in the ground state, since the extra excitation energy is carried away as a result of evaporation of light particles. The isomer in the ground state (if it does not fission) emits only as a result of tunneling transition to the "normal phase." Assuming that the magnitude of the transition barrier is $\Delta \sim \epsilon_d A$, we find that for $A \sim 20$ the barrier factor $R_b \sqrt{2MA\Delta} \sim 20$. As a result, the lifetime of such an isomer may turn out to be long enough for detection in a nuclear emulsion. If such long-lived isomers indeed exist, then they must accumulate in secondary collisions, i.e., the anomaly in the free path $\lambda(R)$ of second-generation fragments becomes stronger. The available statistics of events is as yet insufficient for checking this assertion.

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