V. M. Galitskiĭ. *Anomalous States and Collective Motions of Nuclear Matter*. A. B. Migdal's theoretical analysis of the pion field in nuclear matter[1] indicates that one of the excitation branches, with the quantum numbers of this field, may prove unstable. This phenomenon, which is usually known as π-condensation, arises at nucleon densities n exceeding a certain critical density n_c and may lead to the appearance of a second minimum on the density curve of the energy ε of a single nucleon in the nucleus. The two minima may arise in the following variants: first, the second minimum may occur at densities exceeding the density n_0 of the existing nuclei, with the energy ε_s at the second minimum either smaller or larger than ε_0 (ε_0 is the energy per single nucleon in the existing nuclei); second, the minimum corresponding to the higher density corresponds to ordinary nuclei, while the other minimum occurs at a lower density. The former case implies the existence of stable or metastable superdense nuclei. In the latter case, the π-condensate is present in ordinary nuclei, along with which metastable or stable rarefied nuclei may exist. These cases can be distinguished in experiments in which the π-condensate is sought in existing nuclei.

The case in which stable superdense nuclei exist is of the greatest interest for the discussion that follows (the possibility of existence of such nuclei was discussed in[2] with a different objective). In this case, the ordinary nuclei are unstable and may go over spontaneously to the superdense state. The question arises: how did the atomic nuclei get into the metastable state? This can be explained by the initial formation, during nucleosynthesis, of α particles, from which increasingly heavy nuclides were gradually formed by capture reactions. The calculations in[3] indicate that the critical density n_c decreases with increasing atomic number A. For lighter nuclei, therefore, the barrier separating the ordinary state from the superdense state is high and the transition of these nuclei to the superdense state during nucleosynthesis improbable. From this point of view, it is difficult to entertain the idea that stable rarefied nuclei may exist.

The hypothesis of the existence of stable superdense nuclei can be verified if they are present in ordinary matter and if spontaneous transitions of ordinary nuclei to the superdense state are observed. A search for superdense nuclei was made in[4]. The authors started from the assumption that the binding energy of the neutron should be much larger in superdense nuclei than in ordinary ones. A search was made for γ rays in the energy range from 30 to 250 MeV on capture of thermal neutrons by graphite. The absence of such quanta within the limits of statistical error gives a maximum superdense-nucleus concentration of 10^{-14} of the ordinary-nucleus concentration. Attempts were also made to find superdense radon on the assumption that superdense radon nuclei, unlike ordinary ones, would be stable. The upper concentration limit for superdense radon with respect to silicon was found to be 10^{-29}.

An attempt to detect a spontaneous transition to the superdense state was made in[5] for iodine and tungsten. The absence, within the limits of error, of the γ quanta that accompany this transition permits the conclusion that the lifetime with respect to the transition is longer than 10^{22} yr. The lower limit of the critical density n_c can be estimated on the basis of this value. By solving the problem of hydrodynamic flow of nuclear matter with a time-dependent nuclear radius R and approximating the function $\varepsilon(n)$ by parabolic segments (near the normal state

$$\varepsilon=\varepsilon_0+\frac{k_0}{2}\left(\frac{n-n_0}{n_0}\right)^2,$$

where k_0 is the compressibility, which equals 35 MeV), we arrive at an ordinary quantum subbarrier transition problem. We obtain for the transition probability

$$W=\omega\exp\left[-A^{1/3}F(\xi)\right] \quad (1)$$

($\xi=(n_c-n_0)/n_0$, $\omega\sim S/R$, where s is the velocity of sound in nuclear matter, which gives $\omega\sim 10^{21}$ sec^{-1}).

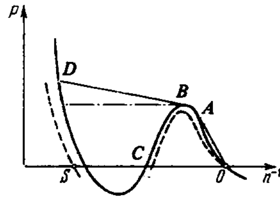

FIG. 1.

Comparison of (1) with the experimental lifetime gives $\xi\gtrsim 0.35$. We note for comparison that this value corresponds to a single-particle barrier height of ~ 5 MeV. Formula (1) cannot be valid for large A. In this range, the transition must be considered in the quantum theory of phase transitions,[6] on the basis of the quantum nucleation mechanism. Calculations similar to those in[5] result in the following formula for the transition probability:

$$W\approx\omega_3\exp\left[-2.9\left(\frac{k_0}{\varepsilon_0-\varepsilon_s}\right)^{7/2}f(\xi)\right] \quad (2)$$

(ω_3 is the vibration frequency of the radius of a small nucleation center). In the range corresponding to the experimental values, the nucleation-center radius is found to be of the same order as the radius of the nucleus, and the two formulas give results that do not differ within the limits of error.

Given long lifetimes and metastability of the superdense state, it can be produced in heavy-ion collision experiments. At incident-ion energies per nucleon ($w=E/A$) exceeding the Fermi energy $\varepsilon\approx 40$ MeV, the Fermi surfaces of the nucleons of the colliding nuclei do not overlap, and the Pauli principle is immaterial. Beginning at $w\sim 200$ MeV, the free path length is of the order of magnitude of the distance between nucleons, i.e., much smaller than the dimensions of the nucleus. Beginning at these energies, the hydrodynamic description is approximately valid for the behavior of the nuclear matter. The motions that arise in the nuclear matter at this point are of the nature of shock waves.[7]

Let us consider a collision of two fast heavy ions with about equal values of A. The collision pattern in the c.m.s. will be symmetrical about the central plane. Therefore the velocity of the matter will be equal to zero behind the wave front and equal to v_0 in front of it (v_0 is the velocity of the colliding ions in the c.m.s.). The change in the variables in the shock wave is given by the shock adiabat, whose approximate shape is indicated in Fig. 1 (the dashed curve is the Poisson adiabat for cold matter, and the points O and S correspond to the ordinary and superdense states). At small v_0, the pressure and density of the compressed nuclear matter are given by a point on segment OA. Approximating this segment, as before, by a parabola with a compressibility constant k_0, we obtain the following relation between energy and density:

$$w=2k_0\left(\frac{n-n_0}{n_0}\right)^2\frac{n}{n_0}. \quad (3)$$

At energies exceeding the critical value $w_c=2k_0\xi^2(1+\xi)$, the final state is determined by point D and not by a point on BC, as was stated erroneously in[8]. Then two shock waves separated by a region of self-similar flow (segments AB) propagate in the nuclear matter. As the energy increases, the point D rises up the shock adiabat and at a certain point line DB becomes an extension of OA. At higher energies, the flow again reduces to a single shock wave behind whose front the pressure and density jump from the undisturbed values to the values corresponding to D. Thus, the presence of an energy range with two shock waves indicates the existence of an inflection on the curve of ε plotted against specific volume.

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