Macroscopic behaviour of nuclear matter

The quantum revolution began with the insight that many classical concepts used to describe macroscopic objects break down when applied to atoms and molecules. Although the replacement of classical descriptions by quantum concepts was thought necessary because of the atoms' microscopic dimensions, several other factors can also determine the importance of quantum effects. Occasionally quantum phenomena appear on a macroscopic scale: superconductivity is an important example, but another is low-temperature helium, which remains liquid even at absolute zero instead of solidifying as a classical liquid would. Conversely, typical classical behaviour is well documented in atomic nuclei, even though they are 10^{-4} times smaller than the atoms in which they reside. The following are some of the remarkable macroscopic features of nuclei.

Density of nuclear matter. The volume of each nucleus is proportional to the number of nucleons it contains: each nucleon requires about $6 \times 10^{-39} \text{ cm}^3$. This uniformity is typical of macroscopic materials; by contrast, atoms are all about the same size whether they contain one electron or 100.

Binding energies. The energy that holds a nucleus together is nearly proportional to the number of constituent nucleons, with corrections for the reduced binding of the nucleons on the surface and for the electrostatic repulsion of the protons. Uniform macroscopic systems share this feature, whereas the binding energy of atoms increases much more rapidly with the number of electrons.

Statistical mechanics. Because the volume and binding energy of a nucleus are

Schematic phase diagram for nuclear matter. Open circle, critical point. G and L (which lie on the spinodal curve) illustrate gas and liquid densities, respectively, for a temperature T near the critical temperature T_c . (From ref. 2.)

proportional to the number of nucleons it contains, we may extrapolate from finite nuclei to the thermodynamic limit of infinitely extensive matter. The standard methods of quantum statistical mechanics permit the definition of a nucleus's entropy via its density of quantum states. When the excitation energy is large enough to eject a nucleon from the nucleus, it is not even necessary to introduce an artificial coarse-graining: a natural energy smearing is provided by the finite lifetime of the nucleus attributable to the emission of nucleons, which is known as evaporation. The concept of temperature can also be

introduced via its canonical relation to the energy and entropy.

Phase transitions. Even though nuclei have no more than a few hundred nucleons, the interplay between the free energy of a low-density gas and the short-range attractive forces that bind the nuclear liquid leads to the possibility of a liquid-gas phase transition for the same reasons as in a classical van der Waals fluid. In a finite system the phase boundaries are not sharp, but nevertheless quite distinct as is well known from molecular-dynamics simulations of classical fluids. The long-range electrostatic forces in nuclei complicate the phase transition but do not eliminate it.

Collective oscillations. Just like a droplet of compressible classical fluid, nuclei exhibit several kinds of collective oscillations. Well documented examples include volume-conserving vibrations of the drop's shape, standing waves of density inside the nucleus, spin waves and even 'isospin' oscillations in which neutrons and protons move oppositely.

Irreversible dissipative motion. Collective oscillations whose energy exceeds that necessary to evaporate a nucleon are damped by their coupling to the heat bath of statistical excitations of the nucleus; true irreversibility is manifest without artificial coarse-graining.

Superconductivity. The ground states of nuclei are dominated by Cooper pairs of nucleons moving in time-reversed quantum states, in close analogy with the BCS picture of superconductivity. The extensive evidence for this nuclear phenomenon is primarily related to the existence of the pairs: no one has yet measured the resistance of a nucleus. P.J.S.

The rate at which density fluctuations grow in nuclear matter is also affected by the quantum suppression of collisions. Heiselberg, Pethick and Ravenhall¹ obtain the first quantitative estimates of the growth of density instabilities in expanding hot nuclei by applying the Landau theory of degenerate Fermi liquids, which was developed² for liquid helium. They take the parameters of the Landau effective interaction from previous studies of the single-particle and collective excitations of cold nuclei. Linearization of Landau's kinetic equation leads to a simple estimate of the growth rate of the unstable modes. Using these growth rates together with simple estimates of the rate of expansion of the hot nuclear matter, they can predict which initial conditions of temperature and density will permit each mode to grow enough to break up the matter. As expected, the short-wavelength modes grow most rapidly; if all modes are randomly excited, the

shortest wavelengths will prevail (of course, only modes with wavelengths larger than the internucleon spacing are considered). The authors point out, however, that the initial conditions of a nuclear collision are not random, but may imply the early preferential excitation of long-wavelength modes.

The application of the known theory of quantum liquids to violent nuclear collisions points the way to a quantitative interpretation of current experiments. Recently commissioned accelerators in France (GANIL, 1987) and the United States (Michigan State, 1988) permit for the first time a systematic determination of the results of nuclear collisions in the range of projectile velocities around half the speed of light, where the effects of the liquid-gas phase transition should be most prominent. The experimental programme is very demanding, because the apparatus must be constructed to identify simultaneously a hundred or more reaction

products with widely-varying masses and speeds. An equally ambitious theoretical programme is needed to extend the techniques pioneered by Heiselberg, Pethick and Ravenhall to include both the highly ordered motion at the beginning of the collisions and the non-linear evolution of the instabilities, as well as to produce detailed predictions of the many-fragment final states. The promised reward for this effort is a terrestrial glimpse at the properties of matter under extreme conditions characteristic of the most extravagant astrophysical phenomena. □

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