Nuclear physics

Engineering with quark matter

Charles Alcock

THE possibility that small drops of 'quark matter' might be stable was first put forward by Witten[1]. More detailed calculations by Farhi and Jaffe[2] showed that the hypothesis was certainly plausible; also these authors named stable quark matter 'strange matter' because of the important role played by strange quarks, a name which has stuck. The strange-matter hypothesis has several interesting consequences, principally in astrophysics (for a review see ref. 3). Two new papers, that of Brügger *et al.* on page 434 of this issue[4] and one by Madsen[5], address the question of how much strange matter there is in our part of the Universe. And Shaw *et al.* on page 436 of this issue[6] suggest a novel scheme for producing small lumps of strange matter, collecting and then growing the lumps; this is a proposal for engineering with quark matter.

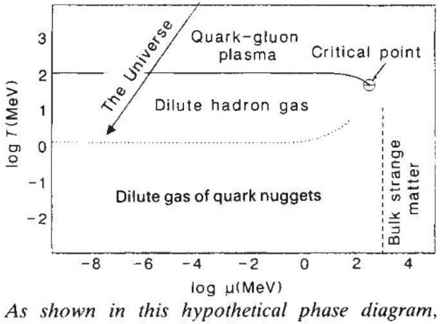
Quark matter is a hypothetical phase in which quarks are not confined in individual hadrons such as the proton (which consists of two 'up' quarks and one 'down') and the neutron (one up and two down quarks), but are free to move about within the phase. Strange matter is a quark-matter phase which contains three flavours of quarks — up, down and strange — and a few electrons. By hypothesis, strange matter is absolutely stable, which means that its mass (energy) per quark is lower than that of iron (which is the most stable ordinary nuclear matter) and cannot decay without violating energy conservation (see figure). This hypothesis is consistent with phenomenological models of the strong interaction, but good first-principle computations of the mass per baryon are not available.

Because strange matter is a bulk phase, it might be found in lumps of atomic mass A in the range 10^2–10^{57}, but with atomic number (charge) Z much less than $A/2$. These positively charged lumps are often known as quark nuggets. They behave chemically as ordinary atoms with the same Z and are, roughly speaking, monstrous isotopes. A quark nugget may grow by absorbing neutrons; charged particles such as protons are not readily absorbed because of Coulomb repulsion.

For theorists, not being able to recognize the true ground state of the strong interactions (is it iron or strange matter?) is very disturbing. It makes sense, therefore, to search for quark nuggets or use experiments to settle the question. Madsen[5] proposes that observations of pulsars should help. Conventionally it is suggested that neutrons are the stable form of matter in the enormous gravitational field of these collapsed stars, but some argue that strange matter is. For his proposal, Madsen adduces the conclusion of Alpar[7] that the radio pulsars which exhibit glitches (abrupt, very small period reductions followed by a few months of relaxation) must be made of neutron matter, not stange matter. This conclusion rests on the success of neutron-star models for the glitch phenomenon and the absence of a model for glitches in the context of strange matter. Because strange matter absorbs neutrons, one seed of strange matter will convert an active neutron star into a 'strange' star. Madsen's analysis rests on the rate at which these seeds would be accreted from the interstellar medium.

Should they exist in the interstellar medium, quark nuggets will rain steadily onto stars, where friction slows them down. Thus a nugget can become bound to a star. If the star is a neutron star, the nugget will act as a seed which will grow until the entire star is converted to strange matter. Furthermore, if the star is the progenitor of a neutron star (a high-mass normal star which eventually explodes as a supernova, compressing its core to a neutron star), then any nuggets it captures will be present later when the neutron star is made. Madsen shows that this latter process is the most interesting and places limits on the number of quark nuggets in the interstellar medium. This is a model-dependent limit, of course, but it does show how to approach issues of fundamental physics using astrophysics.

A more direct method for seeking quark nuggets has been used by Brügger *et al.*[4], who have adapted Rutherford scattering, bombarding material samples with beams of ^{238}U and ^{208}Pb nuclei. Any back-scattering of the beams by angles greater than 90° indicates the presence of scattering centres (the nuggets) more massive than the projectile nuclei.



As shown in this hypothetical phase diagram, strange matter is a high-density, low-temperature phase (density increases with chemical potential μ). At high temperature, strange matter evaporates into ordinary hadrons (dotted line), much as a solid sublimates into vapour on heating; this transition is not a phase transition. At higher temperature, the hadron gas undergoes a phase transition (solid line) to a hot gas of quarks and 'gluons'. Cosmic or experimental production of strange matter occurs by producing the hot quark–gluon plasma with the hope that rapid cooling will trap portions of the matter in the cold, condensed phase. A detailed mechanism for accomplishing this has not been proposed. (Temperature T *in megaelectron volts; 1 MeV ≈ 10^{10} K.) (From ref. 3.)*

Brügger *et al.* applied this elegant technique to various natural samples (including a meteorite) and derive upper limits to the abundance of quark nuggets: 1 per 10^{10} for nuggets with $A \simeq 10^3$ down to 1 per 10^{14} at $A \approx 10^7$. The technique is less readily applied for higher atomic number because the electrostatic potential of the nuggets is not a simple Coulomb form.

Shaw *et al.*[6] propose a much more direct approach to the study of strange matter. They propose that high-energy heavy-ion collisions of the kind studied in present CERN and Brookhaven National Laboratory experiments might make small quark nuggets. They further describe a scheme for isolating, slowing down and storing nuggets which are produced in the experiment. Any nugget which is captured may then be "grown" by the addition of low energy neutrons. This growth phase releases of order 20 megaelectron volts of energy per captured neutron — potentially a useful source of power, as this is nearly 10 times the energy yield per neutron in a conventional fission reactor. In this regard Shaw *et al.* are proposing a first attempt at engineering with quark matter.

There are uncertainities in this proposal. First, it is not clear that the CERN and Brookhaven experiments do indeed make a quark phase. Second, this phase will contain plenty of up and down quarks but strange quarks are produced only as $s\bar{s}$ pairs, and the strange quarks must separate from their anti-strange counterparts. Third, strange matter is a low-temperature phase and these experiments produce a very hot plasma (see figure). And fourth, the isolation scheme proposed looks for negatively charged nuggets, whereas strange matter is almost certainly positively charged in its most stable form.

Despite these reservations, the proposal does not seem to be an expensive addition to experiments that are already in progress. As the payoff in physics would be so large if strange matter were detected, the ideas should be further explored And the new engineering ideas raise interesting long-term prospects for energy generation. ☐

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Charles Alcock is at the Institute of Geophysics and Planetary Physics, Lawrence Livermore National Laboratory, PO Box 808, Livermore, California 94550, USA.