On the possibility of nuclear stability beyond the drip line

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Abstract

As successive neutrons are added to a nucleus their binding becomes weaker and weaker until finally the next neutron is not bound. This defines the neutron drip line. I explore the possibility that nuclear stability may be restored for neutron numbers far beyond the drip line. In this region the extra neutrons can bind into a nuclear cluster, or droplet, that is stable against strong decay and that can bind to an ordinary nucleus to form a nuclear composite. Neutrons can flow between members of the composite until the energy reaches its minimum. The resulting composite nucleus is stable against strong decay. Because there is no upper limit to the size of a neutron droplet there is no upper limit to the masses of such nuclei.

It has long been suspected that a sufficiently large number of neutrons may bind together to form a neutron droplet that is bound and stable against all but beta decay. Ogloblin and Penionzhkevich [1] note that the ^{3}He interatomic potential and the n-n potential are similar, both of them being attractive with a repulsive core but not strong enough to bind a stable molecule or nucleus. A sufficient number of ^{3}He atoms do bind to form a liquid helium drop, and the possibility exists that a sufficient number of neutrons may similarly bind to form a neutron drop. Because the dineutron is unbound by only about 70 keV, a small deepening of the potential would make it stable. If the required additional attraction could be achieved by adding more neutrons to the dineutron system a drop of neutron matter might appear beginning with some critical neutron number.

Two lines of investigation, one theoretical and one experimental, support the Ogloblin and Penionzhkevich idea. The calculation by Efimov [2] shows that a three-body system can be bound even when none of the three possible pairs of participating particles is bound. The strength of this collective binding is expected to increase as the number of particles increases. Because the neutron-neutron interaction is attractive the method of Bardeen, Cooper and Schrieffer [3] is expected to apply, and the binding energy per neutron is expected to grow rapidly stronger as the size of a neutron aggregate grows, until the droplet reaches a coherence volume beyond which the pair correlations no longer remain in phase. The binding energy per additional neutron then varies relatively slowly with size as the proportion of neutrons near the surface of the drop declines. On the experimental side Marqués *et al.*[4] have recently reported evidence that the tetraneutron is bound, suggesting that two pairs already provide enough binding through the BCS mechanism to stabilize ^{4}n.

The coherence volume for neutron matter remains to be determined. I assume tentatively that it includes first- and second-nearest neighbors and a little more, leading to a coherence volume of perhaps 24 neutrons. Beyond this size the energy of the droplet can be approximated by a liquid drop model in which the nuclear interaction energy is represented as the sum of a negative contribution proportional to the droplet volume and a positive contribution proportional to the surface area. The droplet mass excess then is the sum of the mass excesses of the neutrons minus the volumetric energy plus the surface energy,

$$\Delta(^{\mathrm{A}}\mathrm{n}) = \mathrm{A}\Delta(\mathrm{n}) - a_v\mathrm{A} + a_s\mathrm{A}^{2/3}. \tag{1}$$

Now we ask for the configuration that results when an ordinary nucleus and a neutron droplet come in contact. I suggest that the droplet and the ordinary nucleus retain their identities as distinct phases of nuclear matter and that they stick together to form a composite nucleus. I expect that their configuration resembles that of a droplet of oil and a droplet of water bound together by the reduction of surface energy over the area of contact. Following initial contact neutrons flow between the neutron droplet and the ordinary nucleus until their neutron separation energies equilibrate.

We can utilize the liquid drop model to quantify the energy of the resulting nucleus. To Equation 1 we must add two terms, the mass excess of the ordinary nucleus, and a negative energy term that represents a reduction in energy due to the binding of the two members of the composite. For neutron droplets as large or larger than the coherence volume the drop model is expected to apply to the composite with unchanged coefficients a_v and a_s. For a composite composed of an ordinary nucleus $^{\mathrm{B}}\mathrm{Z}$ and a neutron droplet $^{\mathrm{A}}\mathrm{n}$, equation (1) can be generalized to

$$\Delta(^{\mathrm{B}}\mathrm{Z}^{\mathrm{A}}\mathrm{n}) = \Delta(^{\mathrm{B}}\mathrm{Z}) + \mathrm{A}\Delta(\mathrm{n}) - a_v\mathrm{A} + a_s(\mathrm{A})^{2/3} - E_b \tag{2}$$

where $-E_b$ is the net reduction in surface and interfacial energies of the two components. The composite nucleus is written in the form customary for molecules with the individual constituents $^{\mathrm{B}}\mathrm{Z}$ and $^{\mathrm{A}}\mathrm{n}$ written adjacent to each other. (In conventional notation the configuration $^{\mathrm{B}}\mathrm{Z}\,^{\mathrm{A}}\mathrm{n}$ would be written $^{\mathrm{A+B}}\mathrm{Z}$ indicating a nucleus with A+B nucleons including Z protons, but providing no information regarding its composite nature.)

Consider now the transfer of one or more neutrons between a neutron droplet and an ordinary nucleus in contact. The condition for stability is that the reactions

$$^{\mathrm{B}}\mathrm{Z}^{\mathrm{A}}\mathrm{n} \longrightarrow \,^{\mathrm{B+x}}\mathrm{Z}\,^{\mathrm{A-x}}\mathrm{n} \tag{3}$$

must be endothermic for all x. Using the expression for $\Delta(^{\mathrm{B}}\mathrm{Z}^{\mathrm{A}}\mathrm{n})$ in Equation (2), and neglecting the small variations in $a_s(\mathrm{A})^{2/3}$ and E_b that accompany neutron transfer, the conditions for stability become

$$a_v > \Delta(\mathrm{n}) - \mathrm{x}^{-1}\Big(\Delta(^{\mathrm{B+x}}\mathrm{Z}) - \Delta(^{\mathrm{B}}\mathrm{Z})\Big) \tag{4}$$

for transfer of x neutrons from $^{\mathrm{A}}\mathrm{n}$ to $^{\mathrm{B}}\mathrm{Z}$ and

$$a_v < \Delta(\mathrm{n}) + \mathrm{x}^{-1}\Big(\Delta(^{\mathrm{B-x}}\mathrm{Z}) - \Delta(^{\mathrm{B}}\mathrm{Z})\Big) \tag{5}$$

for transfer of x neutrons from ${}^{\rm B}$Z to ${}^{\rm A}$n.

The value of a_v is further constrained by the stability of ordinary nuclei ${}^{\rm A}$Z against the transformation ${}^{\rm A}{\rm Z} \longrightarrow {}^{\rm A-B}{\rm Z}\,{}^{\rm B}{\rm n}$. This transformation would manifest itself by a discontinuous drop in the value of $\partial\Delta({}^{\rm A}{\rm Z})/\partial{\rm A}$ at a value of ${\rm A}_{crit}$ at which the transformation becomes exothermic. For A smaller than ${\rm A}_{crit}$ the slope $\partial\Delta({}^{\rm A}{\rm Z})/\partial{\rm A}$ increases quadratically. For A larger than ${\rm A}_{crit}$ the slope abruptly becomes less steep and increases only linearly. Because this discontinuity is not observed in the reported values of $\Delta({}^{A}{\rm Z})$ we can conclude subject to the caution below that for these values the transformation is endothermic. Taking B $\approx$ 24 in the neighborhood of the coherence volume this constraint suggests

$$a_v < 6 \tag{6}$$

in units of MeV. This is about 40% of the value of the liquid drop model value a_{vo}=15.5 MeV per nucleon for ordinary nuclear matter [5]. (It shuld be noted that at large A the reported values of $\Delta({}^{\rm A}{\rm Z})$ have been determined from shell model statistics, not direct observation, and that a slope discontinuity actually may have occurred at a somewhat smaller value of A than the maximum tabulated value. For this reason the $a_v < 6$ constraint should be considered tentative.)

As a final condition on a_v it is necessary that

$$a_v > 0 \tag{7}$$

since otherwise the neutron droplet would not be bound.

As an example consider the transfer of x neutrons from ${}^{\rm A}$n to ^{4}He in the composite nucleus ${}^{4}{\rm He}\,{}^{\rm A}{\rm n}$. For x $= 1, 2, 3, 4, 5$ the respective stability conditions are $a_v > -0.9, 0.5, 0.2, 0.8, 0.4$ MeV. The most restrictive condition is $a_v > 0.8$ MeV which is required for preventing decay in the reaction channel ${}^{4}{\rm He}\,{}^{\rm A}{\rm n} \longrightarrow {}^{8}{\rm He}\,{}^{\rm A-4}{\rm n}$. Next consider the transfer of x neutrons from ^{4}He to ${}^{\rm A}$n. For x $= 1$ (the only available channel) the stability condition is $a_v < 20.6$ MeV which is required for preventing ${}^{4}{\rm He}\,{}^{\rm A}{\rm n} \longrightarrow {}^{3}{\rm He}\,{}^{\rm A+1}{\rm n}$. Considering all four restrictions (4,5,6,7) the requirement for stability of ${}^{4}{\rm He}\,{}^{\rm A}{\rm n}$ is $0.8 < a_v < 6$ MeV.

The binding energy per nucleon is smaller for neutron droplets than for ordinary matter, perhaps much smaller. Close to the lower limit $a_v = 0$ the ordinary nuclei that are capable of joining with neutron droplets to form stable (against strong decay) composites are limited to ^{3}H, ^{8}He, ^{11}Li, ^{14}Be, ^{15}B, ^{23}N, ^{24}O, and ^{48}S. As a_v approaches its upper limit $a_v = 6$

their identities change and their number expands to include ^{4}He, ^{7}Li, ^{11}Li, ^{14}Be, ^{15}B, ^{14}C, ^{15}N, ^{18}O, and increasingly neutron-rich nuclei from Z = 9 through at least Z = 108, except possibly for Ir and Pt.

Experiments designed to build up the neutron concentrations around ordinary nuclei to the point that stable composites can be obtained are faced with the problem that for low-Z nuclei one or two or three or more neutrons beyond the drip line are not bound, and that it may be necessary to add five or ten or more neutrons to obtain the desired binding. It may be preferable to look for such nuclei as products of high-energy collisions between neutron-rich nuclei where excess neutrons are available for the collision fragments, among which composite nuclei might be detected provided that the data analysis parameters are appropriately adjusted. For high-Z nuclei there may be no gap between ordinary and composite nuclei as the neutron number is incresed. Instead there may be a discontinuity in the rate of increase of mass excess as neutrons are added. High-Z composites might be revealed by mass measurements of extremely neutron-rich nuclei, some of which although detected by their decay patterns have not yet had their mass excesses determined. Although composite nuclei are stable against strong decay for unlimited sizes of their neutron droplet components, those most likely to be formed in collision experiments will have close to the minimum numbers of neutrons that can form bound composites. I thank M. E. Fisher for valuable discussions.

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