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Looking for Precursors of Neutron Matter Exotica

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LOOKING FOR PRECURSORS OF NEUTRON MATTER EXOTICA [†]

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[†] Prepared for The First International Conference on Radioactive Nuclear Beams, 16-18 October 1989, Berkeley, California

LOOKING FOR PRECURSORS OF NEUTRON MATTER EXOTICA †

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ABSTRACT

The question of the possible stability of neutron matter is investigated within the framework of a Thomas-Fermi model of nuclei. Some of the consequences of bound (or slightly unbound) neutron matter are discussed. A comparison is then made between the model predictions and the observed neutron drip line for light nuclei. The tentative conclusion arising from this comparison is that neutron matter is probably unbound, in approximate agreement with an earlier theoretical estimate1). Quantum effects that could lead to extremely large neutron halos are also briefly discussed.

INTRODUCTION

If neutron matter were bound, nuclear physics would be enriched by amazing structures. These structures, with lifetimes limited only by beta decay, would include neutron balls of arbitrary size (no fission or alpha decay to limit the mass number!). They might contain clusters of protons, with topologies not necessarily those of a single sphere, e.g. two or more fragments held apart by their coulomb repulsion, or a hollow proton bubble. (See fig. 1.) Unfortunately, neutron matter is probably not bound. But how far is one from such an exotic generalization of nuclear physics?

If neutron matter is only slightly unbound we might expect to see precursors of exotic neutron matter effects in phenomena that are observable at the neutron drip lines. The best way to proceed is to study nuclei with the largest possible neutron excess, both light and heavy nuclei, since even if bulk neutron matter were bound, small neutron balls would tend to be destabilized by their surface energy. If neutron matter is unbound the maximum neutron excess for a given Z is limited by neutron drip. Otherwise, (for a sufficiently large system) the neutron excess could grow indefinitely.

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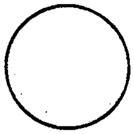
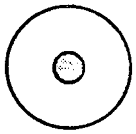
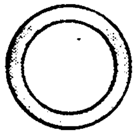
In connection with questions like these, we have undertaken a series of self-consistent, Thomas-Fermi calculations using a phenomenological interaction similar to that of Seyler and Blanchard[2]. In the next section these calculations are briefly described. The following sections discuss how this model can be used to calculate the effect on the neutron drip line of various assumptions about the extent to which neutron matter is bound or unbound. The next section refers to some earlier work where the effect of neutron excess on nuclear surface properties was considered in some detail. In the final section an estimate is made of the extent to which quantum penetration into the forbidden region would produce a halo for a weakly bound neutron.



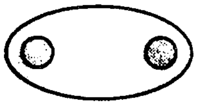
a) A neutron ball of arbitrary size



b) A proton ball inside a neutron ball



c) A proton shell inside neutron ball



d) Two (or more) proton clusters inside a deformed neutron ball

Fig. 1 Configurations that might arise if neutron matter were bound.

THE THOMAS-FERMI METHOD AND THE SEYLER-BLANCHARD FORCE

The phenomenological, momentum-dependent, two-body force of Seyler and Blanchard[2)] has been employed in general studies of saturating two component systems[3)], for predicting nuclear masses and sizes[4)], for studying nuclei at finite temperatures in equilibrium with their associated vapor[5)], and for a detailed study of the behavior of the surface energy of a two-component system[6)]. The nuclear properties are obtained by minimizing the energy of a system of particles whose kinetic energy distribution is obtained from the density by the Thomas-Fermi assumption and whose potential energy is calculated with the phenomenological Seyler-Blanchard force. The Euler equation that results is solved by computer iteration.

We found that it was necessary to generalize the original Seyler-Blanchard force slightly in order to obtain the best possible agreement with the measured charge distributions while retaining agreement with measured values of the nuclear masses.[†] The interaction that was used for two like (l), or unlike (u), nucleons with separation r and relative momentum of magnitude p (where p is in units of the Fermi momentum) was

$$V(r,p) = -\frac{C}{4\pi a^3}\frac{e^{-r/a}}{r/a}[\alpha_{l,u} - \beta_{l,u}p^2 + \gamma_{l,u}/p] \,, \tag{1}$$

The parameters of the model were determined by a fit to nuclear masses[7)] and constrained by comparing our calculated charge distributions with those obtained from electron scattering experiments[8)]. This led to the following nuclear properties:

$$\begin{array}{lrl} \text{nuclear radius constant} & r_0 = & 1.13 \text{ fm,} \\ \text{volume energy} & a_1 = & 16.527 \text{ MeV,} \\ \text{symmetry energy} & J = & 31.375 \text{ MeV,} \\ \text{surface energy} & a_2 = & 20.268 \text{ MeV,} \\ \text{compressibility} & K = & 301.27 \text{ MeV.} \end{array} \tag{2}$$

If in addition the properties of pure neutron matter are adjusted to agree with Friedman & Pandharipande[1)] the following parameter values result:

$$\begin{array}{lcl} C = 455.46 \text{ MeV fm}^3 & , & a = 0.59542 \text{ fm} \\ \alpha_l = 0.74597 & , & \alpha_u = 2.86331 \\ \beta_l = 0.25255 & , & \beta_u = 1.23740 \\ \gamma_l = 0.21329 & , & \gamma_u = 0.0 \,. \end{array} \tag{3}$$

[†] We are currently engaged in an extension of the Seyler-Blanchard, Thomas-Fermi approach to the calculation of fission barriers as a function of angular momentum. One of the consequences of this project will be a more precisely determined set of force parameters.

NEUTRON MATTER

The parameter set of eq. (3) above were chosen so that the predicted properties of neutron matter would be approximately the same as those given in reference 1. However, by varying the ratio $r = \beta_l/(\beta_l + \beta_u)$ we could also survey a range of possibilities, all of which are forced to reproduce the set of values for the nuclear properties given in eq. (3), but which differ in the prediction of neutron matter properties. In fig. 2 the predicted energy per particle for $N = Z$ nuclear matter is plotted versus the Fermi momentum as a solid line. The predicted energy per particle of neutron matter for various values of the coefficient r are shown as dashed lines and the results of Friedman & Pandharipande[1)] are plotted as open squares. (A value of $r = 0.16950$ produces a curve in approximate agreement with these points.)

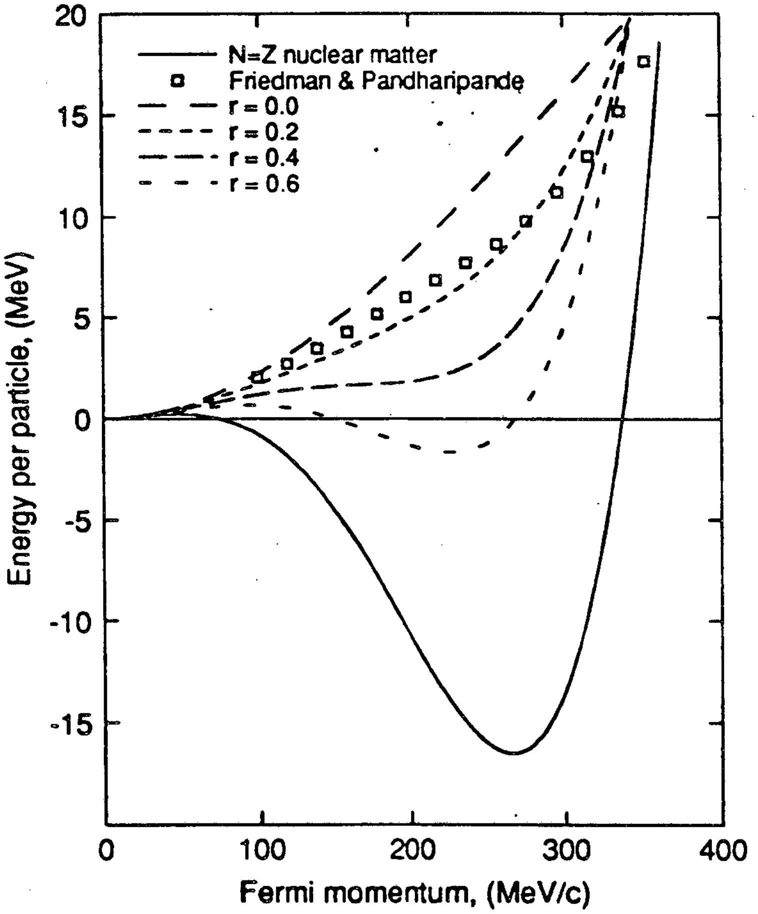


Fig. 2 The energy per particle of $N = Z$ nuclear matter is plotted versus the Fermi momentum as the solid curve. The energy per particle for neutron matter is also shown for various choices of the parameter r. The open squares correspond to the work of Friedman & Pandharipande[1)].

PREDICTED DRIP LINES

We have solved the finite nucleus Euler equation corresponding to eq. (1), the values of eq. (2) and various choices for the parameter r for a broad range of nuclei. Along the line of beta-stability in the nuclide chart the value of r has little effect, but the limit of particle stability at the neutron drip line is strongly effected. In fig. 3 a portion of the nuclide chart is shown where the grey squares represent nuclei that have been observed or are thought to be particle stable on the basis of extrapolation[9]. The heavy lines, labeled with r values from 0.0 to 0.4 correspond to a rough estimate of the corresponding location of the neutron drip line. (The Wigner term and the even-odd correction were not included.) Examination of this figure suggests that the Friedman & Pandharipande[1] value ($r = 0.16950$) is a little small. However, a value higher than 0.4 seems to be clearly excluded. This means that neutron matter is unlikely to be bound. (See fig. 2.)

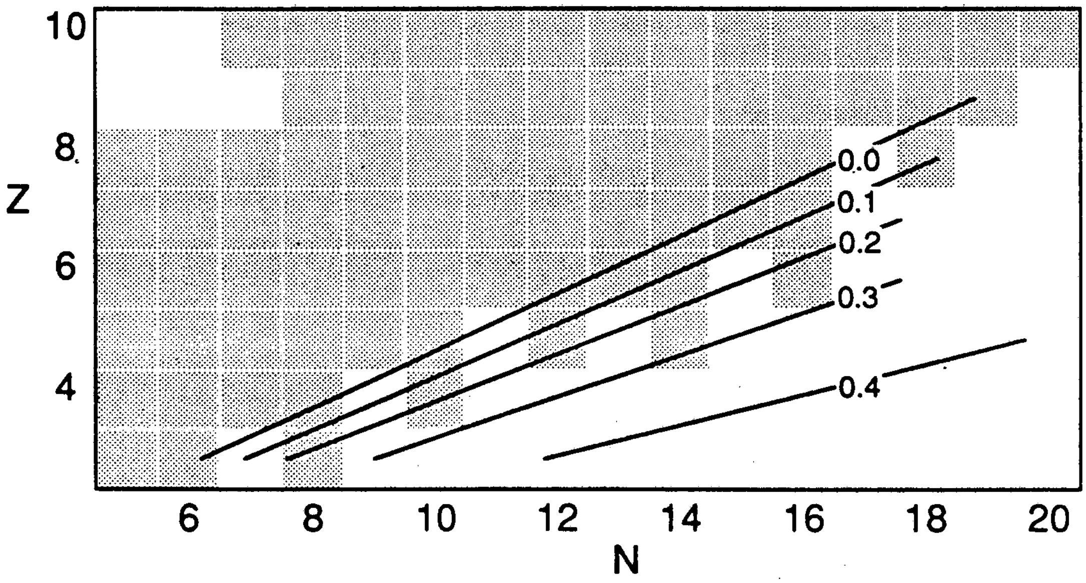


Fig. 3 A portion of the nuclide chart showing as grey squares nuclei that are known (or thought to be) stable against particle emission. The solid lines correspond to the predicted limits of stability for different values of the parameter r.

SURFACE EFFECTS

In an earlier work$^{6)}$ we investigated the dependence of nuclear surface properties on the neutron excess for a Seyler-Blanchard Thomas-Fermi system whose neutron matter equation of state was similar to the one for $r = 0.4$ shown in fig. 2. For such a system neutron matter is still unbound but the energy per particle does not rise as steeply as a function of density as it does for smaller values of r. For slightly larger values of r neutron matter would be metastable since the energy per particle would have a minimum at positive energy. For r somewhere around 0.5 neutron matter becomes stable with a minimum in the energy per particle turning negative. Even though it is unlikely that neutron matter is actually bound the flattening out of the energy per particle curve can produce some interesting surface effects at the neutron drip line that can be considered precursors of binding.

The calculations of interest were performed by solving the Euler equation for semi-infinite nuclear matter for various values of the asymptotic asymmetry $\delta = (\rho_n - \rho_z)/(\rho_n + \rho_z)$, which is the ratio of the difference in the neutron and proton densities to the total density in the interior region remote from the surface. The results of these calculations for four different values of δ are shown in fig. 4. For the parameters chosen for this calculation neutron drip occurs at $\delta \approx 0.3$.

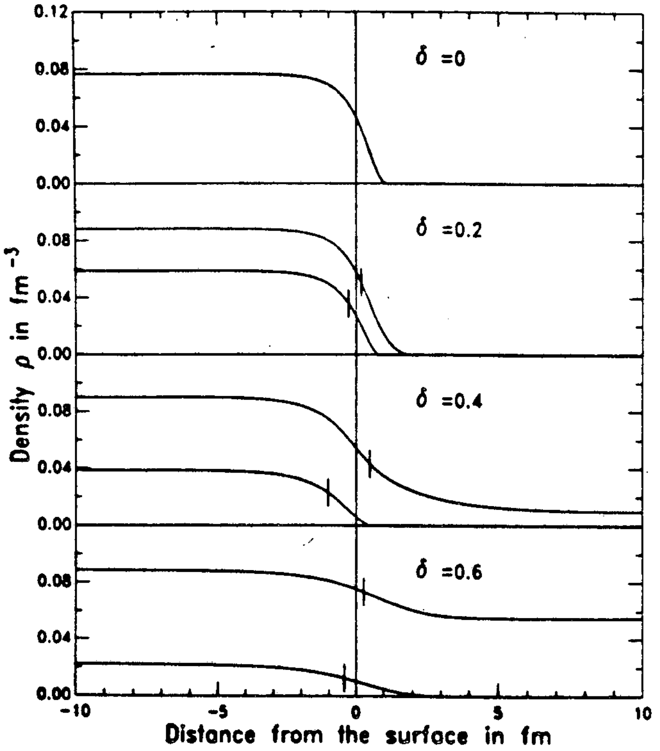


Fig. 4 The Thomas-Fermi density distributions for semi-infinite nuclear matter are plotted with respect to the mean location of the surface for four different values of the asymptotic asymmetry δ. For δ values larger than zero the upper curve represents the neutrons and the lower one the protons. The small vertical bars serve to identify the separate locations of the neutron and proton surfaces.

As δ increases the neutron skin thickness (the distance between the locations of the surfaces of the neutron and proton density distributions) grows. This quantity is shown in fig. 5 along with the corresponding Droplet Model prediction, which is quite accurate for small values of δ. However, the calculated value of the neutron skin thickness increases even more rapidly. At neutron drip the skin thickness is already almost 0.8 fm and at $\delta \approx 0.4$ it passes through a sharp maximum that is probably associated with the flat part of the energy per particle curve for $r = 0.4$ in fig. 2. Indeed, we would expect the skin thickness to increase indefinitely if neutron matter were actually bound.

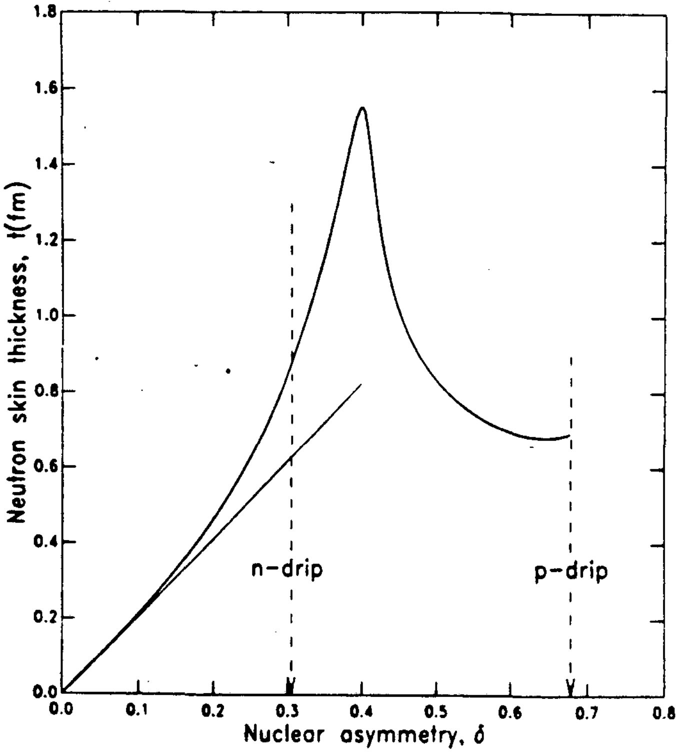


Fig. 5 The neutron skin thickness (the difference between the surface locations of the neutrons and protons) is plotted against the asymptotic asymmetry δ for δ values from zero through the neutron drip point, all the way up to the proton drip point. The thin straight line from the origin is the Droplet Model prediction for this quantity.

The width (diffuseness) of the neutron density distribution also increases with increasing neutron excess. Our Thomas-Fermi results for this effect are plotted in fig. 6 against the asymptotic asymmetry δ. The width is seen to increase by about 60% at the neutron drip point. This change in the density distribution will be reflected in the width of the potential well for the neutrons and affect the positions of the single particle levels. Consequently, one would expect to see different magic numbers at the drip line. Of course, quantum penetration effects (not included, at present, in our statistical model calculations) will substantially increase the neutron halo effect at the drip line. This is discussed in the next section.

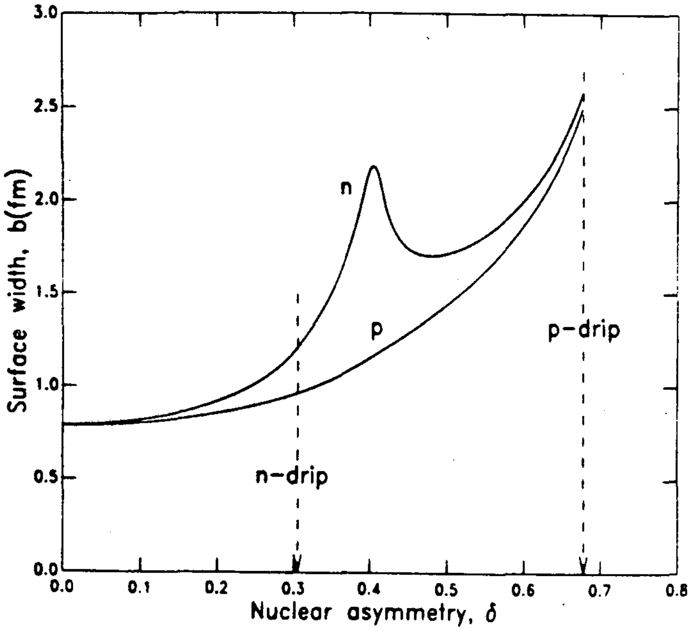


Fig. 6 The widths (diffuseness) of the surfaces of the neutron and proton distributions are plotted against the asymptotic asymmetry δ for δ values from zero through the neutron drip point, all the way up to the proton drip point.

QUANTUM EFFECTS

The observation$^{10)}$ of relatively large interaction radii for ^{11}Li and ^{14}Be has led us to consider an estimate of the size of a loosely bound nucleus. In fig. 7 we have plotted a rough estimate of the probability for finding a neutron (bound by only 100 keV) at a radius larger than R. The calculation was based on a simple WKB estimate of the wave function in the classically forbidden region for a potential consisting of a Woods-Saxon well, with parameters appropriate for a nucleus with 125 particles$^{11)}$, augmented by a centrifugal potential. The probability is plotted for angular momentum values of 0, 1, 2, 3, and $4\hbar$. The results are dramatic. For $L = 0$ there is a 10% chance of finding the neutron at a radius greater than 25 fm. In fact there is still a 1% chance of finding it at a radius greater than 40 fm. Even though the centrifugal potential tends to cut off the wavefunction for larger angular momenta there is still a relatively large probability of finding the neutron at large distances from the nucleus. For $L = 1$ the probability is still 1% at 30 fm and for $L = 2$ it is still 1% at about 20 fm. Smaller binding energies would result in correspondingly larger effects. Such large halos must surely be observable, for example, in cross section measurements such as those done by Tanihata et al.$^{10)}$

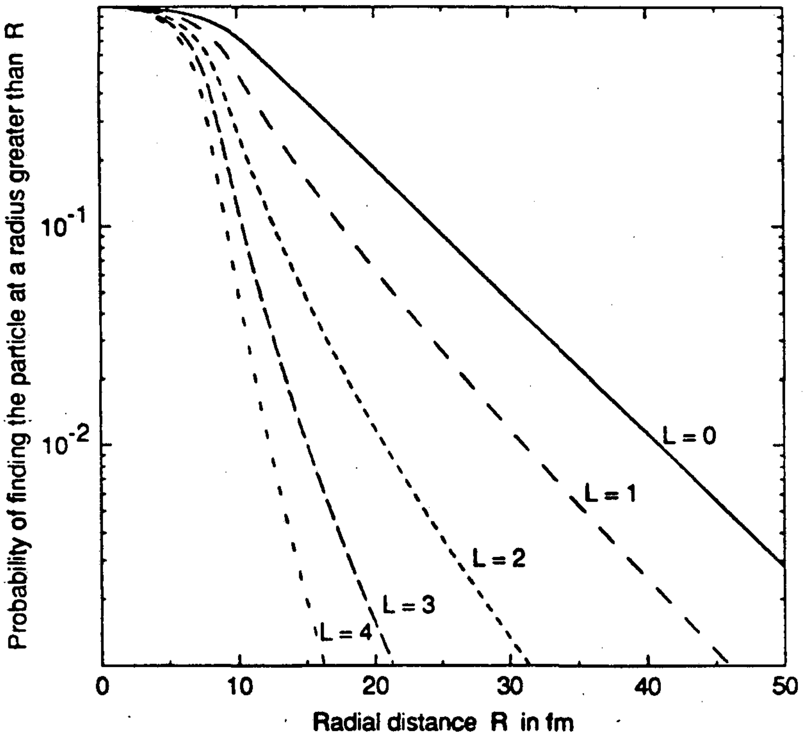


Fig. 7 A simple WKB estimate for the probability of finding a loosely bound neutron (100 keV) at a radius R is plotted versus the radius R for a nucleus containing approximately 125 particles. The different lines correspond to orbital angular momentum values of 0, 1, 2, 3 and $4\hbar$.

CONCLUSION

A Thomas-Fermi nuclear model has been used to see if different assumptions regarding the behavior of neutron matter would have observable effects for finite nuclei. Such effects were found at the neutron drip line and lead us to conclude that neutron matter is probably not bound. (But the equation of state may not be quite as stiff as that predicted by Friedman & Pandharipande$^{1)}$.) In addition an estimate of quantum penetration effects was made for a loosely bound neutron, with the conclusion that large halos are to be expected in some special cases.

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