Title
A NEW MECHANISM LEADING TO DENSITY ISOMERS

Author
Boguta, J.

Publication Date
2012-04-01

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

Submitted to Physics Letters

A NEW MECHANISM LEADING TO DENSITY ISOMERS

J. Boguta

April 1981

NUCLEAR SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract W-7405-ENG-48

DISCLAIMER

LBL-12333

A NEW MECHANISM LEADING TO DENSITY ISOMERS*

J. Boguta

Nuclear Science Division, Lawrence Berkeley Laboratory
University of California, Berkeley, CA 94720

Abstract:

A new mechanism leading to density isomerism in nuclear matter is proposed. The density isomer is produced by the excitation of baryonic degrees of freedom. A self-consistent relativistic model that accounts for known bulk properties of symmetric nuclear matter is explicitly constructed, in which the density isomer occurs at about three times normal density. Thermal excitations are considered.

*This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract W-7405-ENG-48.

Many people have conjectured about the possible existence of nuclear matter density isomers.[1)] The most recent proposal was that of Lee and Wick,[2)] who observed that a nonlinear scalar meson self-interaction model, such as the chiral sigma model, can lead to an abnormal nuclear state. The shortcoming of many of the above proposals was that they either did not attempt to describe the nuclear matter equation of state at various densities or else, as in the case of the chiral sigma model, the description of the known properties of nuclear matter was incorrect.[3)] Since the existence of an isomer state is speculative, it is desirable to construct models that at once contain an isomer state and also describe the known nuclear matter properties in a consistent way. The obstacle for achieving such a model was the bias that a density isomer state could be formed only as a result of scalar meson excitations. In a phenomenological analysis it was shown that the parametrization of the binding energy per particle (-15.75 MeV), saturation density ρ(0.16 baryons/fm^3) and compressibility K ($\approx$280 MeV) eliminates the scalar meson excitations as candidates for nuclear isomerism.[4)] The purpose of this work is to suggest a new mechanism leading to density isomers. In a relativistic mean field model of nuclear matter we include the delta resonance and show that if the delta interaction is sufficiently attractive an isomer state results.

We assume that the nucleon ψ_N and the delta ψ_Δ interact with an isoscalar scalar field σ and isoscalar vector field ω_μ. In symmetric nuclear matter, the pion and rho meson contributions vanish in the mean field approximation. The nucleon field ψ_μ is a four component wave function corresponding to a spin 1/2 particle, while the delta wave function $\psi_{\mu\alpha}, \mu, \alpha = 1,4$ corresponds to the Rarita-Schwinger spin 3/2 particle.[5)] The simplest nonderivative coupling of baryons to meson fields is given by the following Lagrangian.

$$L = -\overline{\psi}_N(\gamma_\mu \partial_\mu + m_N)\psi_N - \overline{\psi}_\Delta(\gamma_\mu \partial_\mu + m_\Delta)\psi_\Delta - \frac{1}{2}(\partial_\mu \sigma)^2 - U(\sigma)$$

$$- \frac{1}{4} F_{\mu\nu}F_{\mu\nu} - \frac{1}{2} m_V^2 \omega_\lambda \omega_\lambda + ig_{\omega N}\overline{\psi}_N \gamma_\lambda \psi_N \omega_\lambda$$

$$+ ig_{\omega\Delta}\overline{\psi}_\Delta \gamma_\mu \psi_\Delta \omega_\mu - g_{SN}\overline{\psi}_N \psi_N \sigma - g_{S\Delta}\overline{\psi}_\Delta \psi_\Delta \sigma \tag{1}$$

where

$$F_{\mu\nu} = \frac{\partial \omega_\nu}{\partial x_\mu} - \frac{\partial \omega_\mu}{\partial x_\nu} \tag{2a}$$

$$U(\sigma) = \frac{m_s^2}{2} \sigma^2 + \frac{b}{3} \sigma^3 + \frac{c}{4} \sigma^4 \tag{2b}$$

with $\quad c > 0 \qquad$ (2c)

For symmetric (N = Z), translationally and rotationally invariant nuclear matter, the resulting field equations are

$$m_S^2 \sigma + b\sigma^2 + c\sigma^3 = -g_{SN}\rho_S(N) - g_{S\Delta}\rho_S(\Delta) \tag{3a}$$

$$m_V^2 \omega = g_{\omega N}\rho_V(N) + g_{\omega\Delta}\rho_V(\Delta) \tag{3b}$$

where ω is the fourth component of ω_μ. The source terms ρ_S and ρ_V are obtained by filling the nucleons and the deltas to the top of the corresponding Fermi surfaces $k_F(N)$ and $k_F(\Delta)$. For zero temperature they are given by

$$\rho_V(N) = \frac{2}{3\pi^2} k_F^3(N) \tag{4a}$$

$$\rho_V(\Delta) = \frac{8}{3\pi^2} k_F^3(\Delta) \tag{4b}$$

$$\rho_S(N) = 4 \int \frac{d^3k}{(2\pi)^3} \frac{m^*(N)}{\sqrt{k^2 + m^{*2}(N)}} \tag{4c}$$

$$\rho_S(\Delta) = 16 \int \frac{d^3k}{(2\pi)^3} \frac{m^*(\Delta)}{\sqrt{k^2 + m^{*2}(\Delta)}} \tag{4d}$$

The effective masses $m^*(\Delta)$, $m^*(N)$ are

$$m^*(N) = m_N + g_{SN}\sigma \tag{5a}$$

$$m^*(\Delta) = m_\Delta + g_{S\Delta}\sigma \tag{5b}$$

and the corresponding Fermi energies are

$$E_F(N) = g_{\omega N}\omega + \sqrt{k_F^2(N) + m^{*2}(N)} \tag{6a}$$

$$E_F(\Delta) = g_{\omega\Delta}\omega + \sqrt{k_F^2(\Delta) + m^{*2}(\Delta)} \tag{6b}$$

The Fermi momentum of the deltas is determined by the requirement of chemical stability. For zero temperature this means that

$$E_F(N) = E_F(\Delta) \tag{7a}$$

For nonzero temperatures the chemical potentials must be equal.

$$\mu_N = \mu_\Delta \tag{7b}$$

In this case the source terms are generalized to include the Fermi-Dirac distributions

$$\rho_S(N) = 4\int \frac{d^3k}{(2\pi)^3} \frac{m^*(N)}{\sqrt{k^2+m^{*2}(N)}} \left[n_N(\theta) + \bar{n}_N(\theta)\right] \tag{8a}$$

$$\rho_V(N) = 4\int \frac{d^3k}{(2\pi)^3} \left[n_N(\theta) - \bar{n}_N(\theta)\right] \tag{8b}$$

$$n_N(\theta) = \left[\exp\left(\sqrt{k^2 + m^{*2}(N)} + g_{\omega N}\omega - \mu\right)\Big/\theta + 1\right]^{-1} \tag{8c}$$

$$\bar{n}_N(\theta) = \left[\exp\left(\sqrt{k^2 + m^{*2}(N)} - g_{\omega N}\omega + \mu\right)\Big/\theta + 1\right]^{-1} \tag{8d}$$

$$\theta = kT \tag{8e}$$

The above expressions are for nucleons. The delta contribution is obtained by increasing the degeneracy factor by four (corresponding to I = 3/2, J = 3/2) and substituting the appropriate delta labels. The total baryon density is given by

$$\rho_B = \rho_V(N) + \rho_V(\Delta) \tag{9}$$

The energy density ε is given by

$$\varepsilon = \frac{g_{\omega N}}{2}\,\rho_V(N)\omega + \frac{g_{\omega\Delta}}{2}\,\rho_V(\Delta)\omega + 4\int\frac{d^3k}{(2\pi)^3}\sqrt{k^2 + m^{*2}(N)}\,[n_N(\theta) + \bar{n}_N(\theta)]$$

$$+ 16\int\frac{d^3k}{(2\pi)^3}\sqrt{k^2 + M^{*2}(\Delta)}\,[n_\Delta(\theta) + \bar{n}_\Delta(\theta)] + U(\sigma) \tag{10}$$

From the field equations Eq. (3a,3b,) we see that the relevant parameters of the model are g_{SN}/m_S, $g_{S\Delta}/m_S$, b/g_{SN}^3, c/g_{SN}^4, $g_{\omega N}/m_V$, $g_{\omega\Delta}/m_V$. For zero temperature, the density at which there will be a nonvanishing number of deltas will be determined by the requirement of chemical stability, Eq. (7a), and the field equations. For the values of the couplings $g_{S\Delta}/m_S$, $g_{\omega\Delta}/m_V$, g_{SN}/m_S, $g_{\omega N}/m_V$ we consider in this work, the deltas will appear only above normal nuclear density. In this case the properties of normal nuclear matter will be completely determined by g_{SN}/m_S, $g_{\omega N}/m_V$, b/g_{SN}^3, c/g_{SN}^4. For a given $C_s = g_{SN}/m_S \cdot m_N$ and $C_v = g_{\omega N}/m_V \cdot m_N$, b/g_{SN}^3 and c/g_{SN}^4 are determined so that nuclear matter saturates at a density of $\rho = 0.1625/\mathrm{fm}^3$ (corresponding to a Fermi momentum of $k_F = 1.34\ \mathrm{fm}^{-1}$) and a binding energy per particle of -15.75 MeV. From the family of constants C_s, C_v we can choose those values of C_s and C_v that reproduce other known properties of nuclear matter such as compressibility $K \approx 280$ MeV and the zero energy optical potential of about -50 MeV. The parameters are then completely determined. They are $C_s = 15.8$, $C_v = 12.5$, $b/g_{SN}^3 = -1 \times 10^{-3}$ and $c/g_{SN}^4 = 2.87 \times 10^{-4}$.

The coupling constants $g_{S\Delta}$ and $g_{\omega\Delta}$ must be determined by considering delta-nucleus interaction. Recently Danos and Williams,[6] in an Independent Particle Model, estimated that the delta-nucleus effective potential could be -150 MeV deep, as compared to -50 MeV for nucleon-nucleus potential. Others have estimated a much shallower potential (≈-30 MeV).[7] If the delta-nucleus potential is taken to be shallow, the onset of the deltas in nuclear matter will just soften the equation of state.[8] But if the potential is in fact significantly stronger, as suggested by the Independent Particle Model, it becomes very advantageous to have more deltas present, with a significant decrease of the energy per particle due to the extra binding of the deltas. An isomer state can result. To be more specific, we take $g_{\omega\Delta} = g_{\omega N}$ on the basis of the quark model[9] and take $g_{S\Delta}$ to be a free parameter. A range of values for $g_{S\Delta}$ are chosen, with the restriction that the isomer state should not lie lower in energy than the normal ground state of matter.

In Fig. 1 we show the energy per particle for $g_{S\Delta}/g_{SN} = 1.4$ as a function of the baryon density for zero temperature. This corresponds to a delta-nucleus potential well depth of -120 MeV. The energy per particle for the case when deltas are completely excluded ($g_{S\Delta} = g_{\omega\Delta} = 0$) is shown for comparison (the dot-dash curve). We see that the delta channel will open at about twice nuclear density with a second minimum in the energy per particle occurring slightly below three times normal nuclear density. The depth of the first minimum is -15.75 MeV and the depth of the second minimum is -11.0 MeV. By decreasing $g_{S\Delta}$ slightly, we can raise the depth of the second minimum. In Fig. 1 we also show the energy per particle for $g_{S\Delta}/g_N = 1.35$ corresponding to a well depth of -110 MeV. In Fig. 2 we show the energy per baryon as a function of the density and temperature for $g_S\ /g_{SN} = 1.4$ and T = 0, 25 MeV, 50 MeV respectively. The phase transition between the two nuclear matter states will be first order in complete analogy to liquid and vapor phase transition. The energy density $\varepsilon(\rho_B,T)$ is a single valued function of the baryon density. The structure of $\varepsilon(\rho_B,T)$ for the chiral sigma model is quite different. In that model, the field equations imply that $\varepsilon(\rho_B,T)$ must be a multivalued function of the density.[3)] There, the transition between various branches of $\varepsilon(\rho_B,T)$ leads not only to a rearrangement in density but also to a new arrangement of the mesonic field (the abnormal Lee-Wick solution).

A constant theme of nuclear physics has been the role of field theory in understanding nuclear structure. A substantial amount of literature, starting with the work of Schiff, Teller and Duerr,[10)] has shown that a field theoretic approach can be very successful in understanding essential nuclear properties such as saturation, spin-orbit splitting, the energy dependence of the optical potential, single particle levels in finite nuclei, and density distributions. One hoped that a dramatic manifestation of mesonic effects would be in the unusual properties of nuclear matter at high densities to be realized in medium energy nuclear collisions.[11)] In this work we showed that the interplay of mesons with baryons can be quite interesting in itself without unusual mesonic excitations. Whether nuclear isomerism really happens must await careful experimental investigation and a better understanding of baryon resonance properties in nuclear matter. We have presented a schematic but completely self-consistent model, in which the properties of an isomer state in infinite and finite systems can be studied and the nuclear matter equation of state is consistent with known bulk properties of normal matter.

The author acknowledges useful conversations with J. Kapusta, H. Stöcker, and M. Gyulassy.

This work was supported by the Director, Office of Energy Research, Division of Nuclear Physics of the Office of High Energy and Nuclear Physics of the U.S. Department of Energy under Contract W-7405-ENG-48.

Figure Captions

Fig. 1. Energy per baryon as a function of density at $T = 0$. The dot-dash curve is for the case when no delta resonances are included. The solid curve is for $g_{S\Delta}/g_{SN} = 1.4$ and the broken curve is for $g_{S\Delta}/g_{SN} = 1.35$.

Fig. 2. Ground state and thermal excitations of nuclear matter for $g_{S\Delta}/g_{SN} = 1.4$ and $T = 0$, 25 MeV and 50 MeV.

References

1. E. Feenberg and H. Primakoff, Phys. Rev. 70, 980 (1946)
A.R. Bodmer, Phys. Rev. D4, 1601 (1971)
A.B. Migdal, Zh. Eksq. Teor. Fiz. 63, 1993 (1972)
Y. Ne'eman, in Physics of Dense Matter, I.A.U. Symposium, Boulder, Colorado, 1972
2. T.D. Lee and G.C. Wick, Phys. Rev. D9, 2291 (1974)
3. A.K. Kerman and L. Dudley Miller, Field Theory Methods for Finite Nuclear Systems and the Possibility of Density Isomerism, MIT-CTP PUB 449 (unpublished)
J. Boguta, Remarks on Density Isomers, Argonne National Lab report (unpublished)
4. J. Boguta and A.R. Bodmer, Nucl. Phys. A292, 413 (1977)
5. W. Rarita and J. Schwinger, Phys. Rev. 60, 61 (1941)
Raymond W. Hayward, The Dynamics of Fields of Higher Spin. National Bureau of Standards, Monograph No. 154
6. M. Danos and H. Thomas Williams, Phys. Lett. 89B, 169 (1980) and Electron Scattering from Baryon Resonances in Nuclei, National Bureau of Standards preprint (1981)

7. F. Lenz and E.J. Moniz, Comments Nucl. Part. Phys. 9, 101 (1980)

8. S.I.A. Garpman, N.K. Glendenning and Y.J. Karant, Nucl. Phys. A322, 382 (1979)

9. P.J. Mulders, A.T. Aerts and J.J. de Swart, Phys. Rev. D19, 2635 (1979)

10. L.I. Schiff, Phys. Rev. 84, 1 (1951), 84, 10 (1951)
M.H. Johnson and E. Teller, Phys. Rev. 98, 783 (1955)
H.P. Duerr, Phys. Rev. 103, 469 (1956)
H.P. Duerr and E. Teller, Phys. Rev. 101, 494 (1956)
J.D. Walecka, Ann. Phys. 83, 491 (1974)
J. Boguta and J. Rafelski, Phys. Lett. 71B, 22 (1977)
M. Jaminon, C. Mahaux and P. Rochus, Phys. Rev. Lett. 43, 1097 (1979)
L.N. Savushkin, Sov. J. Nucl. Phys. 30, 340 (1979)
F.E. Serr and J.D. Walecka, Phys. Lett. 79B, 10 (1978)
A.E.S. Green and T. Sawada, Rev. Mod. Phys. 39 594 (1964)
L.D. Miller and A.E.S. Green, Phys. Rev. C5, 241 (1972)
J. Boguta, LBL reports LBL-11465-11468, 11670, 11894
J.V. Noble, Phys. Rev. C20, 225 (1979)

11. H. Stöcker, R.Y. Cusson, J.A. Maruhn and W. Greiner, Z. Physik A294, 125 (1979)
H. Stöcker, M. Gyulassy and J. Boguta, Probing Dense Nuclear Matter Via Nuclear Collisions, LBL preprint LBL-12095 (1981)

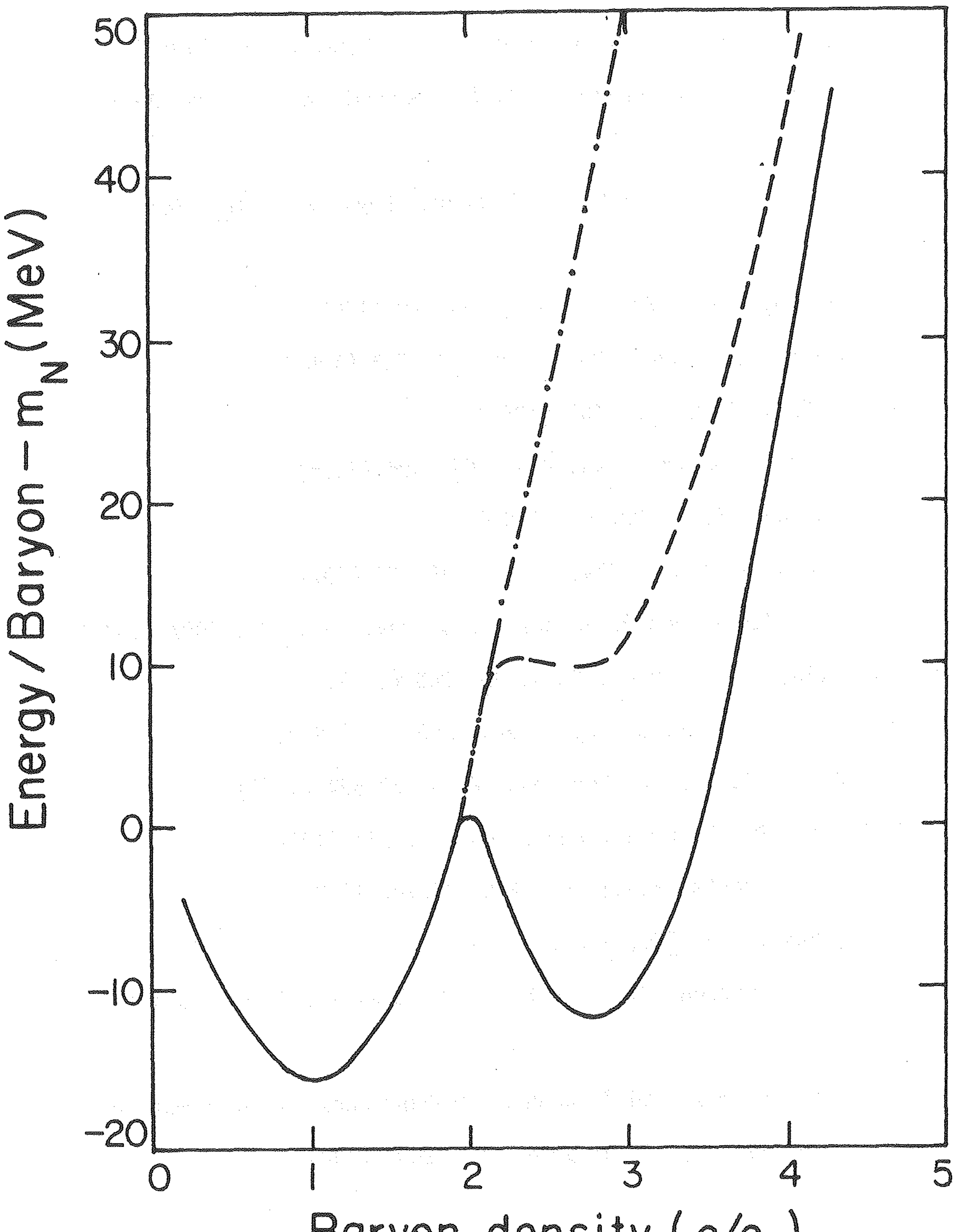

Fig. 1

XBL814-649

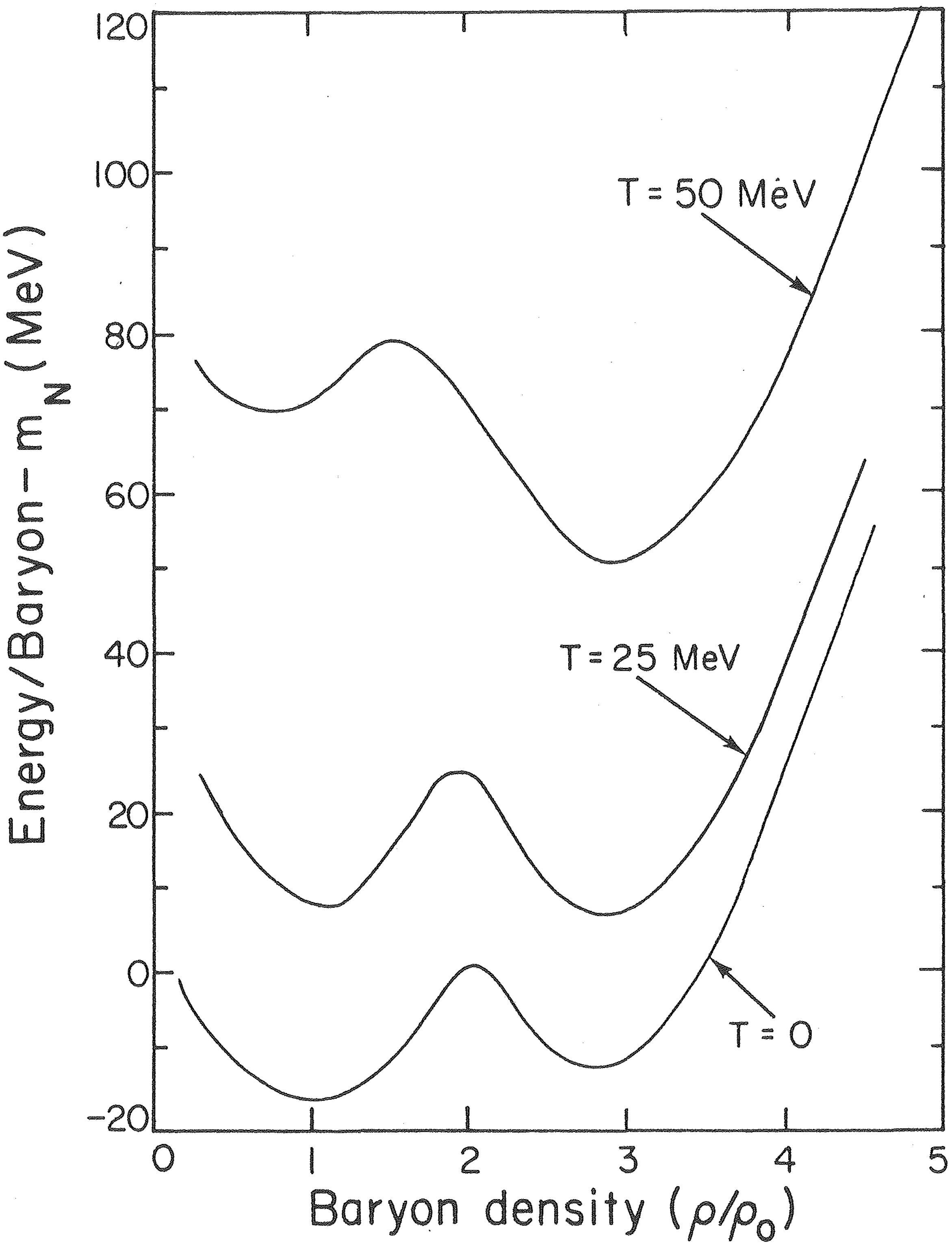

Fig. 2

XBL 814-648