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HEAVY ION REACTIONS AT RELATIVISTIC ENERGIES

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HEAVY ION REACTIONS AT RELATIVISTIC ENERGIES

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The Landscape

Recent studies of relativistic nucleus-nucleus collisions have entered a wide domain of possible interesting new phenomena. In order to examine the possibilities W. Swiatecki has framed the discussion in terms of the space shown in Fig. 1 of all heavy ion energies and masses. The abscissa is the projectile energy in MeV/nucleon and the ordinate is the projectile mass plotted as $A^{1/3}$. The shaded bands define certain regions of fundamental parameters, such that, when one crosses a band, one is confident that the underlying physics will qualitatively change. As an example let us consider the vertical band at 40 MeV/nucleon, which is 20 MeV/nucleon in the center of mass for equal mass target and projectile. The quantity 20 MeV/nucleon is significant because it is roughly the average kinetic energy of the nucleons in the nucleus (about 3/5 the Fermi energy), it is approximately the energy of cold nuclear matter at twice normal density, and it corresponds to the estimated speed of sound in nuclear matter. From this it follows that below 20 MeV/nucleon, one has

conventional nuclear physics: sub sonic, low temperature, where compressibility may be neglected, and the Pauli exclusion principle dominates. Above 20 MeV/nucleon the Maxwell-Boltzmann classical limit is approached and compressive effects must become important. It is conceivable that the pile-up of nuclear density in the overlap region could lead to sidewise squirts of nuclear matter, or possibly even to a process analogous to shock waves in ordinary matter. No effects of higher than normal nuclear density have yet been identified, quite likely because sufficiently heavy projectiles at sufficiently high energy have not yet been available.

In fact most of the space in the figure is unexplored so far, except for the left-hand side which has been reached with low-energy heavy ion machines and along the horizontal axis with high energy proton accelerators. In addition, the Bevalac accelerator at the Lawrence Berkeley Laboratory has made another small region accessible for the last few years, since is has been accelerating heavy ions up to argon at energies between 0.2 and 2.1 GeV/nucleon. Beam currents of Ne ions up to 10^9 particles per second have been reached that are sufficient for counter experiments with good statistics. A proposal has been made for an improvement program that will make beams of nuclei up to uranium available with energies which will then range from 50 MeV to above 1 GeV per incident nucleon. The full area of Fig. 1 ranging from just above the realm of traditional nuclear physics up into the essentially relativistic domain would then be accessible. Its importance is highlighted by a comment by T. D. Lee[1] which says that physicists have concentrated on experiments which put a larger and larger

amount of energy into a region with smaller and smaller dimensions. Now we should investigate phenomena of high energy, high density, over large volumes.

The Experiments

So far, with the present Bevalac, one of the large experimental programs has been concerned with peripheral interactions, in particular with single particle inclusive spectra of the projectile fragments.[2] In such reactions both target and projectile receive relatively little excitation energy, essentially retaining their identities, with their products concentrated at the target and projectile velocities. Such reactions can be fairly well understood[3] in terms of a fast abrasion step and a subsequent slow decay or ablation of target and projectile, exhibiting the familiar statistical features. For the projectile fragments it is probable that their relative cross sections are determined in the second deexcitation stage of the reaction, while their momentum distributions are dominated by the removal of nucleons in the first stage.

Central collisions, on the other hand, lead to much more catastrophic events. This is illustrated in Fig. 2 by a steamer chamber picture[4] of the products emerging when an argon projectile of 1.8 GeV/nucleon interacts with a lead nucleus. Such star explosions represent a significant fraction (about 10%) of the total Ar + Pb reaction cross section. Note, in particular, that no leading particle or even a projectile remnant is observed close to zero degree scattering angle. Fast products are distributed over the whole forward hemisphere; slower, high Z fragments (bright tracks) are emitted into all of 4π. Nuclei are, therefore,

not transparent to each other even at these energies; a large fraction of the incident longitudinal momentum is transformed into transverse momentum.

Preliminary scanning of a sample of streamer chamber exposures of the Ar + Pb system reveals that the total multiplicity of charged particles ranges up to about 130, suggesting that almost all of the protons of the incident system (Z(Pb) + Z(Ar) = 100) are separated and in addition, a large number of mesons are produced. Similar results have been obtained from experiments employing nuclear emulsions.[5] There is a continuous transition from low multiplicity to extremely catastrophic events, suggesting that the observed multiplicities reflect the transition from peripheral to central impact parameters. Other data have been obtained with AgCl crystals.[6]

Recently, spectra and angular distributions of high energy protons, deuterons, tritons, ^{3}He, and ^{4}He fragments, emitted in high multiplicity events, have been measured.[7] The composite particles can be understood as being formed by coalescence of nucleons in close proximity in momentum space due to final state interactions. It appears, therefore, that the emission of nucleons and pions most directly reflect the primary interaction mechanism. Among the possible observable quantities, only the multiplicity and the single particle inclusive spectra are easily obtained from experiment. As indicated by the streamer chamber picture, a high scanning effort and/or elaborate detector arrangements are necessary in order to analyze more exclusive observables such as the total amount of transverse momentum or spatial correlations of the fragments.

The Non-Trivial Physics

Because of the complexity of the problem the experimental search for qualitatively new phenomena may be helped by first performing a calculation under the assumption that "nothing unusual" is happening. This may be studied in an intranuclear cascade calculation where the only ingredients are the free nucleon-nucleon cross sections, properly folded with the single particle distributions of position and momentum in the projectile and target. Such cascade calculations in their simple form, may accentuate the non-trivial features of the reaction through comparison with experimental data.

The non-trivial consequences will probably be identified with collective effects due to nuclear matter at extreme densities and/or temperatures. Such conditions are probably realized in the far interior of neutron stars. The theoretical approach most actively investigated thus far to incorporate collective effects is relativistic nuclear hydrodynamics[8] utilizing an equation of state. This equation is represented by a function relating the mean free energy per baryon to the baryon density and temperature. Its qualitative features at equilibrium for zero temperature are sketched in Fig. 3. The equation of state at densities above twice normal can be affected by first order collective phase transitions to Lee-Wick abnormal matter[1] or density isomers, or second order transitions to a pion condensate.[9] In the absence of such effects one would expect the energy to rise monotonically with density. The pressure in hydrodynamical models is proportional to the first derivative of the energy per particle with respect to density; a possible change to negative slope above twice

normal density would imply negative pressure, e.g., condensation to abnormal matter or density isomers, and may therefore drastically change the development in time and the decay pattern of the nucleons in the interaction region.[10] In hydrodynamical descriptions of central collisions local compression should reach up to considerably more than twice normal density.[11] However, it is still unclear whether there will be enough fast thermalization of energy and momentum, at least locally, to make an equilibrium model applicable. Furthermore, the nuclear temperature may be locally of the order of 100 MeV,[11] which might hinder the phase transitions or render their effect less obvious than indicated by the zero temperature curve shown in Fig. 3. At these temperatures a large fraction of the nucleons are excited to isobaric states,[11] and even concepts of limiting hadronic temperature may become important. These problems are being intensely discussed at the present time. The hope is that the particles emitted from central relativistic heavy ion collisions might carry information pertinent to nuclear matter at high density and temperature. Most probably the interesting data will be in the region of high transverse momentum and with longitudinal momenta intermediate between those of the projectile and the target.

Referring back to Fig. 1, it can be seen that one is just beginning to push into whole new regions where qualitatively new physics has to become important. The main thrust behind the study of central collision is to learn something about nuclear matter at high density and temperature, possibly expressed in terms of its equation of state. The initial gropings, both experimentally and theoretically, highlight

the novelty and the excitement of the field. The present state of the work can be described by saying that one is cutting away the grass in order to search for the flowers.

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Figure Captions

Fig. 1. An attempt by W. Swiatecki to classify different phenomena according to the energy/nucleon and mass number of the projectile. (For definiteness the target mass is thought of as being comparable to the projectile mass.) The three characteristic center-of-mass energies of 20 MeV, 140 MeV and 930 MeV per nucleon are estimates of where the sub-sonic, super-sonic, mesonic, and relativistic domains merge into each other. On the vertical scale macroscopic phenomena come into prominence when $A^{1/3} >> 1$. (The band at $Z \approx 1/2$ (170) is meant as a remainder of the qualitative changes that may be expected when twice Z times the fine structure constant begins to be large compared to unity.)

Fig. 2. A streamer chamber photo[4] of a collision of a 1.8 GeV/nucleon argone nucleus entering from the left, with a lead target.

Fig. 3. Sketch of the free energy per nucleon vs. nuclear matter density in units of the equilibrium density ρ_o. Only the point for normal nuclear matter is well known. The curvature in this region is determined by estimates of nuclear compressibility. The dotted lines at high density indicate possible effects of pion condensation, density isomers, and Lee-Wick condensation.

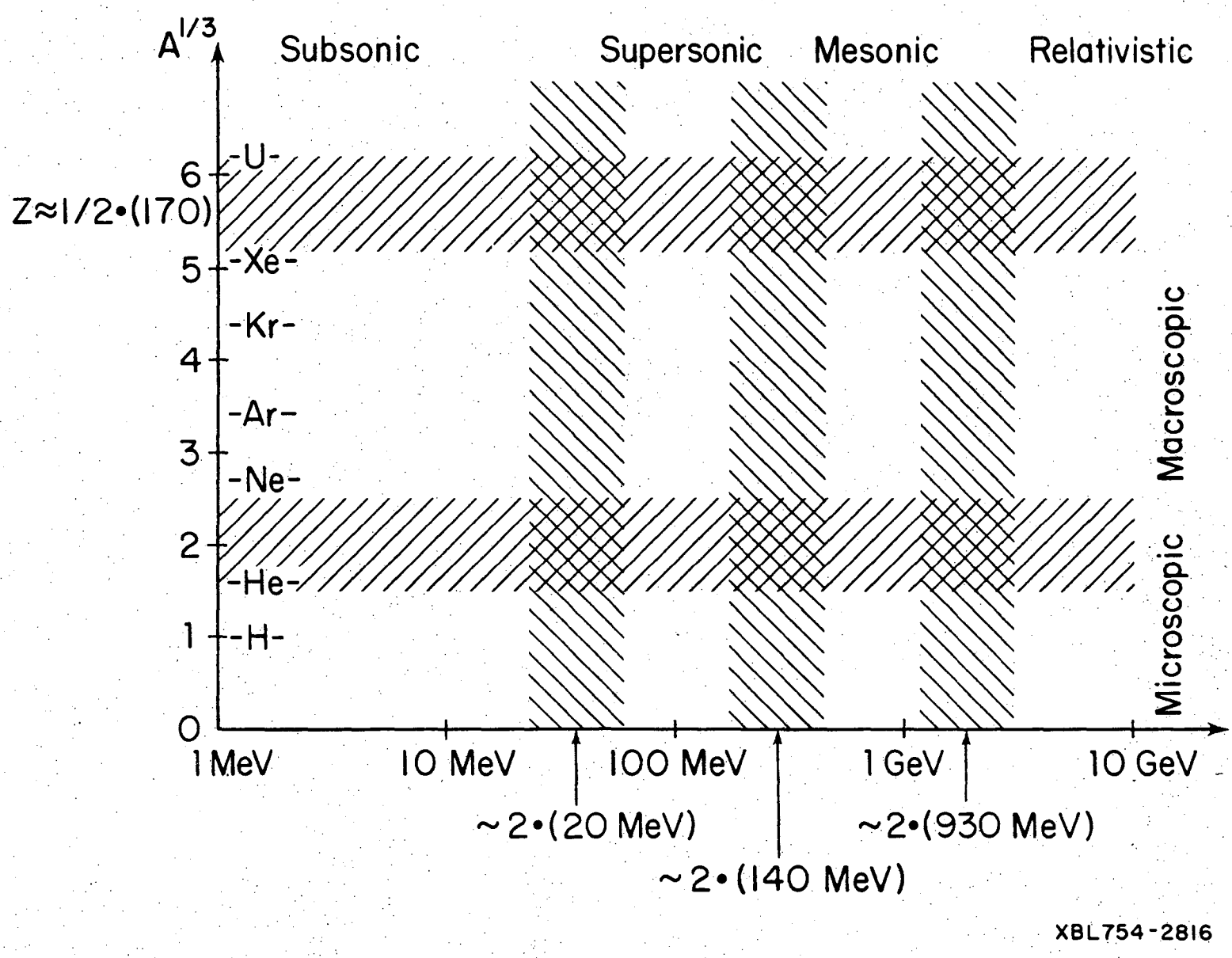
$A^{1/3}$
Subsonic
Supersonic
Mesonic
Relativistic
-U-
$Z \approx 1/2 \cdot (170)$
-Xe-
-Kr-
-Ar-
-Ne-
-He-
-H-
0
1
2
3
4
5
6
Macroscopic
Microscopic
1 MeV
10 MeV
100 MeV
1 GeV
10 GeV
~2•(20 MeV)
~2•(140 MeV)
~2•(930 MeV)
XBL754-2816

Fig. 1

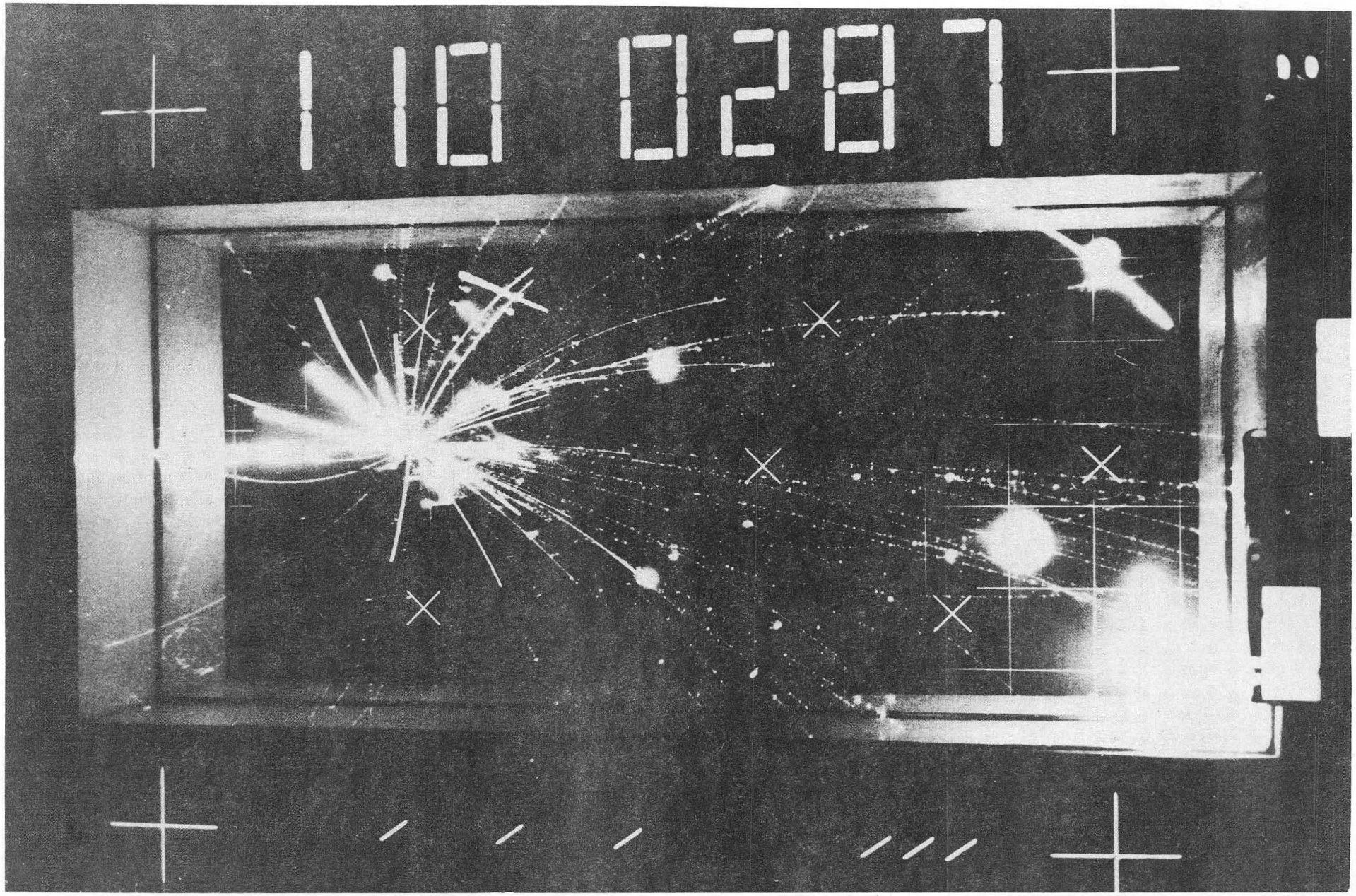

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Fig. 2

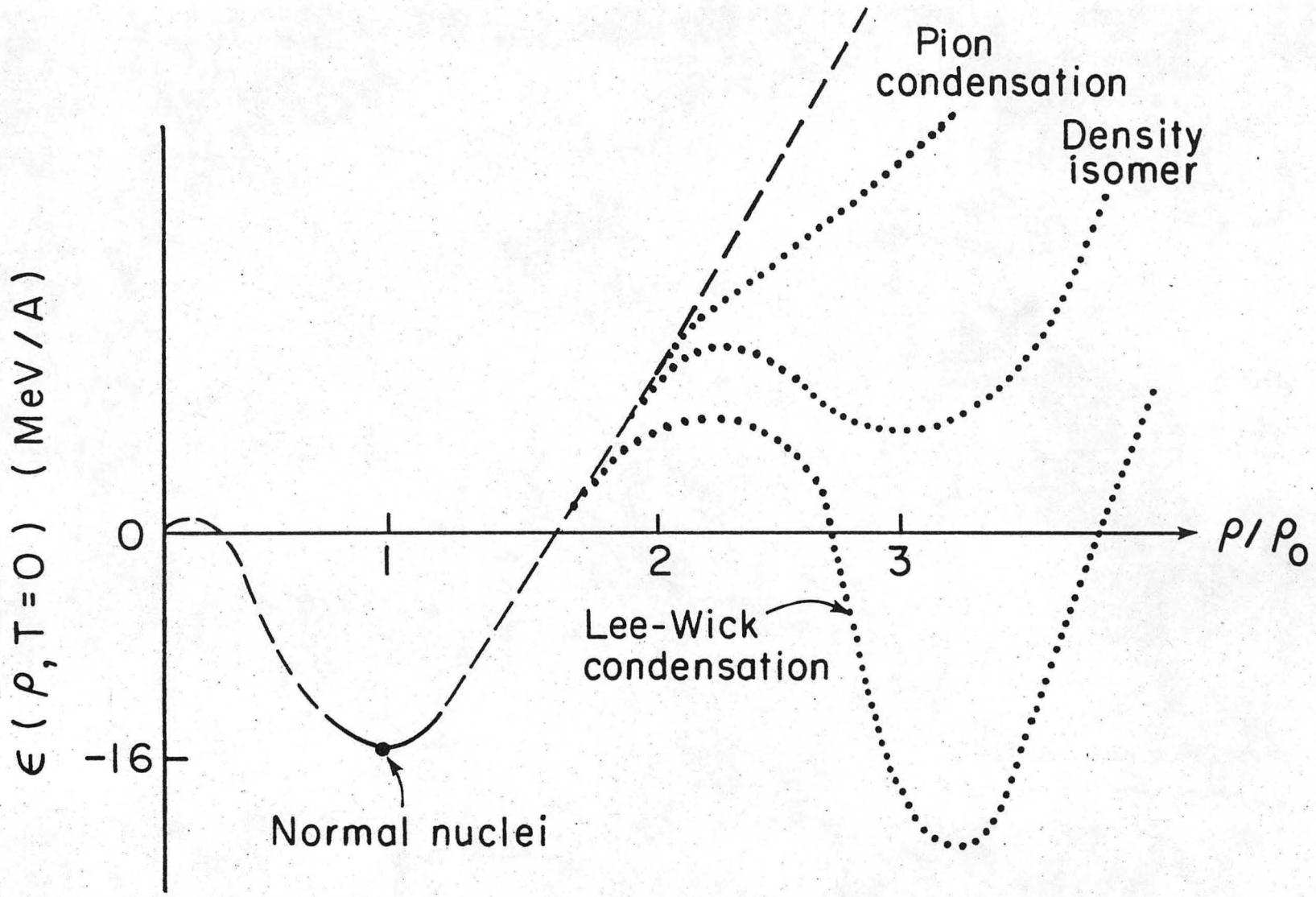

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Fig. 3

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