

# ON SOME RECENT ADVANCES IN NUCLEAR PHYSICS\*

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**I**N recent years, there has been great progress in several newly emerging areas of nuclear physics and heavy-ion physics is one of them. There is much in common between the area of heavy ion physics and that of nuclear fission. Viewed in an approximate way, a heavy-ion nuclear collision represents a time-reversed fission process. Although, details such as excitation energy, collective kinetic energy, angular momentum and the dynamical path are different in the two cases, yet both processes basically involve large scale nuclear motion and interaction between two distinct nuclear fragments. Earlier, fission phenomenon provided the only way to study large scale nuclear motion, but with the availability of heavy-ion accelerators, it has now become possible to study heavy-ion collisions. In this paper, we shall discuss some selected features of current interest pertaining to the fission process, superheavy nuclei and the heavy-ion physics.

Although, on energy considerations alone, the nuclei with mass  $A \gtrsim 120$  should have been unstable towards spontaneous breaking into two parts, the spontaneous fission decay is known to manifest itself only for very heavy nuclei ( $A \gtrsim 230$ ). What keeps the nuclei together and as a whole against this spontaneous breaking off, is the presence of an energy barrier called fission barrier. This energy barrier results from a small difference in the large changes which occur in the attractive nuclear energy and the repulsive Coulomb energy, when a nucleus deforms and undergoes shape changes on its way to fission. Theories<sup>1</sup> of these macroscopic energy changes versus nuclear shape changes based on the classical liquid drop model (LDM) picture or its recent version<sup>2</sup> of the droplet model were fairly successful in providing an overall average description of the process. However, several important details of the process remained unexplained. The late sixties and the early seventies witnessed a great

revival of interest in this process, when some new features<sup>2,3</sup> of this phenomenon, which could be clearly linked<sup>4</sup> to the well-known shell structure of nuclei, were discovered. Two important implications of the inclusion of the nuclear shell effects on the nuclear potential energy map with regard to shape changes, during fission turned out to be the following: (i) the fission barriers of actinide nuclei have double-humped shape, (ii) some very heavy nuclei, expected to have a vanishingly small fission barrier on the basis of the liquid drop model, might show a sizeable barrier if these nuclei have a closed shell structure. This is the basis for the hope that an island of super-heavy nuclei might exist; and some of these super-heavy nuclei may be sufficiently stable to be actually observed.

## SUPER-HEAVY NUCLEI

Based on the trend of decreasing stability as more protons (and neutrons) are added to heavy nuclei, it was the general belief till some 17 years back, that all superheavy nuclei will be so unstable that they cannot exist. Considerable interest was therefore aroused when it was pointed out<sup>5</sup> in 1965 that an island of superheavy nuclei, much beyond the present periodic table was a possibility due to the expected extra stability of the doubly closed shell nuclei. Subsequently, there was intense theoretical activity to predict the location of the shell closures (also called magic numbers) to be expected next to the

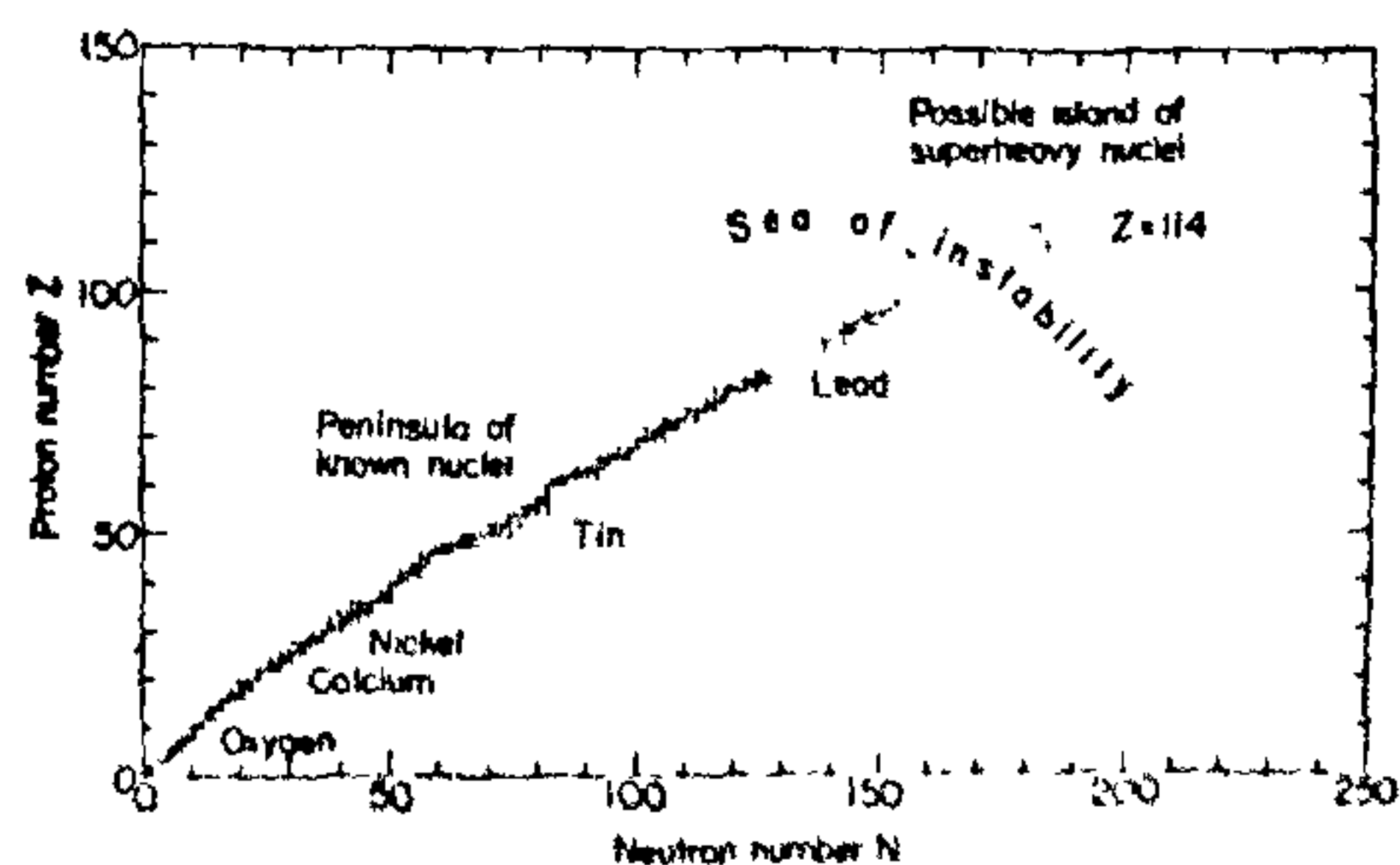
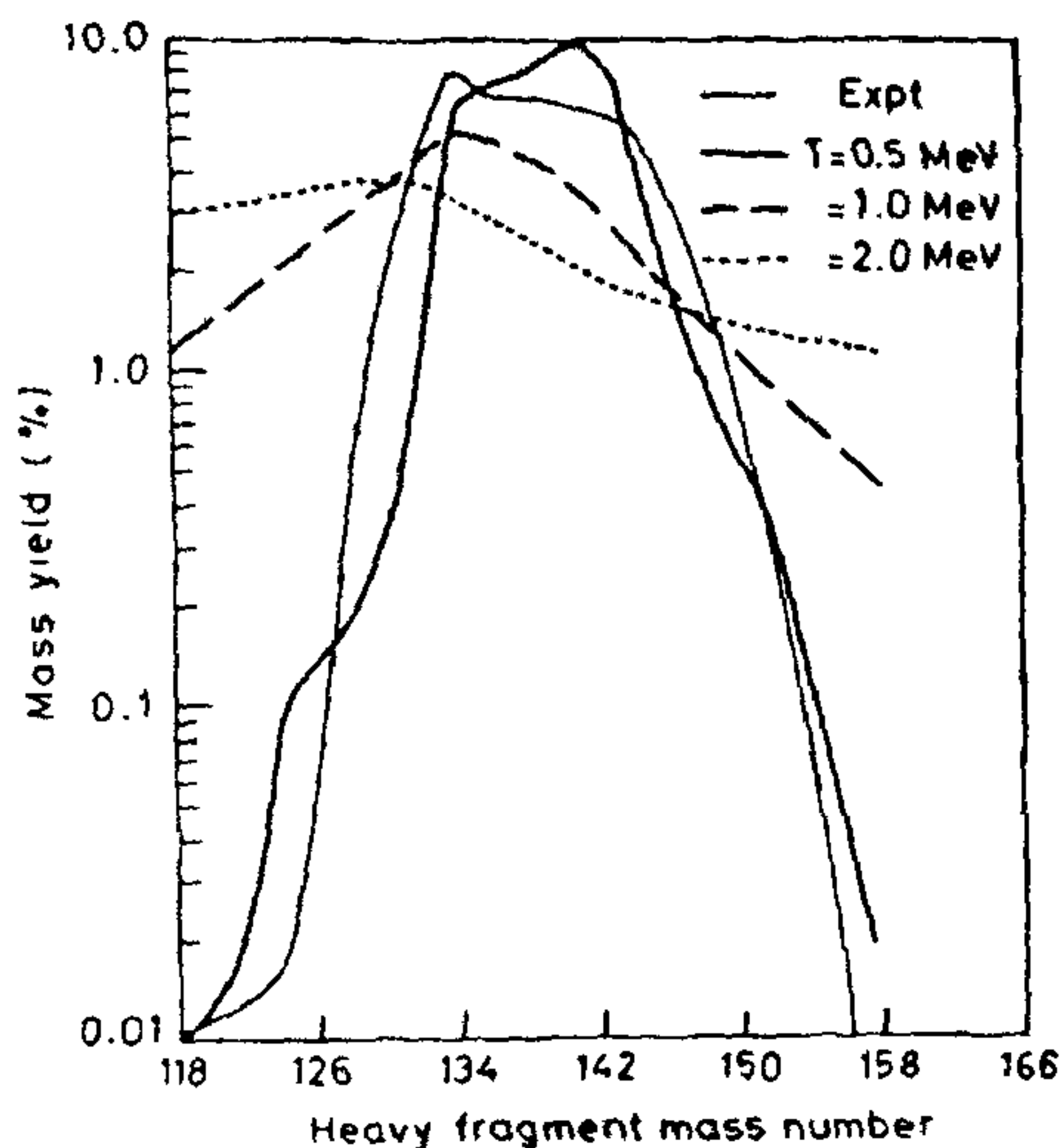


Figure 1. Peninsula of known nuclei and possible island of the superheavy nuclei shown in the  $N-Z$  plane (Ref. 6).

\* Based on the Krishnan Memorial lecture held at the National Physical Laboratory, New Delhi.







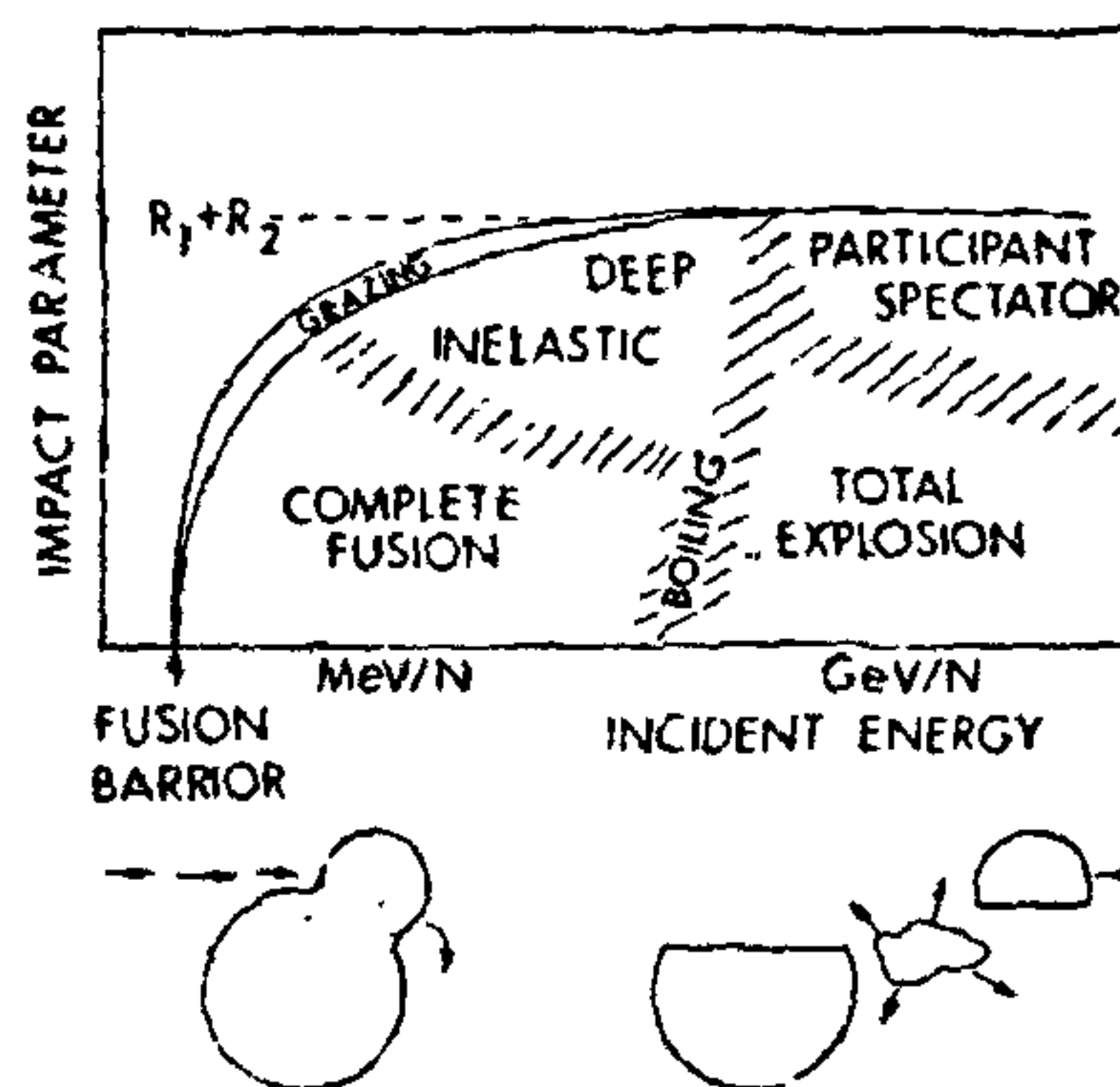
**Figure 3.** Comparison of the calculated yields in the nuclear exchange model with the experimental yields for thermal neutron fission of  $^{235}\text{U}$ . Calculated results are shown for mean fragment temperatures  $T=0.5$ , 1.0 and 2.0 MeV (Ref. 13).

heavy-ion collisions, we have now gathered overwhelming experimental evidence for the occurrence of nucleon-exchange phenomenon between the two colliding nuclei. It is now well-known<sup>14,15</sup> that in the heavy-ion deep inelastic collisions, a considerable number of nucleons are exchanged between the colliding partners in a reaction time as small as  $1-10 \times 10^{-22}$  sec. It is also becoming increasingly clear now that this nucleon exchange process is also mostly responsible for the mechanism of energy dissipation during heavy-ion collisions. These and several other allied features are indeed the topic of current interest in heavy-ion physics, and in the following I shall try to provide a glimpse of some of these areas.

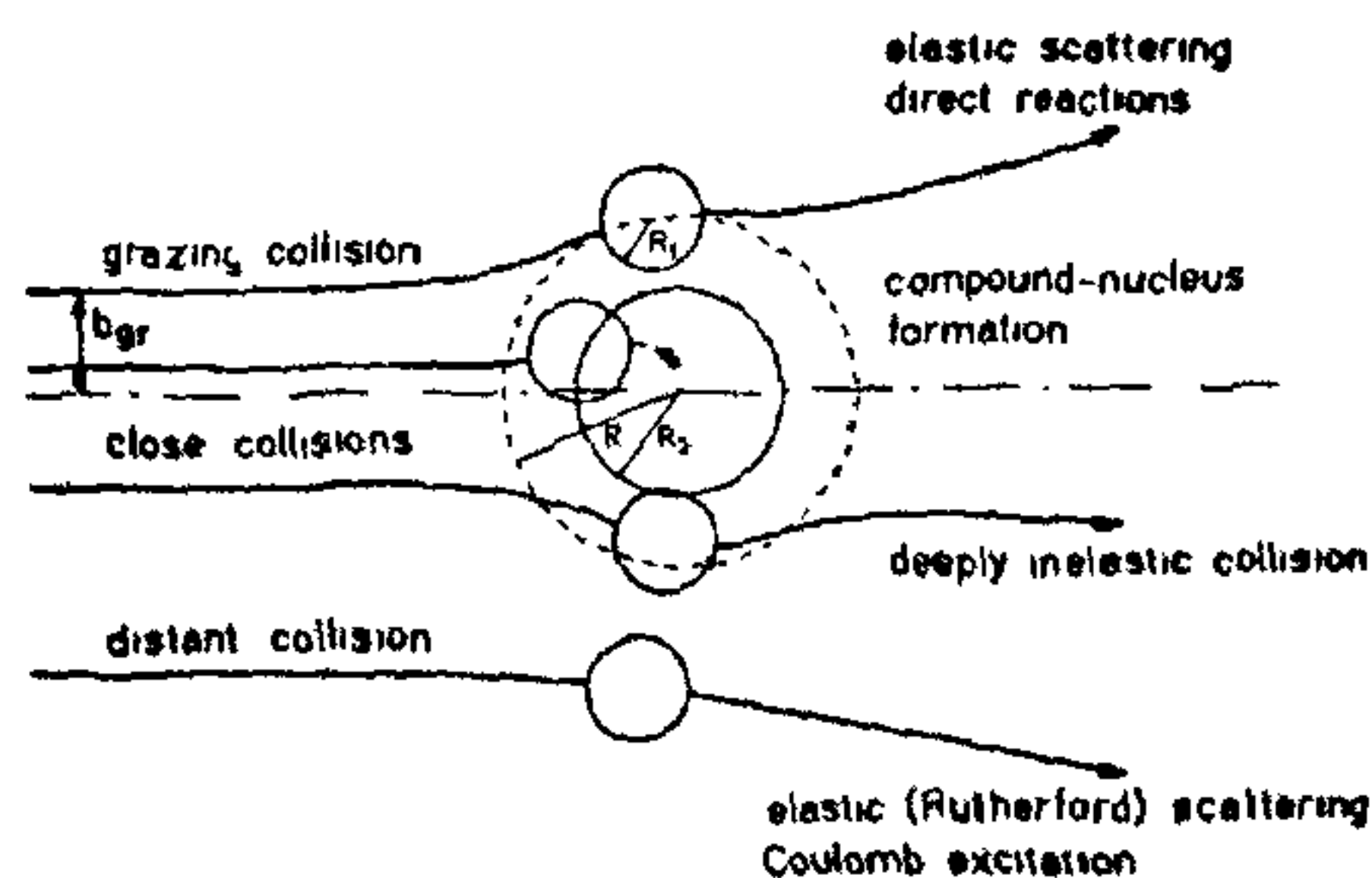
## HEAVY-ION PHYSICS

Recent years have witnessed a growing interest in the area of heavy-ion physics, wherein one accelerates atomic nuclei themselves, and uses them as projectiles to bombard other nuclei. By carefully choosing the projectiles and target nuclei and the collision energy, it is possible to carry out controlled experiments to study systematically the properties of the matter of which the nuclei are composed of and to investigate the

nuclear response to large changes in conditions such as nuclear temperature, density, rate of rotation and composition. The area of heavy-ion physics has thus greatly enlarged the scope of study of nuclei. It is now known that a variety of phenomena can be encountered in the nucleus-nucleus collisions, depending primarily on the incident energy and the impact parameter, and these are shown schematically in figure 4.



**Figure 4.** Phase diagram of the heavy-ion reactions (Ref. 28).



**Figure 5.** Distant, grazing and close collisions in the classical picture of heavy-ion scattering. (Ref. 19).

## LOW AND MEDIUM ENERGY HEAVY ION REACTIONS

Figure 5 shows schematically our present understanding of the low energy heavy ion reaction mechanism versus the impact parameter. In the past, while considering possible alternative reaction mechanisms with lighter nuclei, only two types of reactions—direct interactions and compound nucleus formation—were considered. From heavy-ion reaction studies, we have



now learnt that these two types of reactions, represent only the extreme limits, and a sizeable part of the reaction cross-section can appear in an intermediate type of a process called the deep inelastic collision (DIC). For complete fusion and subsequent compound nucleus formation, a minimum nuclear overlap is required during the collision and in terms of partial wave analysis; this implies that there exists a critical value of  $l$  called  $l_{\text{crit}}$  above which fusion of the two nuclei does not take place. On the other hand for  $l$  near the maximum value  $l_{\text{max}}$  (grazing collision), direct interactions with only one or two nucleon transfers can result. It is then the band of  $l$  waves between  $l_{\text{crit}}$  and  $l_{\text{max}}$ , where collisions take place with sizable overlap to result in the DIC process but insufficient overlap for the fusion process. The time of DIC is also expected to be  $l$ -dependent ranging from the nuclear transit time for  $l=l_{\text{max}}$  to that needed for fusion. The partitioning of the cross-section between fusion and DIC is basically determined by the potential energy, and the energy dissipation which for convenience can be parametrised by the classical concept of friction. Thus the studies of DIC also provide a way to study the nuclear friction coefficients—both radial and tangential components. The tangential friction is responsible for conversion of the orbital angular momentum into the fragment spins, while both the components contribute to the energy dissipation. The fusion is determined by whether or not, a pocket exists in the potential energy of the dinuclear complex as a function of the radial separation distance. Based on the concept of a friction force it is then possible to carry out detailed trajectory calculations<sup>16,17</sup> to determine the fusion cross-sections by numerically solving for the heavy-ion-trajectories during the collision. In the fusion reactions the two nuclei coalesce or fuse into a larger nucleus, which, to conserve energy and angular momentum, would be a hot rotating nuclear system. From such collisions, it is possible to study the effect of stresses resulting from the rotation on the internal structure and shapes of nuclei. As the nucleus rotates more and more rapidly, its shape may change from prolate spheroidal to oblate spheroidal. Further, the fission

barrier is expected to decrease<sup>18</sup> with rotation, eventually becoming zero at some critical rotational speed. Studies of the above processes have just begun and there is every hope of breaking new ground as these studies proceed further.

## DEEP-INELASTIC COLLISIONS

One of the major new findings of the heavy-ion collisions at low collision energies has been the discovery of the deep inelastic collision<sup>14,15</sup> (DIC). The typical times during which the colliding nuclei establish contact in the DIC process is of the order of  $10^{-21}$  sec. which is not much larger than the typical contact time of a direct reaction. Yet, in this short time, a substantial fraction of the incident energy is converted into heat (excitation energy) and the two nuclei exchange neutrons and protons in a diffusion-like process. The salient features of the DIC are as follows:

- (i) It is a binary process, with a strongly non-isotropic fragment angular distribution, characteristic of a peripheral fast reaction.
- (ii) A large number of nucleons may be exchanged during the collision and the cross-section for the formation of fragments with a given composition varies smoothly with the charge and mass transfer involved.
- (iii) A large fraction of the incident energy is converted into intrinsic excitation of the fragments leading to energy losses extending up to several hundred million electron volts.
- (iv) A significant fraction of the angular momentum of the relative motion is converted into the intrinsic fragment spins.
- (v) The energy dissipated and the average number of nucleons exchanged are correlated.
- (vi) The cross-section for the DIC process increases with increasing masses of the colliding nuclei and with bombarding energy. The DIC process has been observed with a variety of projectiles and targets with  $A \gtrsim 40$ , and incident energies typically in the range of 2–10 MeV per nucleon above the barrier.

The time evolution of the charge or mass distributions in the DIC process is now being theoretically<sup>19</sup> treated by the transport models such as Fokker-Planck equations, involving parameters like particle diffusion coefficients and drift



velocities. The mechanism of the energy dissipation in DIC process has also been a subject of several theoretical studies<sup>20</sup> in an attempt to find a satisfactory microscopic interpretation of the energy loss. An important mechanism for the energy loss is now well recognised to be the particle exchange mechanism itself. If the two colliding nuclei in relative motion exchange nucleons, it is easily seen that every time a nucleon is exchanged a part of the energy in relative motion would be converted into the excitation energy by creating a particle-hole configuration. If one includes the effect of Fermi-motion inside a nucleus, and also considers that transfers can take place to only unoccupied orbitals (Pauli-blocking effect), the energy dissipation and  $\sigma_A^2$ , the variance of the fragment mass distributions, can be related<sup>21</sup>. In recent studies<sup>22,23</sup> experimental results for a variety of target-projectile combinations and bombarding energies have been compared with the above model. One of the points which enters in the above comparison relates to the degree of neutron-proton correlation in the exchange process. In most of the experiments the quantity which is measured is  $\sigma_Z^2$ , the variance of the fragment charge distributions. In order to convert this to  $\sigma_A^2$  one has to assume the degree of neutron-proton correlations. In a recent Trombay work<sup>24</sup>, it is shown that in a consistent accounting of the degree of iso-spin correlation, both in the experimental deduction of  $\sigma_A^2$  and in the theoretical model, a better quantitative agreement with the experimental results is obtained, bringing out in an unambiguous way, the dominant role of the nucleon exchange process in the energy loss mechanism.

Another problem of current interest is the correlation of the angular momentum transfer into the individual fragment spins with the other observables such as the energy loss. The nucleon exchange mechanism is also responsible in causing misalignment of the fragment spins from a direction perpendicular to the reaction plane due to the addition of a randomly varying angular momentum component arising from the nucleon exchange process. One way to experimentally study<sup>25,26</sup> this problem of angular momentum

transfer and misalignment is to study the angular distributions of the fission fragments in the sequential fission of one of the intermediate nuclei formed in the deep-inelastic collisions. Another way to measure spins of the fragments is through measurements of the gamma-ray multiplicity. A large gamma-ray detector facility<sup>27</sup> is under construction for such studies by the Heidelberg-Darmstadt group, and this is called the NaI-crystal ball project. It has close to  $4\pi$  geometry and comprises 162 individual NaI modules which are arranged to form a spherical shell of the detecting material. With its completion, this facility will probably be the biggest gamma-ray detector system for nuclear physics use; and will provide some crucial data on gamma-ray multiplicity in heavy-ion reactions.

To conclude my remarks on the DIC process let me emphasize that the unexpected discovery of this process in heavy-ion collisions has provided a unique tool to study the response of a nucleus to the perturbations caused by the proximity of another nucleus in relative motion. The nucleon exchange process, energy dissipation, transfer of angular momentum, and correlations in the neutron-proton transfer process are in the early stages of investigations with much work still waiting to be done. Finally, the nucleon exchange mechanism in the DIC process is also considered to be a promising way to populate exotic nuclei including, perhaps the yet undiscovered "Super heavies".

## EXOTIC NUCLEI

Another interesting domain of study through heavy-ion collisions is the study of nuclei far from the valley of  $\beta$ -stability. Much of our present knowledge of nuclear behaviour comes from the study of only the small fraction of nuclear species lying in the valley of  $\beta$ -stability. Heavy-ion reactions provide us a way to drastically alter the nuclear composition, and thus make accessible study of exotic nuclei involving large changes in composition. In the heavy-ion fusion process, the resulting excited nucleus can evaporate a large number of neutrons, thus leaving the residual nuclei highly proton rich. In another type of collision<sup>28</sup> involving large impact parameter,



some protons and neutrons of the projectile can be sheared away during the collision. In some cases, this process can produce a highly neutron rich nucleus. As one produces these exotic nuclei and studies their properties, one is exploring a completely new ground in the landscape of nuclear composition. As an example of a recent accomplishment in this area one can mention the recently reported discovery<sup>29</sup> of the ground state proton radioactivity by the Darmstadt group using the UNILAC heavy-ion accelerator at GSI, Darmstadt. Prior to this work, proton emission had been observed only from excited states.

### COLLISIONS WITH HIGH ENERGY HEAVY ION BEAMS INCLUDING RELATIVISTIC AND ULTRA- RELATIVISTIC REGIONS

The present period is just seeing the beginning of experiments dealing with the relativistic heavy-ions. These collisions can broadly be classified as peripheral and central. In the peripheral case where the two nuclei just brush against each other, the dominant process is projectile fragmentation. In the central collisions, where the collision is head on, the fragments of both nuclei are formed over a wide range of angles. A clearer understanding of the central collisions is yet to emerge and future experiments aimed at the measurements of correlation among particles should prove to be rewarding.

In these collisions of very energetic nuclei, the description of the resulting hot matter in terms of neutrons and protons is also no longer adequate. These collisions also produce pions and some other heavier objects. It is suggested<sup>30</sup> that at extremely high excitations, the nuclear matter may behave like a soup containing a number of different constituents. The treatment of multiparticle final states theoretically, and the experimental determination of crucial multiparticle correlations is needed to relate these data to fundamental aspects of nuclear behaviour.

One of the most intriguing theoretical speculations<sup>31</sup> is the possible existence of "abnormal" or "collapsed" states of nuclear matter which may be stable or metastable with densities much greater than that of the normal nucleus. At these

higher densities, a pion condensate may be formed. The only way to find experimental evidence for these new states of nuclear matter is through relativistic heavy-ion reactions. The expected high densities generated in the shock front caused by the relativistic heavy-ion reactions could lead to phase transitions to these unusual states of nuclear matter. Much work is still needed to be carried out to determine the optimum conditions for producing this type of abnormal states, to know their life times and to determine how they would manifest themselves.

In the ultra-relativistic domain of energies exceeding several GeV per nucleon, the energy densities created in the collision may become much larger than the average density existing inside a nucleus or even that existing inside a nucleon. The system then can no longer be described in terms of nucleons and it would be necessary to take into account the quark matter not localized inside nucleons. It is indeed an exciting prospect if these new states of matter can be created and studied and if such studies can contribute to the most basic questions of quantum chromodynamics (QCD), quark confinement and ultimate reality of matter.

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## ANNOUNCEMENT

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An International Symposium on **LIGHT METALS: SCIENCE AND TECHNOLOGY** will be held on November 14 and 15, 1983 in the Department of Metallurgical Engineering, Institute of Technology, Banaras Hindu University, Varanasi 221 005, India. This Symposium is being organized to coincide with the Diamond Jubilee Celebrations of Department scheduled for November 14-18, 1983. All aspects of Light Metals including Ore Processing, Extraction, Structure-Property Correlations, Working, Applications and Recent Developments in Aluminium, Titanium, Magnesium and Beryllium will be discussed. In

addition to invited lectures, contributions are invited to be presented at Poster Session. The Symposium will be followed by the 37th Annual Technical Meeting of the Indian Institute of Metals. The last date for receiving abstracts is August 1, 1983. For further details please contact:

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