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RELATIVISTIC NUCLEAR COLLISIONS

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In the last few years the Bevalac Accelerator at Berkeley has allowed the study of collisions of nuclei at energies which before were accessible only with cosmic rays. The maximum energy attainable, 2 GeV/nucleon, is two orders of magnitude higher than was previously available in the laboratory. At present, beams as heavy as ^{40}Ar are in use, but a two-year improvement project has started which will allow acceleration of beams up to uranium. The construction of similar relativistic heavy ion accelerators has been proposed in West Germany, Russia, and Japan. This article will discuss the physics goals which have excited so much interest, and comment on the initial results.

The main goal of studies of relativistic nuclear collisions is to make nuclear matter at high density and temperature, aiming toward the possibility of studying the equation of state of nuclear matter. A sketch of the theoretical binding energy of nuclear matter as a function of density is shown as the first figure; the derivative of this curve with respect to density is the equation of state. What is known experimentally about nuclear matter at present is one point on the graph; the equilibrium density of nuclei, and the binding energy of nuclear matter at this density. Also, we know that at this point there is a minimum, which is to say, nuclei are bound. Even the curvature at this point, that is, the compressibility, is poorly known experimentally. The various curves are some of the speculations about what might happen at high density. At still higher densities it is possible that the nucleons might break up into their constituents to produce quark matter.

A pictorial representation of a relativistic nuclear collision is shown in the second figure, where, because of the high relative velocity of the nuclei, they are assumed to cut through each other. This leads to the useful concept of spectator and participant nucleons. Thus, we may expect that there will be nucleons from the target spectator, the projectile spectator (if the impact parameter is large enough), but most importantly, nucleons which participate in the initial energy and momentum transfer. It is clear that the first requirement for making nuclear matter at high density and temperature is colliding a high energy heavy projectile at small impact parameter on a heavy target. Goldhaber [Nature 275, 114 (1978)] estimates that densities of four to ten times normal nuclear density could be achieved in collisions on uranium nuclei

with uranium ions of 2 to 8 GeV/nucleon. Thus, in a system containing almost 500 nucleons, one may produce both matter and energy densities far in excess of any previously attained in a volume of nuclear size.

However, research proceeds in smaller steps for practical reasons and the first results on central collisions were for 250 and 400 MeV/nucleon ^{20}Ne ions on a uranium target [Gosset et al., Phys. Rev. C 16, 629 (1977)]. These results, on the energy spectra of protons and light nuclei emitted in the reactions, have generated enormous interest, and by now have been fit by 20 groups of researchers using twelve distinct models. The extreme disparity in the bases of these models is best typified by comparing the fireball model, a so-called thermal model, to the intranuclear cascade model. In the nuclear fireball model one assumes the clean-cut geometry shown in the second figure and then that the participants achieve thermal equilibrium before separating. In the cascade model the two-body collisions of all the constituents are followed. The aim in these model calculations has been to describe the "background" physics of what goes on, so that one could search for interesting new effects. In the metaphor of the Berkeley Summer Studies, the models are tools for cutting through the weeds to look for the flowers. The amazing thing is that, within factors of two, most of the models were able to fit the data. It was thought that energy and momentum conservation together with the spectator-participant concept, constrains the models so that differentiating between them must await more accurate and extensive data. However, let us examine another possible explanation.

The most recent publication of a calculation is by J. D. Stevenson [Phys. Rev. Lett. 41, 1702 (1978)]. It contains results from one of the five intranuclear cascade calculations which are in progress. Because of the reasonable fit obtained he concludes that "this calculation shows that the radical assumption that a hot nuclear fireball is formed in nucleus-nucleus collisions is not necessary to explain existing experimental results." On the other hand, he also shows that the average emitted nucleon has undergone five to six scatterings and quotes results from gas studies to the effect that this is more than enough to show equilibrium features. Thus, it appears that Stevenson has shown microscopically that there is some justification to the macroscopic thermal models. He has possibly also given another explanation of why most of the model calculations agree: the large degree of thermalization obscures the initial assumptions of the models. The significance of this point buried in Stevenson's article is not trivial. Although one can follow collective motion microscopically, macroscopic models are enormously simpler, and much more easily relate effects to observations. In addition, all the interesting effects we are looking for are macroscopic effects. Classical microscopic calculations, like the one by Stevenson, are useful in testing model assumptions, such as the degree of thermal equilibration, but provide little insight into the collective properties of hundreds of nucleons. We need macroscopic models characterized by a few bulk parameters, such as the compressibility modulus, which are adjusted to experimental data in order to learn new physics. For instance, for compression and reexpansion effects, some macroscopic calculations have just recently pointed out the effects which might be seen experimentally.

The data fit by Stevenson were taken with a detector of small solid angle so that the experiment looked at only one particle from each event but accumulated data for many events. However, present experiments measure the multiplicity of charged particles associated with the particle in the main detector, and thus are able to select central collisions based on their high multiplicities. Experiments that measure two particles in each event are in their early stages. These two-particle correlation studies will give a much better indication of the degree of thermalization, because in a single nucleon-nucleon scattering the two nucleons tend to be correlated at 180° in the center of mass, while in a thermal model they would be uncorrelated at large angles. Also, recent two-particle correlation experiments at small angles have lead to fascinating studies to determine the fireball size and lifetime [M.Gyulassy, Nature ___, (1979)]. However, the future lies in measuring as many of the final particles as possible in each event and thus determining the collective motion of the nucleons emitted. Hopefully, one day it will be possible to relate data of this kind back to the equation of state of the compressed nuclear matter.

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Figure 1

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Figure 2

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