CREATING HIGH ENERGY DENSITY IN NUCLEI WITH ENERGETIC ANTIPARTICLES

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Abstract

The possibility of creating a phase change in nuclear matter using energetic antiprotons and antideuterons is examined. It is found that energy densities of the order of 2 GeV/c can be obtained for periods of ~2 fm/c with the proper experimental selection of events.

I. Introduction

In this talk I wish to consider the possibility of using antiproton beams to create the conditions necessary for a change of state of nuclear matter to that often referred to as a "Quark-Gluon Plasma". While there are many estimates in the literature for the appropriate physical parameters for this transition, I will not use these but instead rely on what might be "natural" expectations. Since the quark-gluon state exists inside a single nucleon, one might expect that an energy density over an extended volume of the same order as that in a nucleon would produce the change of state in that larger region as well. For a nucleon considered as a sphere of radius 0.8 fm the energy density is 0.44 GeV/fm^3 and for a radius of 0.6 fm it is 1.04 GeV/fm^3. To be sure we are well into the other phase something on the order of 1-2 GeV/fm^3 is needed (2-3 is better).

Thus we might have a mass density of the order of >6 times normal nuclear matter density, with no increase in kinetic energy or, alternatively, an increase in kinetic energy corresponding to a "Temperature" of ~180-200 MeV. It has been proposed to use heavy ions to explore the low temperature-high density region. As we shall see the use of energetic antiparticle beams will allow us to explore another part of the nuclear matter phase diagram[(1)].

The experimental work has already begun with the work of DiGiacomo et al.[(2)], Breivik, Jacobsen and Sorensen[(3)] and the streamer chamber group[(4)]. These experiments at CERN were carried out at relatively low incident momentum (0.6 and 1.5 GeV/c) compared to what could be done. We wish to consider the possibility of using higher energy incident antiprotons. There is, in fact, some interesting bubble chamber data at 4 GeV/c.[(5)]

Before going on to actual calculations of energy densities and temperatures to be expected from $\bar{p}$ annihilation in nuclei it is useful to discuss what we should expect from simple considerations. To do this it is useful to make two comparisons. The first is between annihilation of low energy (P_{lab}< 2 GeV/c) and medium energy (2 GeV/c < P_{lab}< 10 GeV/c) antiprotons, and the second is between antiprotons and protons, as a means of heating nuclei.

The first advantage of the energetic particles is that the higher momenta antiprotons penetrate more deeply (the annihilation cross section decreases with increasing energy). This means that the mesons produced in the annihilation are more nearly contained within the nuclear medium. At low energies (or in atomic systems) the annihilation occurs on the surface and many of the pions simply scatter a single time and leave the nuclear environment so that they have no chance to be absorbed and thereby deposit all of their energy.

The annihilation products from a fast moving antiproton are also very forward peaked and tend to form a beam of mesons so that the energy density does not disperse as rapidly. Figure 1 shows the distribution in $\cos\theta$ for three incident momentum antiprotons. At around 6 GeV/c almost all pions are within a cone of 20°. The momentum spectrum of pions is also expanded as shown in Figure 2 but the loss in the lower energy region is only about a factor of 2 for 6 GeV/c $\bar{p}$ momentum. Another way of looking at this forward propagation of particles is to consider the total energy density in some initial region propagating with a velocity equal to the velocity of the center of momentum of the $\bar{p}N$ initial system. If we allow this system to emit particles (pions) isotropically with velocity c from a uniform distribution within a sphere, we can calculate an effective radius of this "swarm" of particles. Dividing the corresponding volume into the total energy available gives us an estimate of the energy density as a function of time. Figure 3 shows a plot of results generated in this way. Note that for $\bar{p}$'s at rest the expansion is much faster (as well as the initial total energy available being less). In this view of an expanding swarm of mesons we see the effect of the relativistic contraction of the perpendicular velocity ($P_\perp$ is an invariant so $v_\perp = p_\perp/\omega$ is smaller). It is interesting to note that relativistic heavy ions make use of the contraction along the direction of motion to increase the density of the nuclei while we use velocity contraction in the <u>two</u> perpendicular directions to retard the spread of the energy density. This graph sets the time scale at the order of 3 fm/c, because we must somehow convert the energy contained in the swarm (largely meson kinetic energy) to nucleon (or other) thermal energy and/or compressional energy within this time scale in order to achieve a useful energy density.

We have just seen that raising the energy of the beam is useful because of the additional energy available in the form of kinetic energy. Of course we must convert this energy to a more useable form; a large number of pions proceeding at high velocity is of little value by itself. It is this problem that is now addressed by comparing with proton collisions.

Pions have large scattering cross sections and a high probability of absorption. A pion typically undergoes several scatterings before absorbing on a pair of nucleons so that the 8-12 pions produced by an energetic annihilation share their energy among several (~5-10) nucleons. Thus a large fraction of the total energy and momentum of the annihilating antinucleon-nucleon system may be transferred to N nucleons. Under these conditions a considerable fraction of the kinetic energy (of order 1 - 1/N) is converted to degrees of freedom other than forward motion. It is useful to compare this effect with the coupling of a moving freight car into a set of stationary cars. In that case also, most of the kinetic energy is converted to heat. Note one difference with this analogy, however. In the present case all of the energy-momentum transfer is done directly by the pions and not by successive collisions among the recipients of the energy-momentum.

When protons collide with a nucleus they tend to proceed in a very forward direction. This means that most of the energy remains with the projectile and only a small fraction is given up to a few nucleons. The antiproton couples to the nucleus much more strongly by means of the intermediate pions as described above.

II. Results

Let me now go on to specific calculations for the quantities of interest. The results I shall present were obtained with an Intra-Nuclear Cascade model.

In approaching the problem of the INC calculation I, of course, realized that there were already at least two codes in current use. A program of the classic type is available[7] and I could have used it. The problem is that one wants to be able to measure energy deposition and to take into account the motion of all of the nucleons. This is difficult (if not impossible) with the present version of this code. The nucleons are not "realized" until a mean-free-path calculation indicates that they have been struck. One needs to follow all the nucleons at all times to know the total nuclear state at early, as well as late, times.

A code which follows all nucleons exists as well,[8] but is based on a heavy ion code and was not available to me at the time. I felt that it was worth the trouble to design a calculation specifically for the purpose at hand -- $\bar{p}$ annihilation. The general features of this code turned out to be similar to those of a (heavy ion) code designed by Kitazoe <u>et al</u>.[9]

An intranuclear cascade code consists of a series of rules for the time development of a model of nuclear processes. I shall now briefly review these rules for the current model.

The nucleons move with classical (Newtonian) motion in a potential well of Woods-Saxon form, and depth of 50 MeV. They each have a binding energy of 25 MeV. If left alone at this point they would simply continue to move in "orbits" with total energy -25 MeV, executing "Fermi" motion. Collisions are added such that if the nucleons are closer to each other than a given distance they are scattered isotropically in the nucleon-nucleon center of mass. The collision distance is chosen to be the radius of a circle whose area is 40 mb.

Pions move in free space (no potential) except for collisions with nucleons. The pions propagate relativistically and the collision distance is governed by the pion-nucleon cross section at the current pion energy. Pion absorption on a nucleon pair is allowed, starting with the second collision. The total energy of the absorbed pion is shared between the current nucleon and the previous one. The additional relative momenta of the two nucleons coming from the pion mass is directed along the direction of the pion trajectory between the two nucleons. The probability of absorption was taken as a fixed number chosen to fit pion-nucleus "true" absorption cross section data. Typical for the number of nucleons struck before absorption is 3-4. Pauli blocking of low-momentum transfer collisions is included but is of importance only for the applications of the code for pion-nucleus cross sections.

A version of the code was prepared for a single incident pion and comparison was made with a number of reactions.[10] In particular, results from inelastic scattering, single charge exchange, double charge exchange, true absorption cross sections and the proton spectra resulting from the absorption of incident pions were studied. A reasonably good agreement was achieved in all of these cases.

A second version of the code was then prepared to allow the creation of a distribution of pions isotropic in the center of mass of the $\bar{p}N$ system. The method used for this is esssentially identical to that used by Clover, et al.[7] The resulting pions were then transformed into the laboratory frame. The distributions shown in figures 1 and 2 were obtained from this code. Antiproton annihilation was assumed to take place on the central beam axis 1 fm inside the nuclear surface corresponding to an experimental cut being taken on central collisions.

Much of the interesting physics in this problem consists of how to interpret the results in terms meaningful to physicists. One aspect which is relatively simple is the nucleon density. One can simply count the number of particles in a set of small volumes as a function of position and time. This has the disadvantage that the effects one sees can depend on the size of the volumes chosen. Another way of estimating density is to use an nth nearest neighbor distance. This has two advantages: 1) A density is always associated with the vicinity of a particle (density is not defined for an arbitrary point in space, although it could be); 2) The number of particles which define a density can be fixed in advance (the present code used 4th nearest neighbors so there are 5 particles involved in each density calculation). A probability distribution of densities can also be calculated. For the present calculations I will not go into more detail except to say that both methods applied to the INC give maximum densities of the order of 1.5 ρ_0, in substantial agreement with the hydrodynamic calculations of Dan Strottman which gives 1.8 ρ_0.

One can ask about the distribution of kinetic energies of the nucleons. A plot showing the number of particles with a given kinetic energy vs. that kinetic energy for some selected times during the process is given in figure 4. An interesting feature is that (to the far left) most of the nucleons have moderate kinetic energies corresponding to the Fermi motion in the nucleus and a small fraction have a distribution of kinetic energies extending much higher. One sees that an exponential shape gives a good representation of the "high temperature" portion of these curves <u>even at very early times</u>. Thus one cannot use the shape of the curves as a measure of thermalization. If one integrates these curves the population of the "hotter" group can be obtained. This is a little misleading, however, since one does not know how many of the events produce these particles in the high energy part of the distribution. For example, the curve at 0.6 fm/c integrates to only 1 nucleon. Does this mean that only one nucleon was involved in the nucleus for each event? No. It could be that 80% of the events produced no particles in this region at 0.6 fm/c and 20% produced five. This latter possibility is not so far from the truth as we shall see shortly.

If one identifies a number, which I shall call "temperature", with the inverse slope of these curves one can characterize the behavior of this more energetic component as a function of time. Figure 5 shows results for 2, 4, 6 and 8 GeV/c incident momentum antiprotons as well as the time development of the temperature for antiprotons annihilating at rest on the surface of the nucleus. One sees that there is a steady increase in the average temperatures obtainable. The hydrodynamic results lie somewhat higher (and/or later) because of the hadronization length (not included in the INC calculations), but the general features are very similar. Also shown are estimates of the temperatures achieved using antideuterons. These results are very encouraging since they do represent only average (central) events. One can arrive at more extreme conditions by selecting on the "proper" final observables. The best criterion is not clear but a simple one is to make cuts based on the fraction of the energy transferred to the nucleons. This only corresponds approximately to a realistic experimental condition since there is no pion production in the present code and all of the energy can be transferred to nucleons. If one makes this kind of selection the result is shown in figure 6. When 90-100% of the total energy available is converted into nucleon kinetic energy we see that temperatures above 200 MeV remain until times of the order of 4.2 fm/c when ~ 10 nucleons are involved in the hot distribution. For 50-60% of the energy converted the temperatures and number of particles involved are correspondingly more modest (T~160 MeV, N~4). Thus, at least in this model problem, the conditions for high-energy density can be altered rather drastically by selection of the fraction of energy in nucleons vs. pions.

One can also tabulate statistics on the relative momentum of the nucleon pairs colliding. This is done separately for each of the three Cartesian directions. No difference is seen between the three components to the present level of statistics. These distributions can be used to compute processes, such as bremstrahlung or strange particle production, pertubatively. Nothing has been done as yet along these last lines.

One can attempt to look at the energy deposited (converted to nucleons) as a function of time. Since the interest lies in early time energy deposition, favorable cases can be chosen by eye. I selected two events from a sample of 60 (thus ~3% of central events) which deposited their energy rapidly. If I multiply the fraction deposited by the energy density in the fireball (from the earlier calculation assuming all particles moving with the speed of light) I find the curves shown in figure 7. One sees that the process can happen rapidly in comparison with 3 fm/c. Note that the rapid drop in the curve is pessimistic since the nucleons are moving with velocity less than c. This energy density includes the simple translational energy of the nucleons so the "freight train factor", from the beginning of the talk, still needs to be applied. This reduces the curve by 10-20%. In any case we see that energy densities of the order desired are obtained and maintained for the order of 1-2 fm/c for about 1% of the events.

III. Conclusions

I have presented the results of a model attempting to follow the process of $\bar{p}$ annihilation in nuclei and I have tried to analyze the results in physical terms. Clearly this is an ongoing process. The fundamental question of the time evolution of the strong interaction is a disturbing one. If it takes the order of 1 fm/c (in the CM) for hadrons to form, then the process, as calculated here, will be retarded. If the hadronization of the fireball is simply moved downsteam then there is no problem until we reach 10 GeV/c incident lab momentum, when the hadronization length is the order of 10 fm in the lab and pions don't form until they are outside of the nucleus. If the fireball spreads during this time the problem may be serious. In what way should the physics of this process be treated? A better understanding of this effect must be in hand before a truly reliable calculation of this effect can be made.

In summary I conclude that antiproton beams offer a different, and complementary, means of achieving high-energy density in nuclei from the use of heavy ion reactions.

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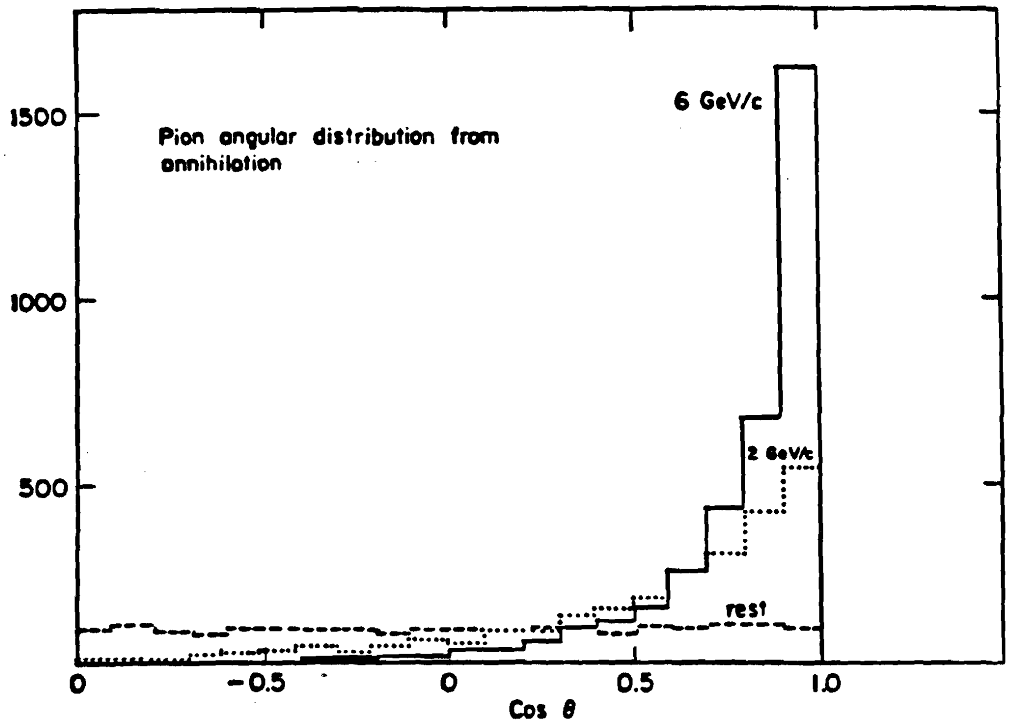

Figure 1. Number of pions produced in $\bar{p}$-p annihilation as a function of cosθ. The curves were generated using phase space in the center of mass of the annihilation to produce isotropic distributions.

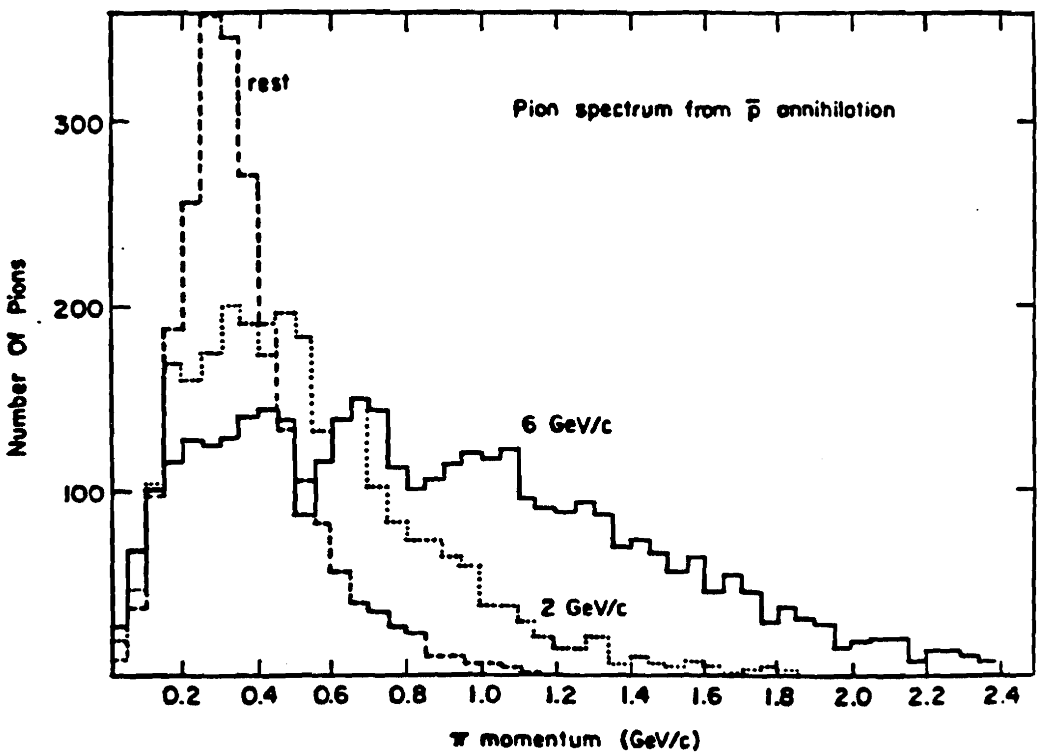

Figure 2. The momentum spectrum of pions produced in the same manner as described in Figure 1.

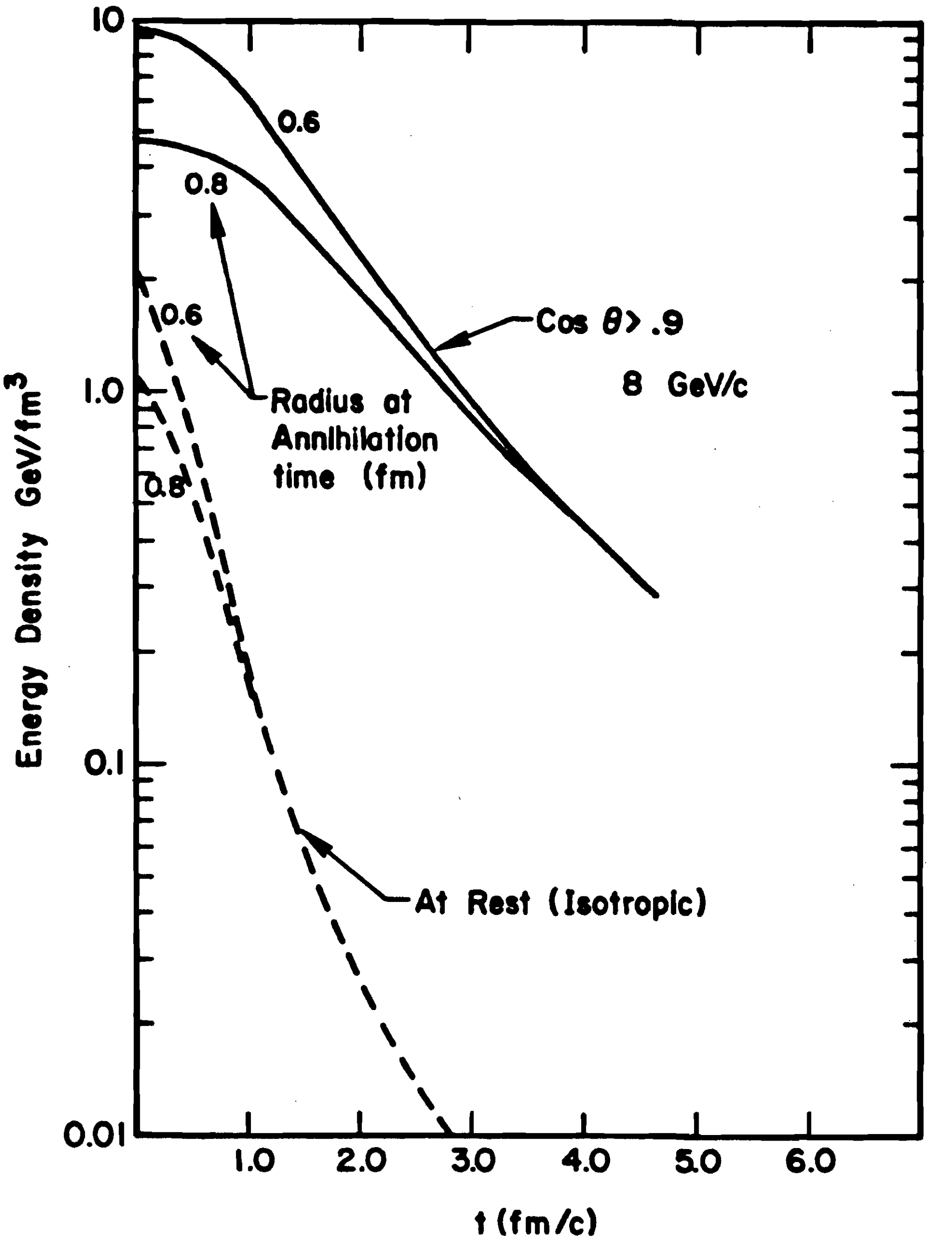

Figure 3. "Fireball" expansion calculated as described in the text.

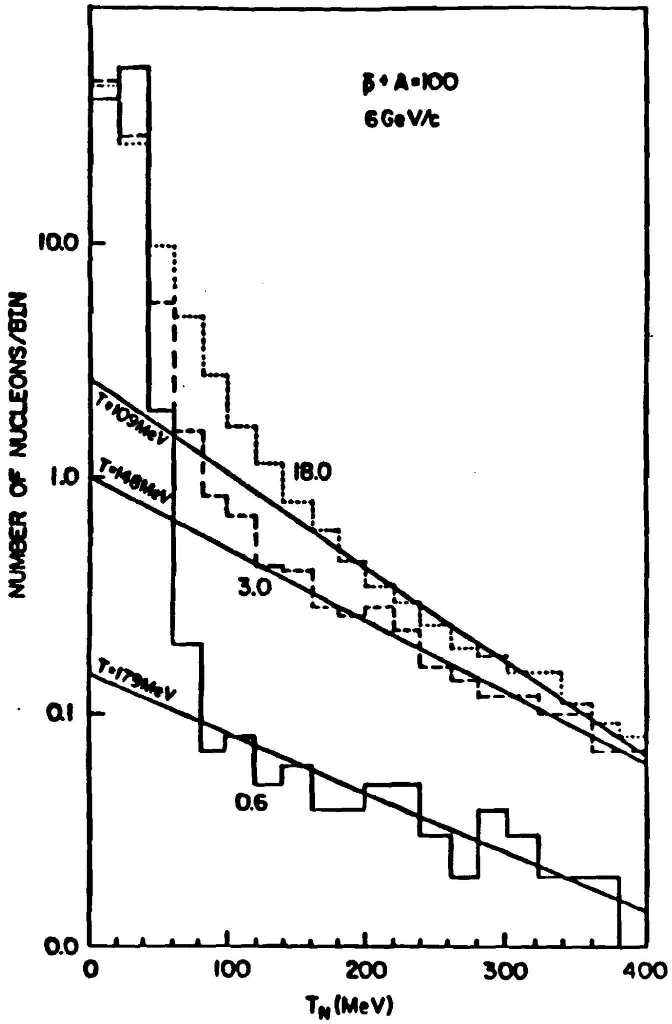

Figure 4. Distribution of kinetic energies of the nucleons at three selected times after annihilation. The existence of a two component structure ("hot" and "cold") is clear.

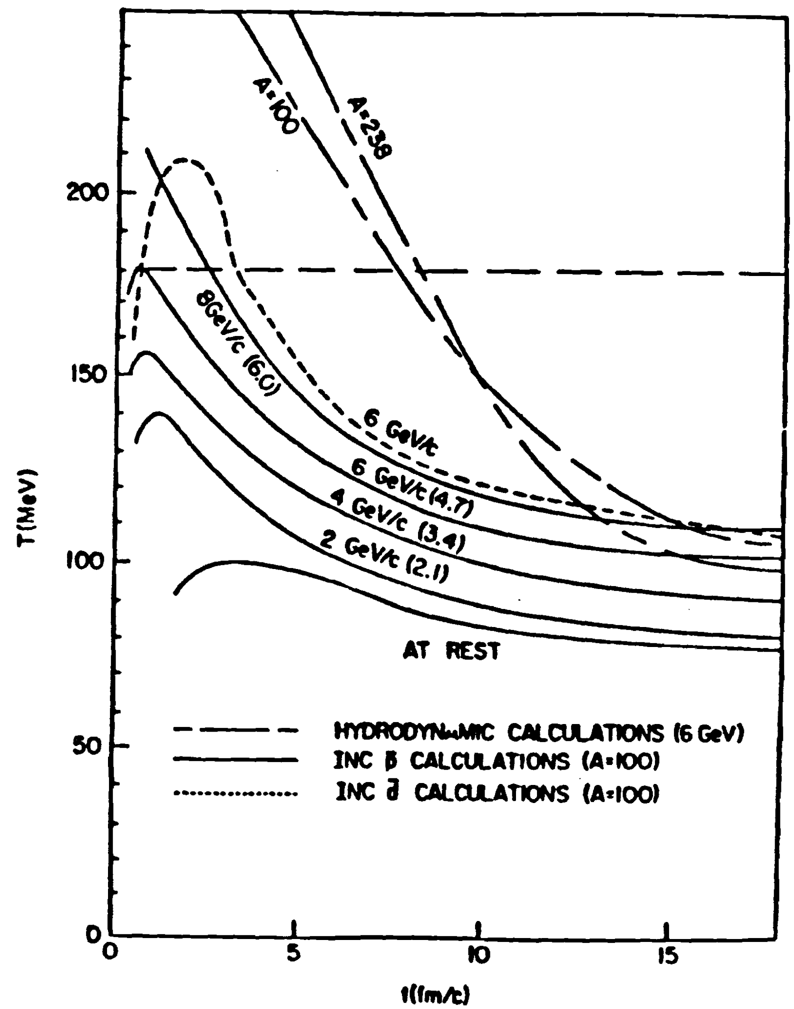

Figure 5. Comparison of "temperatures" achieved under various conditions. For the antideuteron case the incident momentum is 6 GeV/c per antinucleon.

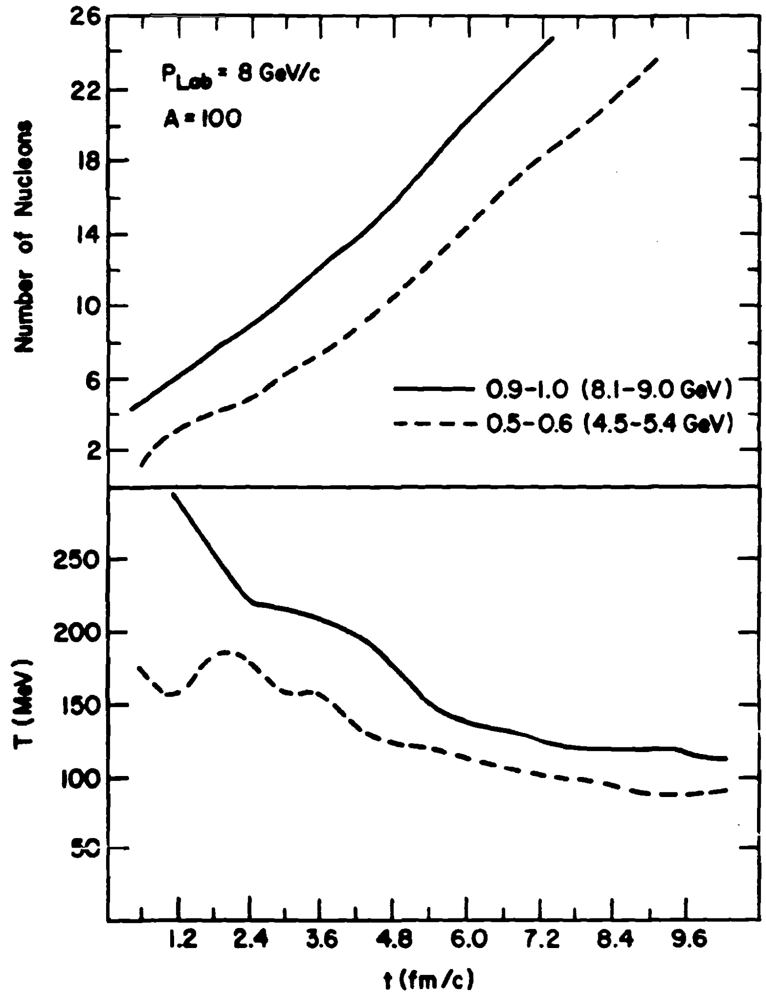

Figure 6. Comparison of the number of nucleons involved in the "temperature" for two different conditions of energy deposition.

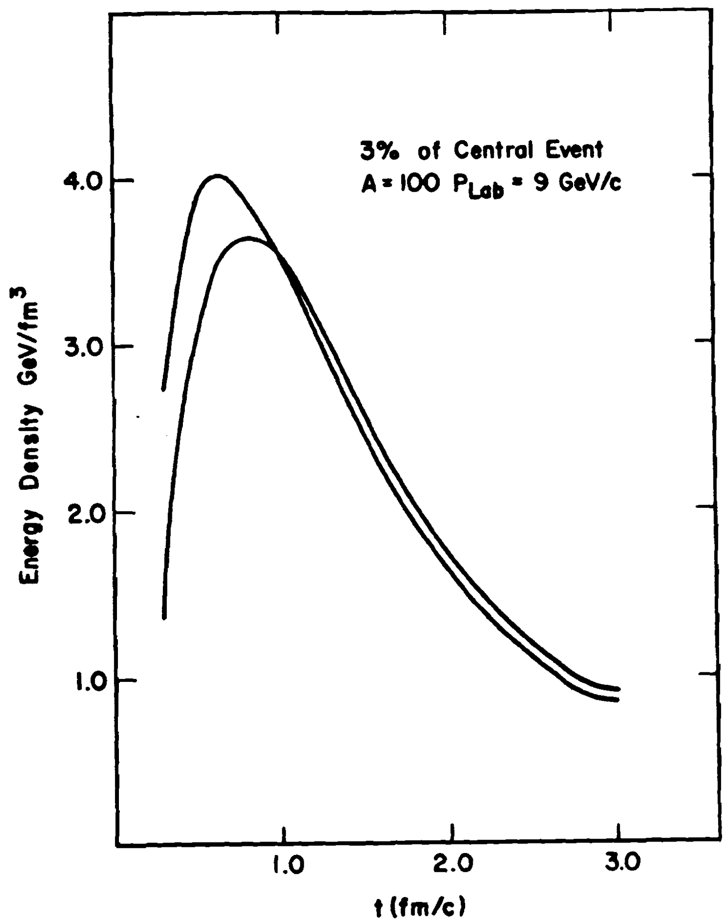

Figure 7. Estimated energy density in nucleons for two favorable events. These curves should be multiplied by 0.8 - 0.9 to take account of center of mass motion.