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TITLE HIGH NUCLEAR TEMPERATURES BY ANTIMATTER-MATTER ANNIHILATION

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HIGH NUCLEAR TEMPERATURES BY ANTIMATTER-MATTER ANNIHILATION

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In order to investigate the properties of nuclear matter it is useful to be able to vary the conditions of the system. We wish to consider the possibility of raising the energy density of a localized region of nuclear material.[1] If we ask "What are the conditions which would lead to interesting physics?" there are many possible answers corresponding to different models of the nuclear equation of state. One of the most intriguing candidates is that of raising the energy density of some fraction of the nucleus to that of a nucleon. In this case one may expect the quarks to "deconfine" from the individual nucleons and form a quark-gluon plasma in which the nucleons have lost their identity. Since the energy density of a nucleon is the order of 1 GeV/fm^3 (perhaps a bit more) baryon densities greater than 6 times nuclear matter density would be in order. Another possible method would be to raise the kinetic energy of the nucleons to a "temperature" of the order of 180 MeV (or greater). In general both of these variables will be involved and it is fashionable to draw a phase diagram in this temperature-density space with a hadronic phase and a quark-gluon phase. It has been proposed to try to create this "new" form of matter by collisions of heavy ions. We suggest a possible alternative through the use of antiproton (or antideuteron) beams.

The experimental work has already begun with the work of DiGiacomo et al.[2] and Breivik, Jacobsen and Sorensen.[3] These experiments at LEAR and CERN are 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 possibly of using higher energy antiprotons.

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

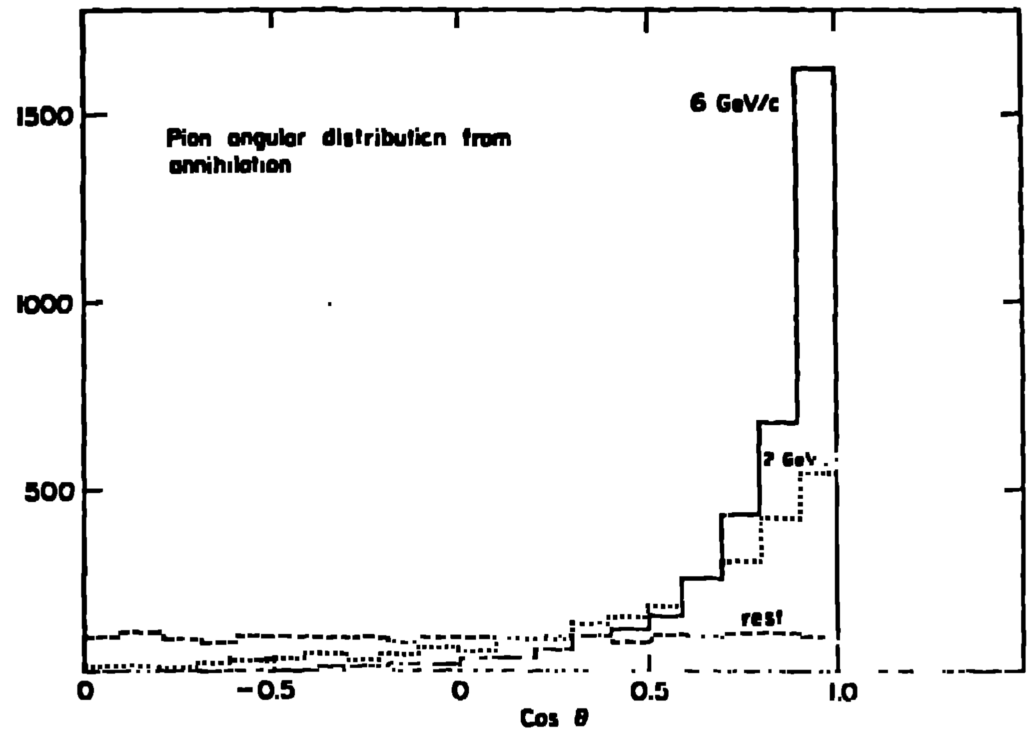

Fig. 1 Angular distribution of pions from p̄p annihilation. The pions are assumed to be produced isotropically in the center of momentum.

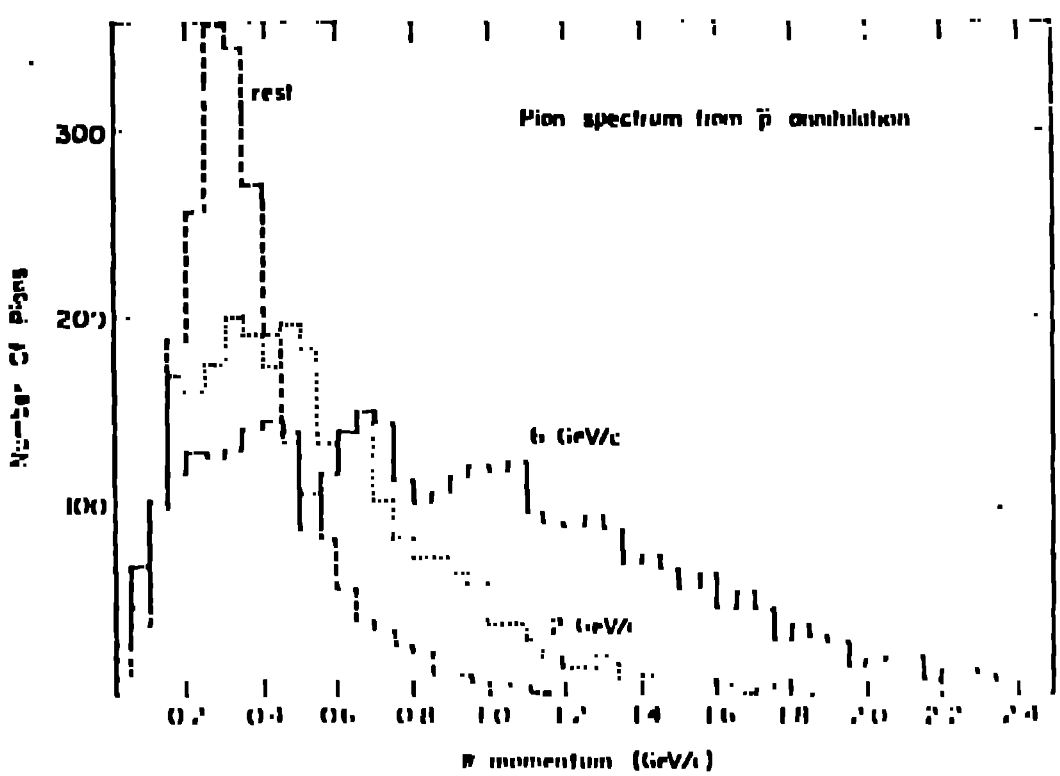

Fig. 2 Momentum distribution ...

Second, the annihilation products are very forward peaked and tend to form a beam of mesons so that the energy density does not disperse very rapidly. Figure 1 shows this effect. Above 6 GeV/c almost all pions are within a cone of 20°. The energy 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 which is propagating with the 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 this 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 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 two 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 (mostly meson kinetic energy) to nucleon (or other) thermal energy and/or compressional energy in this time in order to achieve the desired energy density.

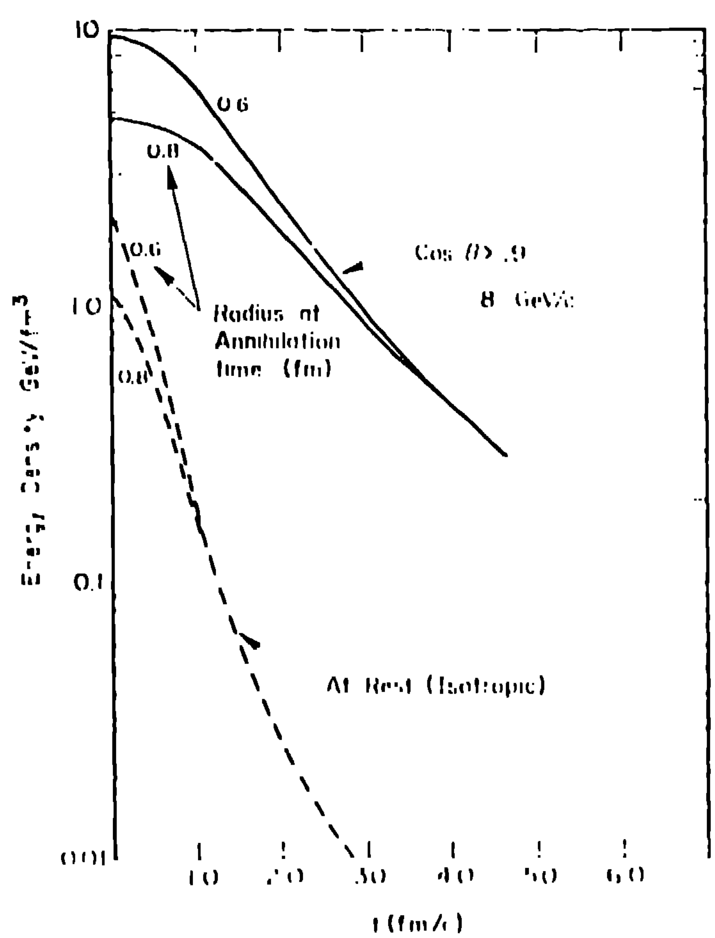

Fig. 3 Total energy density available in the annihilation process at rest and

The third reason for wanting to raise the energy of the beam is 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 in a general way. 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. This is very different from a proton nucleus collision scenario where a small fraction of the incident proton energy is given to a very few nucleons.

From these encouraging first considerations Dan and I decided to try more complete calculations to see if we could follow the process of annihilation, in some detail. Since he had already done a calculation of $\bar{p}$ annihilation at rest[4] using his hydrodynamic code he continued in this direction by improving the calculation and allowing higher energy antiprotons.

Because arguments rage over the relative merits of hydrodynamic vs. intranuclear cascade calculations in heavy ion physics and we were interested in the physics content more than the result of a given model, I decided to do an INC calculation for comparison. The two methods each have their strengths and weaknesses. Some of these are given in Table I. The reader can probably

TABLE I

HYDRODYNAMIC	INC
Allows variation of nuclear eq. of state	Uses "billiard ball" mechanism
Can give a visual display of results	Not easy to extract the information
Has naturally associated thermodynamic variables	Must treat as a finite of particles
Energy deposition is modeled separately	Energy deposition is part of the cascade process
Treats average motion of the matter	Fluctuation effects may be important
Assumes chemical and thermal equilibium	No equilibrium assumed

think of more. Since I am much more involved with the INC code I will spend more time on it but let me first mention briefly the basic aspects of the hydrodynamic approach:

a) The technique is very similar to that used in the study of heavy ion collisions so that, if one is interested in the relative merits of the two methods, a direct comparison is available. It should be said at the outset, however, that the scenarios are very different in the two cases leading to the exploration of different regions in temperature-density space.
b) The results are obtained by the solution of three-dimensional, covariant, relativistic hydrodynamic equations.
c) Effects of viscosity and thermal conductivity were not included in the present calculation.
d) Fixed cubical eulerian cells were used.
e) The average energy deposition was obtained from a Monte Carlo simulation of annihilation using pions only.
f) After a hadronization time of 1 fm/c in the rest frame of the primordial pion, half of its remaining energy was deposited after each mean free path.
g) The equation of state was taken to be quadratic in the square root of the density.

In approaching the problem of the INC calculation I, of course, realized that there were already at least two codes in current use. A code of the classic type is available at Los Alamos[5] and I could have used it. The problem is that one wished 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 says they have been struck. One needs to follow all of the nucleons at all times to know the total nuclear state at early, as well as late, times.

A code of this general type exists as well,[6] 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 et al.[7]

An intranuclear cascade code consists of a series of rules for the time development of a model of nuclear processes. I shall now briefly give 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 scatter 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 data. [illegible] nucleons struck before absorption is 3-4. Pauli blocking of low momentum transfer scatters 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.[8] In particular, results from inelastic scattering, single charge exchange, double charge exchange, true absorption cross sections and the proton spectra resulting from incident pions were studied. A reasonably good agreement was achieved in all of these cases, at least as far as magnitude was concerned.

A second version of the code was 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 essentially identical to that used by Clover et al.[5] The resulting pions were then boosted into the laboratory frame. The distributions shown in figures 1 and 2 were obtained from this code. Annihilation was assumed to take place on the central axis 1 fm inside the nuclear surface corresponding to a 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 uses 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_o, in substantial agreement with the hydrodynamic calculation which gives 1.8 ρ_o.

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 even at very early times. 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 lead to the particles. 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 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 possible temperatures obtainable. The hydrodynamic [illegible]

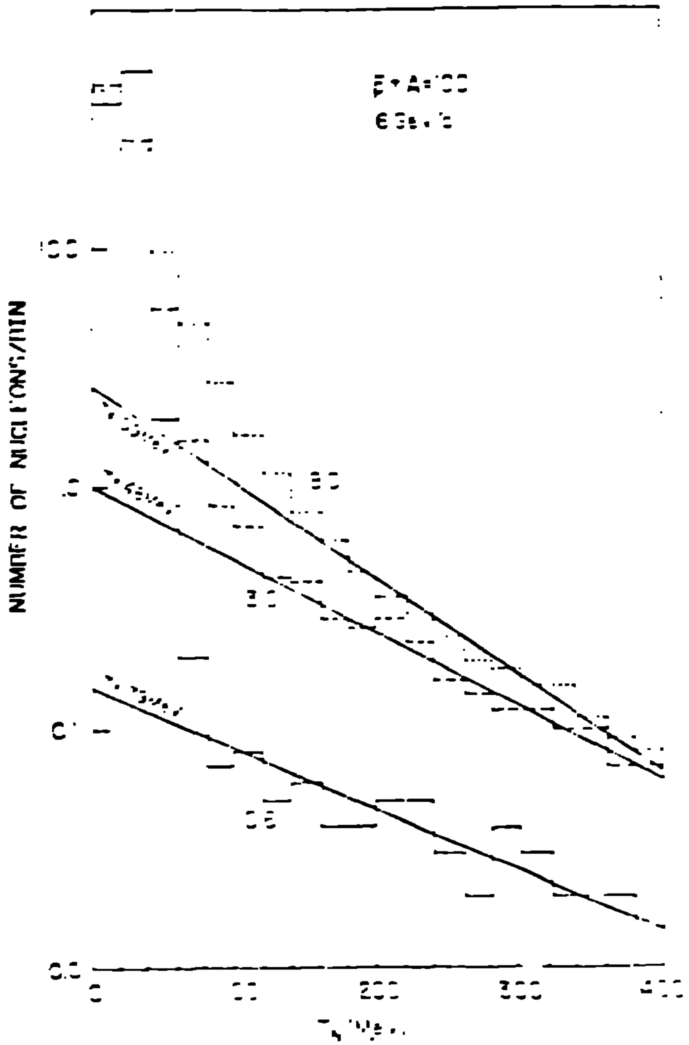

Fig. 4 Example of the distribution of nucleon kinetic energies for times 0.6, 3.0 and 18.0 fm/c, illustrating the existence of a "cold" and a "hot" component.

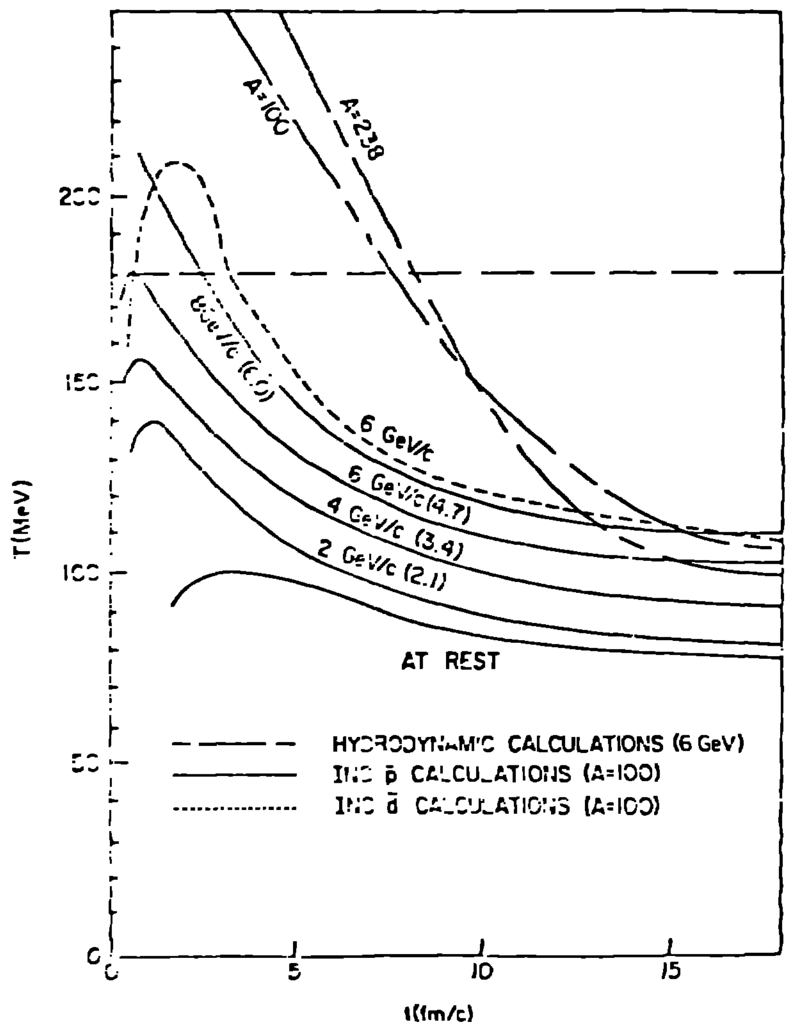

Fig. 5 Temperatures achieved as a function of time for the INC and hydrodynamic calculations for various conditions.

(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 represent only average (central) events. One can arrive at more extreme conditions by selecting on the "proper" final observables. It is not clear what the best criterion is, 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 cut the result is shown in figure 6. For 90-100% of the total energy available being 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 numbers 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.

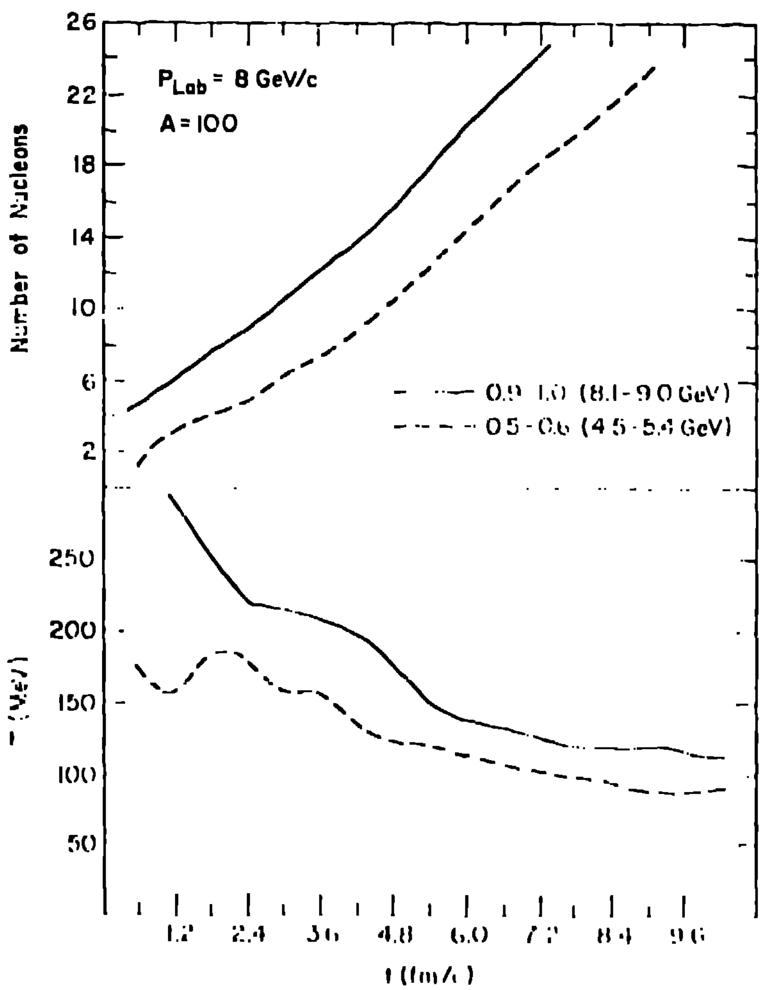

FIG. 6 Temperatures and number of nucleons involved in the "hot" distribution as a function of time for two different cuts on energy deposition. The solid curve shows results for > 90% energy conversion to nucleons and the dotted curve for 50-60% deposition.

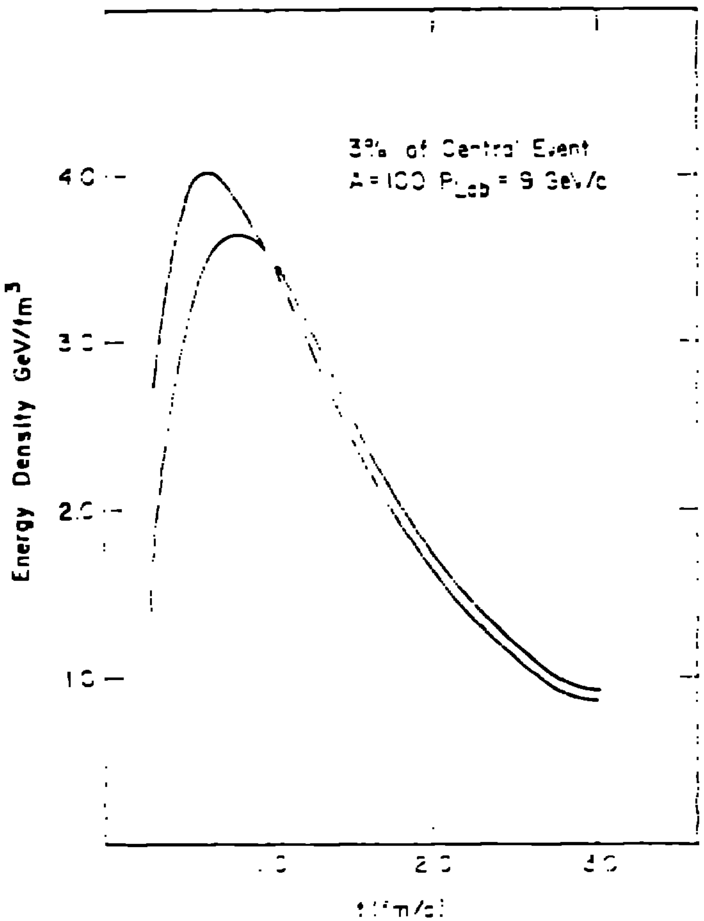

Fig. 7 The time development of maximum energy density for two events obtained by multiplying the fraction of total energy converted by the appropriate curve from figure 3. This estimate is pessimistic for the descending portion but must also be corrected for the fact that some energy (10-20%) remains as translational motion.

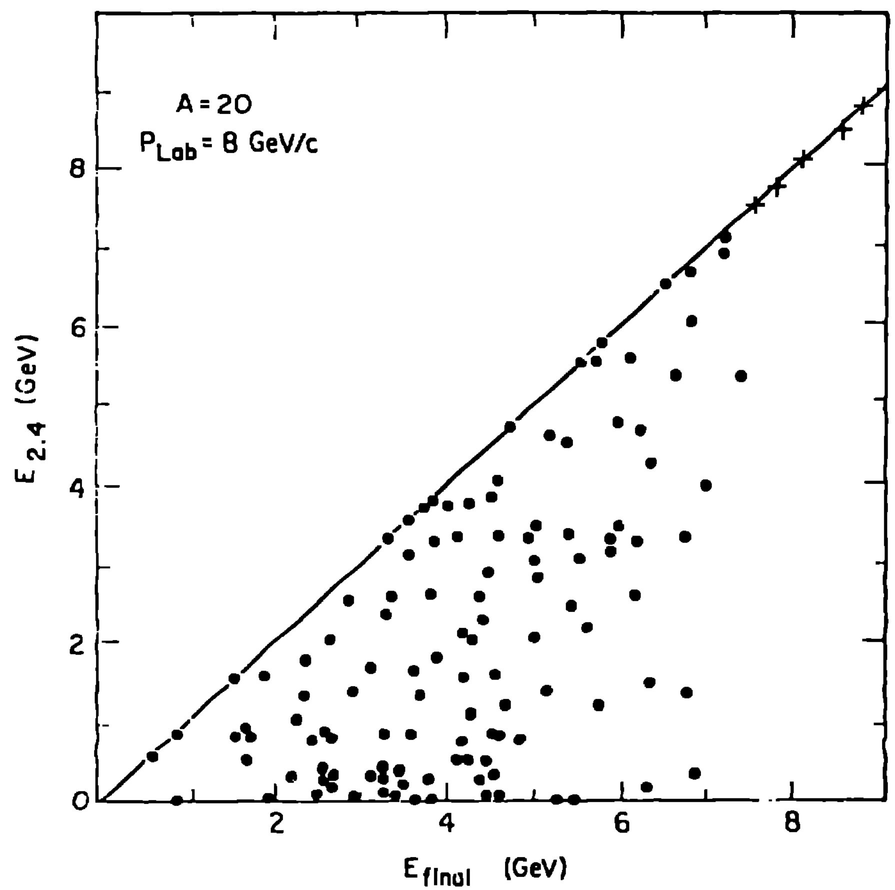

Fig. 8 Scatterplot comparing early deposition of energy with final deposition. Note that for high energy deposition to occur the process must happen very soon after annihilation.

One can also tabulate statistics on the relative momentum of the nucleon pairs colliding. This is done separately for each of the three cartesien 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 early 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.

To try to find these rapid events from external indications I made the scatterplot shown in figure 8. It compares the energy deposited by 2.4 fm/c with the total energy deposited by ploting a point on the graph at the corresponding position. The points lying on the diagonal line correspond to those events in which there was no action after 2.4 fm/c. In most cases there will be more scattering, of course, although the fraction is not so great as one might suspect naively. The astonishing thing about the graph is that for final energy depositions above ∿ 7 GeV all of the energy is deposited at a very early time. This is a very sharp condition and its origin is not well understood. It is likely that it is related to absorption on clusters of nucleons (statistical clustering only, there is no dynamical clustering in this model). If this is true then it could be an artifact of the model requiring the inclusion of short range nucleon-nucleon correlations in the initial wave function to correct it. If one goes to a heavier nucleus (A = 100) the effect persists but the onset appears at a higher energy (∿ 8 GeV).

I have presented the results of a model attempting to follow the process of $\bar{p}$ annihilation in nuclei and analyze the results in physical terms. Clearly this is an ongoing process. There are, in addition, several weaknesses in the present INC approach. Some of the problems are:

a) The nucleons are treated non-relativistically;
b) Meson resonances are not included, i.e. the p annihilation goes directly to pions;
c) The "temperature" is not such a well defined idea in the approach;
d) π, 2π reactions are not included;
e) Pion production in nucleon-nucleon collisions is not present.

It seems to me that none of the corrections for these effects will change the general conclusions about energy deposition at short times.

Is there anything which could "make the wheels come off?" Maybe. The fundamental question of the time evolution of the strong interaction is a disturbing one. If it takes of the order of 1 fm/c (in the CM) for hadrons to form then the process 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 is more serious. In what way should the physics of this process be treated? A reasonable understanding of this physics must be in hand before a reliable calculation of this effect can be made.

As summary we conclude that antiprotons offer a different and complementary means of achieving high energy density from heavy ion reactions.

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