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PRODUCTION OF HIGH ENERGY DENSITY IN $\bar{N}$-NUCLEUS INTERACTIONS

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ABSTRACT

The results of an investigation of $\bar{p}$- (and to a lesser extent) $\bar{d}$-nucleus interactions are reported. The technique involves following the classical production and propagation of mesons ($\pi, K^+, K^\circ, K^-, \bar{K}^\circ, K^*, \eta, \omega, \phi$) and baryons ($N, \Lambda, \Sigma$) in nuclei after antiparticle annihilation. It is found that small regions of the nucleus can be raised to sufficiently high energy densities that some predictions of a quark-gluon phase transition can be tested with the use of energetic antiprotons (5-10 GeV/c). The strangeness signal is examined and compared with the amount of strangeness produced in a recent experiment with 4 GeV/c incident antiprotons. A general expression is given for the total amount of strangeness produced which is invariant under intranuclear strangeness exchange reactions.

I. Introduction

It is clear that the $\bar{p}$-nucleus interaction is one of the really new and exciting tools available for the exploration of the nucleus, and hadronic physics in general. In no other system is the production of a particle beam available directly within the nuclear medium. The first question that arises, from a fundamental and pedantic point of view is "When is a hadron (a member of this 'particle beam') a hadron?" This question touches on the time structure of the strong interactions in the most fundamental manner. If one is willing to assume that the time required for hadron formation is small (or that the interactions of the constituents lead to approximately equivalent results) then the problem can be addressed from an hadronic viewpoint. This does not immediately take us to the meson and excited baryon picture -- far from it. Since we made the initial assumption on the basis of lifetimes we will continue to do so. While the contribution to the spectral representation of hadronic interactions of the Δ or ρ may be substantial, the approximation of these short lived systems by a "particle" which moves around in our coordinate space seems inappropriate. On the other hand, long lived entities, such as the eta or omega should be treated as real objects. Note that this has little contact with the modern boson exchange picture.

While this discussion has in no way resolved the fundamental question of the time structure of hadronic interactions, it does suggest a hierarchy for the development of a theory of non-coherent nuclear interactions. This is the type of theoretical structure needed for reactions in which radical changes occur in the nuclear system. In such reactions, where many states are averaged over in the final system, the quantum mechanical phase information is lost and classical mechanics is approximately restored. In this case we may use (relativistic) Newtonian mechanics employing classical probabilities based on bilinear quantum-mechanical calculations or, better yet, measured cross sections.

I shall present the results of such a calculation of two interesting quantities. The first is the energy density in the nuclear medium. This is of fundamental interest because, if it can be made of the same order as that in a nucleon, it is possible that a substantial volume of the nucleus can be transformed into a state resembling that of the nucleonic interior. In this advent we shall have our first macroscopic (on a nuclear scale) view of the true hadronic "soup". This is the closest we are likely to come, in the laboratory, to conditions that existed in the first instants of the universe. Such conditions are very challanging to achieve and great efforts are being made to arrive there in the heavy-ion arena. It would seem that these conditions are quite possible with antiprotons (or anti-deuterons) and, while the volumes attainable are modest, the control of "external" systems makes the study potentially very interesting.

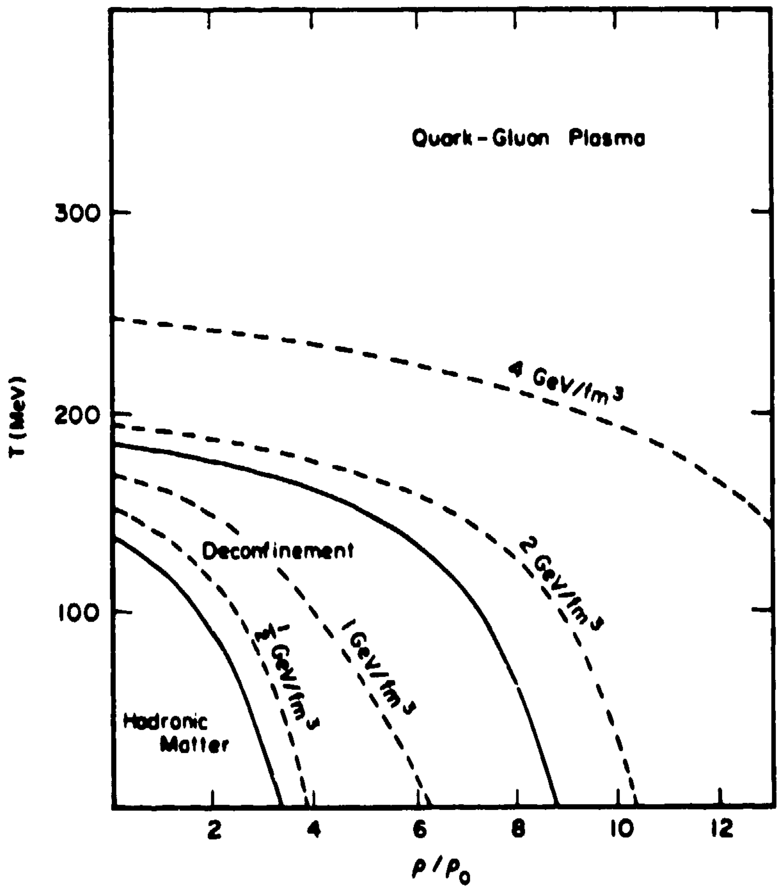

Figure 1. The general view of the possible phases of nuclear matter.

To understand this last comment consider figure 1. It represents a simplified schematic phase diagram of nuclear matter as conjectured by a number of people[1]. While the formation of the universe presumably followed a path originating from a point at very high temperature and low density, along the vertical axis and progressed along this axis to arrive at the cold nuclei which form stable matter, we must start with target nuclei and trace out a heating, as well as cooling, curve. As we shall see shortly, the antiproton annihilation forms a small pocket of high energy density involving several baryons. This volume has a natural center-of-mass velocity determined by the incident antiproton momentum and is usually formed not very far into the nucleus (at about 1 fm depth as estimated from the mean-free-path for annihilation). If a phase transition takes place in this small volume so that quark and gluon, rather than hadronic, degrees of freedom are the relevant ones, then one needs to study the cooling of this system. While the new state is within the nucleus it is cooled by conduction (collisions with the "colder" nucleons surrounding it) and convection (mixing the "cold" nucleons into the "hot" system itself). When it exits the back side of the nucleus it finds itself in free space and will cool radiatively only. By varying the size of the nucleus one can control the time that the hot matter remains in the nucleus, and hence the rate of cooling of the high energy density region. In this way we may study the "signals" of the phase transition as a function of the "temperature" at which the object breaks into free space. In this introduction I have freely used the colorful jargon of thermodynamics; in the actual reactions one should define the finite-particle-number analogue of these concepts and use them.

The second result that I will present concerns the signals that one can use to determine the possible presence of a quark-gluon plasma. The only one I will discuss is that measured by the quantity of strangeness produced, relative to, for example, light q-$\bar{q}$ pairs. If, as has been discussed by Rafelski[2] and co-workers, the gluon-gluon interactions Bremsstrahlung $S\bar{S}$ pairs with the same probability as lighter pairs, then the amount of strangeness produced will increase dramatically over that available from the usual, OZI forbidden mechanisms. As he points out there will already be considerable enhancement in a hot hadronic soup, so some quantitative understanding must be in hand before the significance of an enhancement in strangeness production can be evaluated. I note a point here which will be emphasized later: Strangeness exchange may rearrange significantly the individual strangeness channels so it is not sufficient to look at a single channel (such as only Λ or only K^+, etc.).

It is with these two goals in mind that the calculations are undertaken. Before going on to describe the calculation and present the results, it is useful to obtain an intuitive view of the process.

Energetic antiprotons are much more efficient for energy deposition than very low energy antiprotons for three reasons: 1) The mesonic debris from the annihilation is pushed into the nucleus by the overall motion of the system, 2) The annihilation takes place well within the nuclear system due to the decrease in annihilation cross section and 3) The total energy available is greater, assuming that a reasonable fraction of the energy can be shared among several nucleons. With respect to this last point I note that pions are very efficient as a means of distributing energy among many nucleons since they make ~3-4 collisions with nucleons during the absorption process. A more complete discussion of this energy sharing process can be found in some previous lectures[3].

II. Calculational Technique

The nuclear target is modeled by a system of A nucleons propagating in a Saxon-Woods potential with classical motion. Isotropic (in the CM) NN collisions are governed by an approach distance corresponding to a classical circular cross section of 40 mb. The antiproton is assumed to annihilate 1 Fermi inside the surface of the nucleus on the beam axis. For the antideuteron calculations it is assumed that the two antinucleons annihilate simultaneously ± 1/2 Fermi away from the central axis. The products of annihilation are taken to be pions and $K\bar{K}$ pairs according to the experimentally measured fractions. $\Lambda\bar{\Lambda}$ production is neglected in the present version of the code.

The mesons thus produced are then propagated within the nucleus with no mean field (in contrast to the case for the nucleons) but with the

Table 1. Channels included in the current version of the code.

$NN \rightarrow NN$	$\pi N \rightarrow \pi N$	$\pi N \rightarrow \phi N$	$\bar{K}N \rightarrow \bar{K}N$
	$\pi N \rightarrow \pi N$	$\pi N \rightarrow K\Lambda$	$\bar{K}N \rightarrow \pi\Lambda$
	$\pi N \rightarrow \pi\Delta$ ($\Delta \rightarrow \pi N$)	$\pi N \rightarrow K\Sigma$	$\bar{K}N \rightarrow \pi\Sigma$
		$\pi N \rightarrow K^*\Lambda$	$KN \rightarrow KN$
	$\pi N \rightarrow \pi\pi\pi N$	$\pi N \rightarrow K^*\Sigma$	
	$\pi N \rightarrow \omega N$		
	$\pi N \rightarrow \eta N$		

reactions in table I occuring. The pion induced reactions are very important since these deposit most of the energy and produce strangeness as well. Their calculation is implemented by first deciding if there is to be a pion-nucleon collision based on the pion-nucleon distance compared to the pion-nucleon total cross section in the laboratory. The momentum used for the calculation of the cross section is the effective momentum that the π-N system would have *if* the nucleon were at rest, i.e., the Fermi motion of the nucleon is taken into account as if it were on shell. Once it is determined that a pion-nucleon collision will take place a number of branches are possible. These are chosen according to the cumulative probabilities given in Figure 2. The logarithmic graph is used so that the small, OZI forbidden, particle productions can be seen. The π-2π and π-3π reactions are important for an estimate of energy deposition. These probabilities were calculated from data taken from the CERN-HERA[4] reports.

The kaon reactions are treated in a similar, but less exhaustive manner.

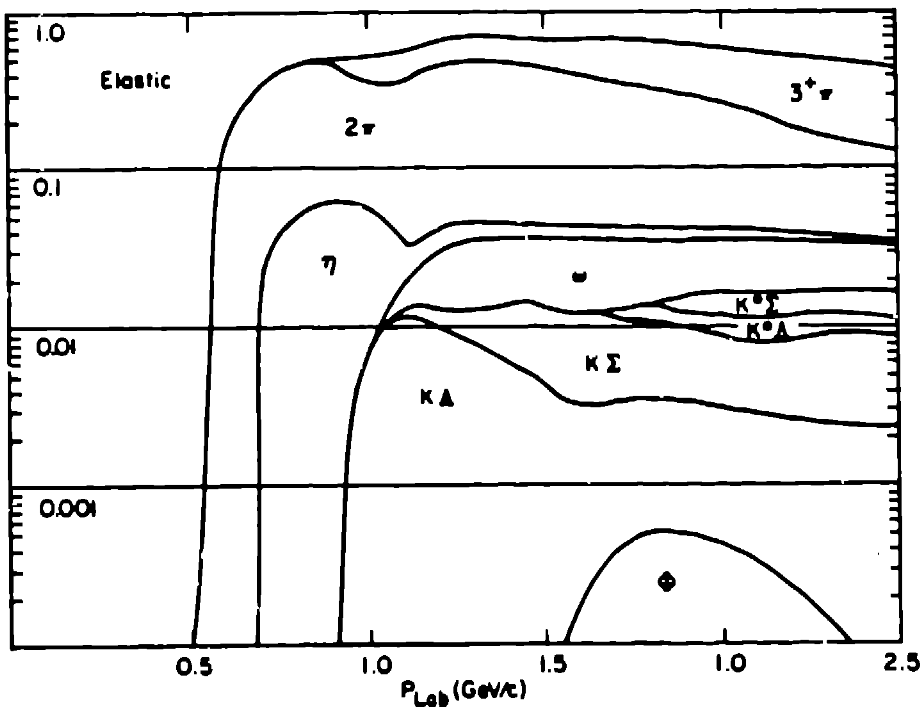

Figure 2. Branching ratios from πN collisions.

III. Results for Energy Densities

To estimate the degree to which the conditions necessary for a phase transition are achieved several approaches are possible. One way is to tabulate the kinetic energies of all of the nucleons and then plot the number of nucleons as a function of their energy. This distribution is seen to consist of two components; one corresponds to the nucleus in its "cold" state and the other to the heated portion. From an analysis of the hot distribution one can obtain both a "temperature" and the number of nucleons involved in the distribution. Since these results have been published elsewhere[3,5] I won't repeat them here, but temperatures in excess of 200 MeV are achieved. This conclusion is in agreement with the results of hydrodynamic calculations as well[5].

Another way to estimate the usefulness of antimatter annihilation to achieve a phase transition is to look at the energy density directly. The brute force method is to choose a set of small volumes and directly calculate the energy contained in the volumes. Since we are not interested in the energy associated with overall translational motion only the density in the volume's rest frame is counted, i.e., the invariant mass density. One might choose to look at the energy contained in all particles (nucleons, pions, kaons, lambdas, etc.) in the volume. This has the disadvantage that the full fireball energy is contained, and even in free

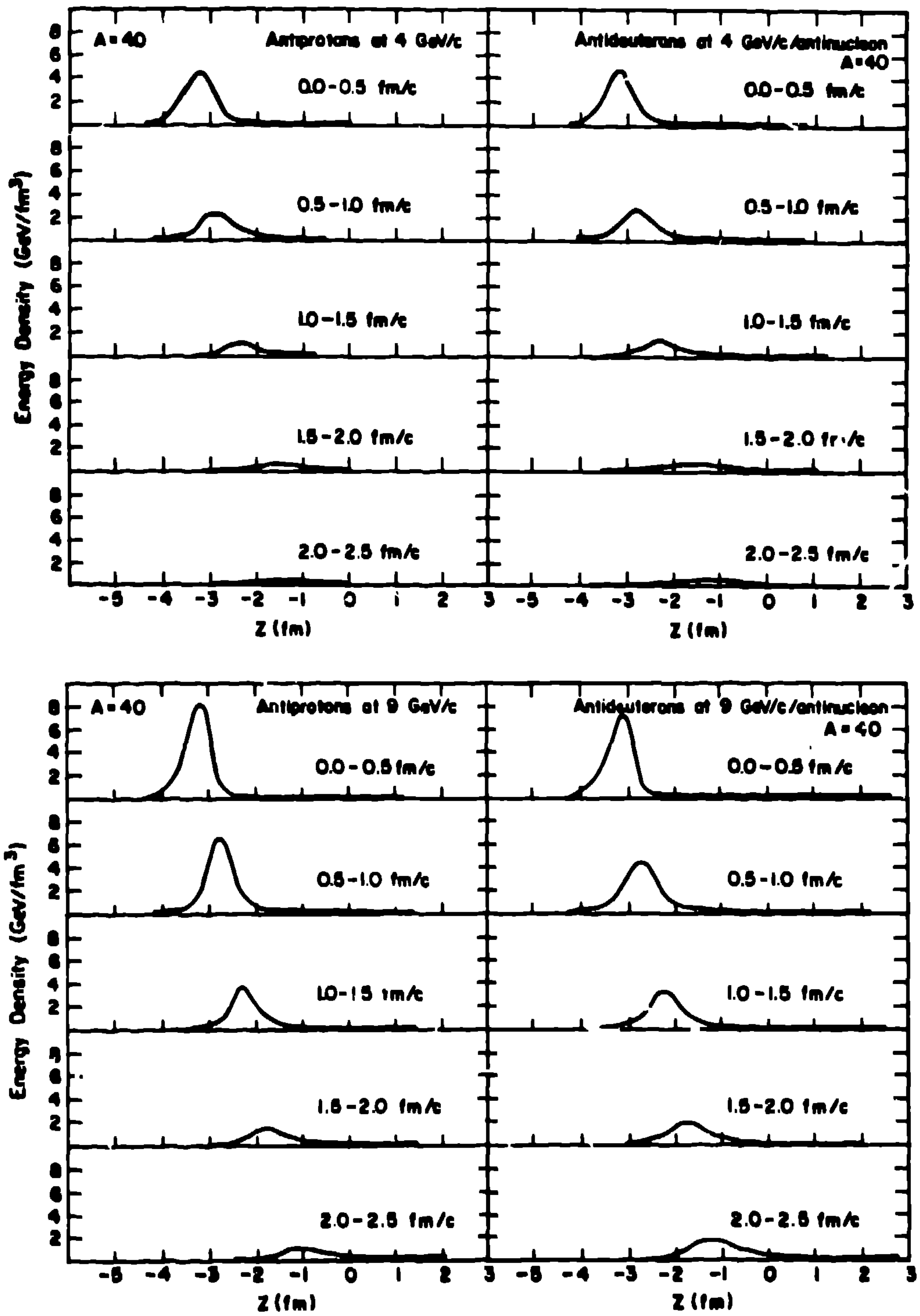

Figure 3. Maximal antiproton and antideuteron induced nuclear energy densities, such densities may be expected in 1-3% of central annihilations.

space one will see a high energy density. From previous work we know that an appreciable amount of energy is transferred to nucleons in a short period of time in a few percent of the cases. Thus this estimate can be used if one is careful to say that it only is applicable in about 3% of annihilations. These results are shown in figure 3 for both antiproton and antideuteron annihilation. It is clear that the maximum energy density is sufficient to cause a phase transition. Clear questions exist regarding whether the space-time extent is sufficient for the required parton equilibrium to be established. Clearly the reactions initiated with antideuterons are superior.

One might also choose to look only at the energy transfered to the nucleons. The problem with this is that this energy transfer to nucleons seems to occur at different places for different events. Since we are interested in the energy deposited in each individual case the average will spread the energy density around and dilute it. In this case we must examine individual events, which forces us to deal with much poorer statistics. The sampling volumes must not be taken too small or the nucleon granularity can cause artificial and arbitrarily large energy densities. Figure 4 shows two cases of single events. The energy densities in this case are more modest but we should remember that there really are mesons in these volumes which are not being counted. It is clear that the decay of the energy density with time is now much slower.

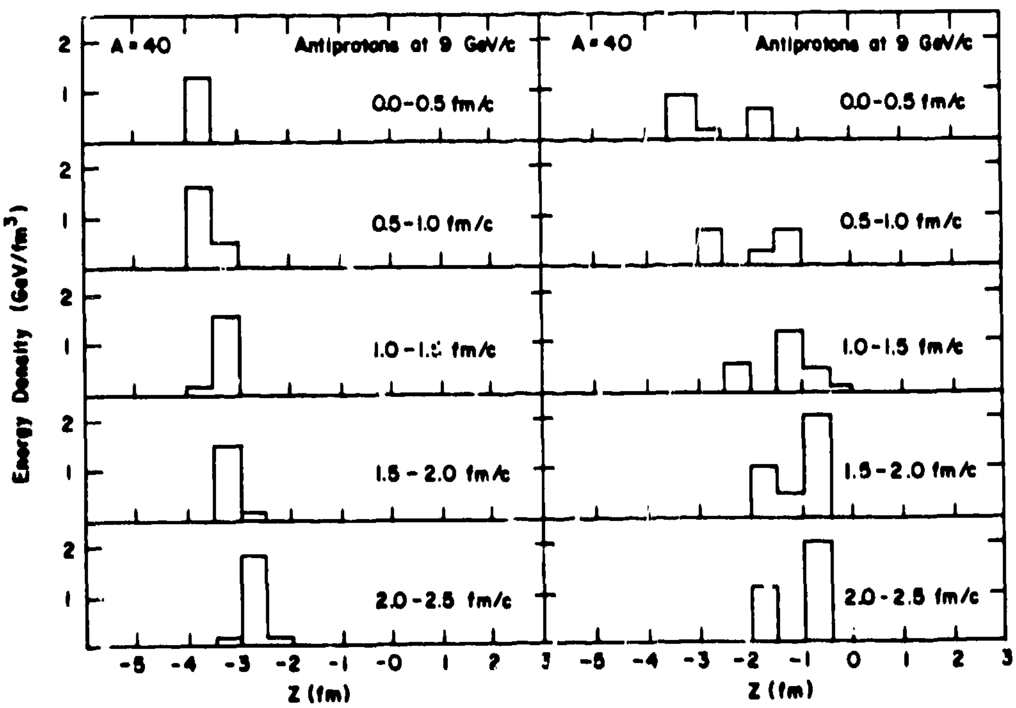

Figure 4. Single events showing energy deposited in nucleons only. This may be expected to be a minimum of the energy density deposited in nuclei by antiparticles.

The relevant parameters may be expected to lie between the two estimates.

Table II. Λ Production

P_{LAB}(GeV/c)	Target	Λ/Ann (%)	Ref
0.0	D	0.36	Bizzarri, et al. Lett. Nuovo Cimento 9, 431 (1969)
≤ .3	C,Ti,Ta,Pb	1.9	Condo, et al. Phys. Rev. C29, 1531 (1984)
0.6	Ne	~2.0	Balestra, et al. Nucl. Phys. A452, 573 (1986)
4.0	^{181}Ta	11.8	Miyano, et al. Phys. Rev. Lett. 53, 1725 (1984)

IV. Strangeness Production

As mentioned earlier an enhancement in strangeness production has been suggested as a signal of the formation of a quark-gluon plasma. Table II gives a brief summary of Λ production as measured in p̄-nucleus collisions. In order to set the investigation of this signal in a realistic framework it is particularly useful to compare with the recent KEK data(6) taken in a regime which approaches the relevant regions. The incident p̄ momentum was

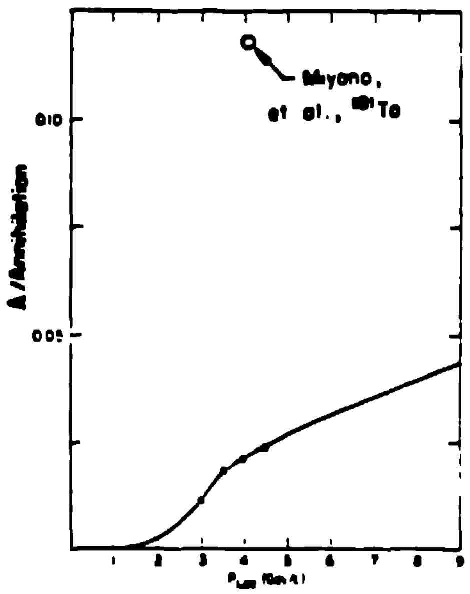

Figure 5. Production of Λ hyperons with p̄-beams.

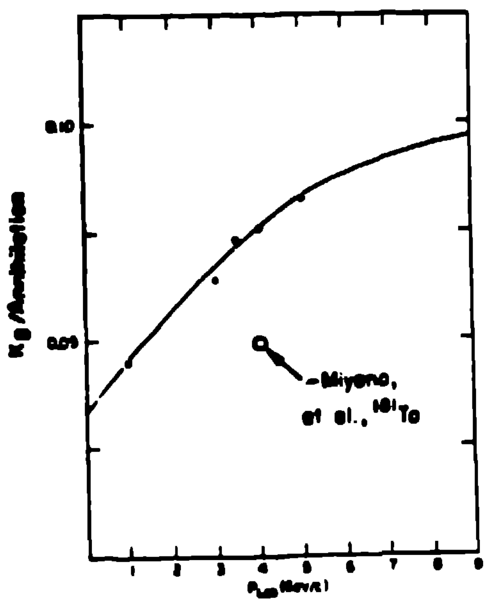

Figure 6. Production of K-shorts with p̄-beams.

4 GeV/c and the target ^{181}Ta. Observed was the number of K_s, Λ and $\bar{\Lambda}$ which follow antiproton interaction with the nucleus. Few $\bar{\Lambda}$'s were observed, consistent with $\bar{\Lambda}$ annihilation in the nuclear medium. The number of Λ's seen was greatly enhanced, however, as indicated in figure 5. Is this large enhancement to be interpreted as evidence for a phase transition? After all, a very recent estimate[7] based on the non-topological soliton bag model, has predicted the quark-gluon phase transition to occur at a temperature of ~112 MeV. It seems extremely likely that such temperatures were reached in this experiment. Figure 6 points out that a slightly smaller number of K-shorts than expected were observed.

Running the classical nuclear modeling code previously described leads to predictions agreeing quite well with the experimental results. The code created about 3% of strangeness (.03 $S\bar{S}$ pairs per annihilation) but this is probably an overestimate since only central collisions were considered. This is not a major effect in any case. The most important reaction was $\bar{K}N \rightarrow \pi\Lambda$ creating Λ's in about 7% of the annihilations and depleting the K_s population. Table III gives the strangeness balance corresponding to the results of the calculation.

Table III. Strangeness Balance on ^{181}Ta at 4 GeV/c

	Λ(%)	K_s(%)
$\bar{p}p \rightarrow \Lambda\bar{\Lambda}$, $K\bar{K}$	2.0	6.5
$\bar{K}N \rightarrow \pi\Lambda$, $\pi\Sigma$	7.1	-2.5
$\pi N \rightarrow K\Lambda$, $K\Sigma$	3.1	1.0
	12.2	5.0
Experiment[6]	11.8	5.0

While it is instructive to follow the strangeness exchange in detail to learn about the reaction process, it is not necessary if one only wishes to know the total strangeness produced. Note that the observation of a K_s does not distinguish the presence of an S quark or an $\bar{S}$ quark, so one cannot just count S or $\bar{S}$ quarks. However, if one assigns a probability for strange quark exchange between bags, i.e., for $\bar{K}N \rightarrow \pi\Lambda$ and $\bar{\Lambda}N \rightarrow K +$ anything, as well as a probability for $S\bar{S}$ formation, then one can eliminate these first two probabilities algebraically from the species transformation equations to find an expression which is invariant under all strangeness exchange reactions. This measure is:

$$S = \frac{1}{2}\,(4N_{K_s} + N_Y + N_{\bar{Y}})$$

where S is the number of $S\bar{S}$ pairs produced and N_{K_s}, N_Y, $N_{\bar{Y}}$ are the numbers of K-shorts, hyperons and antihyperons respectively produced. As an example let us apply this equation to the experiment at 4 GeV/c. In free space: $S = \frac{1}{2}(4\text{x}\ 0.065 + 0.02 + 0.02) = \underline{0.15}$. From Ref. 6: $S = \frac{1}{2}(4\text{x}0.05 + 0.118 + 0.002) = \underline{0.16}$

This leaves 1% to be produced in (OZI forbidden) hadronic interactions. Remember that the classical code (over)estimated 3%, so that, if anything, the experiment observed less than expected. Certainly these small differences are in the noise at this point. What is anticipated from a phase change is an enhancement in S by about an order of magnitude. It seems that this experiment could be taken for evidence against such a transition, at least at some level.

V. Conclusions

We have seen that energy densities of the order of that required for a phase transition to a quark-gluon plasma are present in energetic antimatter-matter interactions. Whether the space-time extent is sufficient for the parton thermalization to become complete, and for the signals to be generated, is not clear, but the conditions would seem to be of comparable quality to those generated in the heavy-ion collisions. Greater control of the cooling curve could well provide an advantage in interpreting any anomalous behavior in signals at the critical energy density.

Analysis of the strangeness produced in one recent antiproton experiment shows it to be completely consistent with no enhanced strangeness production, both from a detailed model and from a relation derived from invariance under strangeness exchange in strong interactions.

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