LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

LA-UR--89-3426

DE90 002383

TITLE THE CREATION OF HIGH ENERGY DENSITIES
WITH ANTIMATTER BEAMS

AUTHOR(S) W. R. Gibbs, and J. W. Kruk

SUBMITTED TO Invited talk presented at the Bad Honnef Conference on
"The Physics to be Done at KAON", JUNE 9-11, 1989, Bad
Honnef, West Germany. To be published in the Proceedings.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, and to allow others to do so, for U.S. Government purposes.

The U.S. Agency for International Development requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

THE CREATION OF HIGH ENERGY DENSITIES WITH ANTIMATTER BEAMS

W. R. Gibbs

Theoretical Division
Los Alamos National Laboratory
Los Alamos, NM 87545 USA

J. W. Kruk

T. W. Bonner Nuclear Laboratory, Physics Department
Rice University
Houston, TX 77251 USA

ABSTRACT

The use of antiprotons (and antideuterons) for the study of the behavior of nuclear matter at high energy density is considered. It is shown that high temperatures and high energy densities can be achieved for small volumes. Also investigated is the strangeness production in antimatter annihilation. It is found that the high rate of Lambda production seen in a recent experiment is easily understood. The Lambda and $\bar{K}$ -short rapidity distributions are also reproduced by the model considered.

Received

Introduction

The use of the antiproton as a nuclear probe provides many opportunities for the study of hadronic physics. One of its outstanding features is the ability to deposit several GeV of energy in a small nuclear volume, thus creating a region of high energy density in the nucleus(1,2).

While such conditions are of great interest to study the nuclear equation of state, important in themselves for the investigation of stellar structure, they have recently received special attention because of the possibility of a phase change of hadronic matter (3). Viewed simply, we may expect a (possibly sudden) change in the behavior of a many-body system when the relevant degrees of freedom change. In the nucleus we are accustomed to the normal degrees of freedom being the nucleons, while for the nucleon itself we expect the description to be in terms of quarks and gluons. Note that the meson degrees of freedom have been bypassed in this picture, possibly a serious error.

We can anticipate that the relevant degrees of freedom will change when the energy density of the nucleus becomes equal to that of a single nucleon. In this case the quarks should be able to move freely within the heated region. This simple estimate gives 0.35 GeV/fm^3 for a nucleon radius of 0.86 fm and 1.8 GeV/fm^3 for a radius of 0.5 fm . Recall that the energy density in normal nuclear matter is around 0.16 GeV/fm^3 . The scenario just presented is certainly too naive but it sets the scale for the onset of possible new physics.

The excitation of the nucleus is often discussed in terms of temperature, meaning simply the random kinetic energies of the nucleons involved and not implying necessarily that an equilibrium has been reached. The numbers most often quoted for the temperature for such a phase change are around 180 to 200 MeV.

This idea raises several important questions. How might one form such a high energy density region? How do we know that we have indeed created it? What is the signal for the possible phase transition? The second and third questions are related and involve a detailed understanding of hadronic mechanisms in the nucleus and of the properties of the particles.

created. At this point in time, a much more complete knowledge of the mechanism of production of hadrons in the nucleus, and their evolution in the nuclear medium, is necessary before any high energy density experiment can be interpreted. For the purposes of this talk, let us focus our attention on the first and third questions.

Obtaining High Energy Densities

The deposition of a substantial amount of energy in the nucleus is not an easy task. If one tries to do it with high energy proton beams it is seen that the proton tends to make very few collisions with the nucleons in the nucleus. Since the angular distribution for nucleon-nucleon elastic scattering is (to a fair approximation) a function of momentum transfer only the probability distribution of energy transfer is independent of energy, at least for low and moderate bombarding energies. Hence there is no gain in energy transfer until the energy regime in which most of the collisions are highly inelastic is reached. At these high energies the cascade process (involving the mesons produced) seems to be inhibited. By the use of heavy ions one can mitigate this problem by hitting the nucleus with many nucleons at once. Note the importance of transferring the kinetic energy of the projectile to many nucleons in the nuclear target. If all of the energy is transferred to a single nucleon then the presence of the remainder of the nucleus is useless.

Besides heavy ions, another possible way to create high energy density is to use energetic antiprotons (or antideuterons). The argument is a good deal more subtle than just saying that antiproton annihilation deposits 2 GeV of energy in a relatively small volume. For example, if one considers annihilation of stopped antiprotons only a small fraction of the 2 GeV available is given to the nucleus(4). Because most of the annihilations take place on the extreme nuclear surface (5) and since the annihilation products are distributed isotropically most of them miss the nucleus completely.

Increasing the antiproton beam energy improves the situation dramatically. First of all, because of the center of mass motion, the annihilation products are pushed forward in the laboratory so that, by a 1 GeV/c p momentum essentially all of the mesons enter the nucleus. Thus a

significant fraction of the energy is available in the form of mesons. Of course these mesons (mostly pions) are also carrying more energy since they are the recipients of the kinetic energy of the antiproton as well. Pions do not behave as the nucleons discussed above, but are often absorbed, thus transferring all of their energy (including their mass) to two or more nucleons. The multiplicity of pions in the annihilation process also increases so that it is not unusual if a 20 GeV/c antideuteron annihilates on two nucleons to find 18 pions. Since the average number of nucleons involved in a pion absorption is of the order of 4, one can imagine 72 nucleons being excited in one antideuteron annihilation. Of course all of these nucleons are not independent (i.e. more than one pion can transfer energy to a single nucleon) so that the actual number of nucleons is of the order of half of that, still a very substantial number.

To understand the heating effect of this partition of the initial energy among pions let us suppose that the antiproton momentum is shared among n nucleons in the final state. The problem of following the energy-momentum conservation is very similar to that of coupling a single moving freight car to n freight cars stationary on a track (at least non-relativistically it is). Using the conservation of momentum we find that only $1/n$ of the original kinetic energy remains as directed motion in the final state. The rest of the initial kinetic energy is converted into heat and sound. Thus antiproton annihilation is a very efficient way to create a high energy density and raise the temperature of the nucleus by converting kinetic energy into thermal degrees of freedom.

The Classical Modeling Code

An intranuclear cascade code was developed to make quantitative estimates of these effects and since some of the results, as well as a description of the code, have been reported elsewhere(6) I will only mention briefly its workings and the main conclusions. The code has many points of similarity with those developed by Cahay, Cugnon and Vandermeulen (7).

The nuclear target is modeled by a system of A nucleons propagating in 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 annihilation and scattering of the antiproton is determined by the antiproton-nucleon cross sections. The products of $\bar{p}$ interactions are taken to be pions, Kaons, Λ s and $\bar{\Lambda}$ s according to the experimentally measured fractions. The antiproton channels included were:

$$\begin{aligned}\bar{p}N &= \bar{p}N \\ \bar{p}N &= \bar{p}N\pi \\ \bar{p}N &= \bar{\Lambda}\Lambda \\ \bar{p}N &= \bar{\Lambda}K^+N \\ \bar{p}N &= \bar{N}\Lambda K^- \\ \bar{p}N &= \pi's \\ \bar{p}N &= K^+K^-\pi's\end{aligned}$$

The mesons thus produced are then propagated within the nucleus with no central potential (in contrast to the case for the nucleons) but with the reactions shown below occurring.

$$\begin{aligned}\pi N &= \pi N & \pi N &= \phi N & K^+N &= K^+N \\ \pi N &= \pi N^* & \pi N &= K^+\Lambda & K^+N &= \pi\Lambda \\ \pi N &= \pi\Delta & \pi N &= K^+\Sigma & K^+N &= \pi\Sigma \\ \pi N &= \pi\pi\pi N & \pi N &= K^+\Lambda & K^+N &= K^+N \\ \pi N &= \omega N & \pi N &= K^+\Sigma \\ \pi N &= \eta N\end{aligned}$$

The pion induced reactions are especially important since they deposit most of the energy and can produce strangeness as well. The calculation of their reactions is implemented by first deciding if there is to be a collision based on each 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 momentum that the πN 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 1. The logarithmic graph is used so that the small particle production cross sections can be seen. The $\pi-2\pi$ and $\pi-3\pi$ reactions are important for an estimate of energy deposition. They also shadow the strangeness producing reactions. These probabilities were calculated from data taken from the CERN-HERA(8) reports.

The kaon reactions are very important for the transfer of strangeness especially the $\bar{K}$ conversion to Λ s. The $\bar{\Lambda}$ interactions were also included in the following channels:

Results for Energy Densities

One of the first things one can do, after running a series of cascades, is to look at the distribution of kinetic energies of the nucleons. It is expected that there will be two distinct populations; a cold one corresponding to the nucleons which have not been affected by the annihilation process, and a hot one for the nucleons on which pions have been scattered or absorbed. Indeed, by plotting a graph of the number of nucleons vs. their kinetic energy, the two distributions are easily seen (Figure 2). Since the "hot" component is roughly exponential in shape it is natural to determine a "temperature" from it. I put the word in quotation marks since it is only a slope parameter that one extracts, but it does indicate the distribution of kinetic energies of the nucleons in the hot region.

One can follow this temperature to see how long the hot gas is confined as shown in Figure 3. Also shown there are estimates by means of a hydrodynamic calculation (1). It is clear that a high temperature remains for several fm/c, a result that compares favorably with the times in heavy ion collisions.

Passing from this simple measure of excitation, the temperature, to something more precise, the energy density, we see that there are still some ambiguities. If we discuss the energy transfer to nucleons alone then things are well defined in terms of what energy density is being discussed. However, the deposition of energy among nucleons is quite variable in position in the nucleus from event to event and by following along the axis of annihilation we get a rather pessimistic view of the energy density, of the order of 1 GeV/fm^3 .

If we consider the energy density of all particles (including the mesons from annihilation) in a given volume we obtain the result shown in Figure 4. This gives a much larger number, of course. Note that it is the energy density of invariant mass which is shown, i.e. the kinetic energy of forward motion has been removed.

Strangeness

One of the possible signals that we are dealing with different degrees of freedom is the amount of strangeness created in an annihilation event. We are accustomed to the suppressed production of strange particles due partly to the higher mass of the strange quark and the difficulty of concentrating enough energy to produce $S\bar{S}$ pairs in hadronic interactions.

One may well expect the fraction of strange quark production in a quark-gluon plasma to be different from that in a hadronic "soup". Rafelski (9) has discussed the two scenarios. Thus a sudden change in strangeness production as a function of temperature or energy density may be interpreted as a signal of a modification of the structure of the hadronic system.

Strangeness production is normally very small so that only a few percent of strange and antistrange quarks are produced in hadronic reactions. We note that for rapidly occurring reactions, within the nuclear time scale, the strange quarks are essentially stable so we shall treat strangeness as a conserved quantity. For this reason there is only pair (strange-antistrange) production. As discussed by Rafelski (9), in a Quark-Gluon plasma all quarks will be on the same footing so the number of strange quarks would be equal to the number of light (up and down) quarks. The fraction of strange quarks obtained in this manner is considerably larger than found in ordinary hadronic reactions. He also pointed out that the hot (color singlet) soup will produce an appreciable amount of strangeness by means of associated production reactions because there are many (non-strange) mesons and hence many such reactions take place in the nucleus. This component of strangeness production must be understood since it is the background for any signal observed indicating the occurrence of a phase transition.

Before entering into the details of how this component can be estimated, we need to discuss the measurement of the strangeness signal itself. The normal convenient experimental variables are the short lived kaons (K-shorts), the Λ s and the $\bar{\Lambda}$ s. While the measurement of a Λ gives evidence of the presence of a strange quark and that of an $\bar{\Lambda}$ an antistrange quark, the observation of a K-short only shows, because its observation is by means of a weak decay not conserving strangeness, that there was either a strange or an antistrange quark present. We note that once the strange-antistrange quark pair is produced in the nucleus that both members can be transferred more or less freely between hadrons. For example, $\bar{\Lambda}$ s will annihilate in the nuclear medium, with high probability, leaving their antistrange quark in a K^+ or K^0 meson. The $\bar{K}$ mesons produced in the $\bar{p}N$ annihilation (or otherwise) have a very strong interaction with nucleons and tend to convert, also with high probability, to Λ s by the $\bar{K}N \rightarrow \pi\Lambda$ reaction. Thus conclusions drawn from the observation of a single type of strange particle can be very misleading.

As we just remarked we do not have, because of the ambiguity of the K-short detection, a direct measure of the strange (or antistrange) quarks contained in mesons. However, if we use the additional constraint that the number of strange quarks is equal to the number of antistrange quarks, we can obtain a measure of the strangeness produced. We simply compute the number of strange quarks plus the number of antistrange quarks and divide by two. The number of hyperons plus the number of antihyperons gives us the part of this sum contained in the baryonic sector. For the K-shorts we must take into account that they signal the existence of either a strange or an antistrange quark. In addition, we must also include unobserved events inferred from these observed particles. First of all, the K-shorts represent only one half of the neutral kaons produced, the other half being long lived and hence not observed in the experiment. Since it is known that half of the neutral kaons decay by the two pion mode we can simply multiply by two to obtain the total number of neutral kaons. In many experiments the charged kaons are not observed. If this is the case then we expect, by isospin symmetry, that there are as many charged as neutral kaons. (We neglect the small correction due to the possibility that the nucleus may not have an equal number of neutrons and protons.) Thus included in the measure of the total number of strange plus antistrange quarks should be a factor of 4 times the number of K-shorts observed. Thus

the total number of strange (or antistrange) quarks produced in a reaction is:

$$S = (4N_S + N_Y + N_{\bar{Y}})/2$$

where N_S is the number of K-shorts, N_Y is the number of hyperons and $N_{\bar{Y}}$ is the number of antihyperons observed in each case per annihilation. For a signal of the phase transition one could plot "S" as a function of temperature or energy density or even simply energy deposition to see if there is an abrupt increase at some given critical value.

Let us take as an example the experiment of Miyano *et al.* (10) which comes the closest to providing the conditions necessary to produce the putative phase transition. In this experiment a large enhancement in the number of Λ s was observed but a large decrease in the number of $\bar{\Lambda}$ s and a sizeable decrease in the number of K-shorts was also seen, compared to the $\bar{p}N$ annihilation in free space. Computing the amount of strangeness, "S", in the $\bar{p}p$ system at 4 GeV/c gives:

$$S_0 = (4 \times 0.079 + 0.021 + 0.021)/2 = 0.179 .$$

Calculating the same quantity for the Miyano experiment we find:

$$S = (4 \times 0.055 + 0.129 + 0.003)/2 = 0.176 .$$

Since the code indicates that associated production reactions occurring during the cascade process contribute about 0.018 to S the experiment observes less strangeness than expected, but the discrepancy is within the uncertainties. We note that for a signal of excess strangeness production it is the amount above the value of S in $\bar{p}p$ collisions which matters. Thus one should measure $S - S_0$.

By running the classical nuclear modeling code described above we obtain results for the various strangeness channels in good agreement with those seen by Miyano *et al.* and in agreement with the simple formula just derived. This last is expected since the formula is general. The real question to be answered by the code is "how much strangeness is produced in the pion-nucleon reactions?" This is the amount that the nuclear

production of "S" should exceed the $\bar{p}p$ production. The table shows the strangeness balance from intranuclear reactions. Note that, since all channels have not been included in the code, there are slight differences in input from the general formula. For example, the total percentage of Λ production is 2.1 while the two largest mechanisms (the only two included in the code) add up to 1.5.

			$\Lambda(\%)$	$K_S(\%)$	$\bar{\Lambda}(\%)$
$\bar{p}N$	$\rightarrow$	$\Lambda\bar{\Lambda}$	0.99	0.00	0.99
$\bar{p}N$	$\rightarrow$	$\Lambda\bar{K}\bar{N}$	0.52	0.13	0.00
$\bar{p}N$	$\rightarrow$	$\bar{\Lambda}\bar{K}N$	0.00	0.14	0.55
$\bar{p}N$	$\rightarrow$	$K\bar{K}\pi's$	0.00	7.02	0.00
$\bar{\Lambda}N$	$\rightarrow$	$K(K\bar{K})\pi's$	0.00	0.33	-1.07
$\bar{K}N$	$\rightarrow$	$\pi\Lambda, \pi\Sigma$	8.48	-2.70	0.00
πN	$\rightarrow$	$K\Lambda$ or $K\Sigma$	1.57	0.51	0.00
<i>sum</i>			11.56	5.43	0.47
<i>Exp.</i>			12.88 ± 0.80	5.47 ± 0.40	0.25 ± 0.13

Frequency of occurrence of various channels,
expressed as a percentage of the annihilation rate.

The code has also been used to calculate rapidity distributions. The Λ distribution is shown in Figure 5 and the K-short distribution in Figure 6. Both distributions are in excellent agreement with the data. Thus it seems that no exotic effects are needed to explain the data, (11) and that there is evidence against the formation of a quark-gluon plasma in the reaction considered.

Conclusions

Analysis of the strangeness produced in the recent antiproton-nucleus experiment by Miyano et al. shows it to be completely consistent with no enhanced strangeness production both from the detailed model calculation

and from general strangeness conservation considerations. The rapidity distributions are in excellent agreement with the data as well even though they depend on more detailed assumptions of the model.

Acknowledgements

This work was supported by the U. S. Department of Energy.

References

1. D. Strottman and W. R. Gibbs, Phys. Lett. 149B, 288 (1984).
2. J. Rafelski, Phys. Lett. B91, 281 (1980).
3. J. Kogut, M. Stone, H. W. Wyld, W. R. Gibbs, J. Shigemitsu, S. H. Shenker and D. K. Sinclair, Phys. Rev. Lett. 50, 393 (1983); J. B. Kogut, E. V. E. Kovacs and D. K. Sinclair, Nucl. Phys. B290, 431 (1987).
4. T. A. Armstrong, R. Bishop, V. Harris, R. A. Lewis, E. Minor and G. A. Smith, Z. fur Phys. A332, 467 (1989).
5. W. B. Kaufmann and H. Pilkuhn, Phys. Lett. 62B, 165 (1976).
6. W. R. Gibbs and D. Strottman, Proceedings of the "International Conference on Antinucleon- and Nucleon-Nucleon Interactions", Telluride, CO, March 18-21, 1985. Plenum Press, New York; W. R. Gibbs, Proceedings of the "Fermilab Workshop on Low-Energy Antiproton Physics"; W. R. Gibbs, Proceedings of the "Intersections Between Particle and Nuclear Physics", Lake Louise, Canada 1986 AIP conference proceedings 150, p. 505.
7. M. Cahay, J. Cugnon and J. Vandermeulen, Nucl. Phys. A393, 217 (1983).
8. CERN-HERA Reports 83-01, 83-02, 84-01.
9. J. Rafelski, Nucl. Phys. A418, 215c (1984).
10. Miyano et al., Phys. Rev. Lett. 53, 1725 (1984); Phys. Rev. C38, 2788 (1988).
11. J. Rafelski, Phys. Lett. B207, 371 (1988).

Figure 1 Branching ratios of the pion-nucleon interaction

Figure 2 Distribution of the kinetic energies of nucleons after antiproton annihilation in nuclei. Note the "cold" and "hot" distributions.

Figure 3 Evolution of the temperature of the hot component as a function of time. One can see the cooling which comes about as the hot part of the gas mixes with the colder surrounding nucleons.

Figure 4. Energy densities along the central axis of annihilation for all particles. Only the density of invariant mass is plotted so as not to include the centre of mass motion.

Figure 5 Rapidity distribution of Lambdas produced in an antiproton annihilation in Tantalum at 6 GeV/c

Figure 5 Rapidity distribution of K-shorts produced in an antiproton annihilation in Tantalum at 4 GeV/c