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THE ANNIHILATION OF LOW-ENERGY ANTIPROTONS IN NUCLEI

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INTRODUCTION

We discuss the effect of antiproton annihilation within nuclei from the perspective of realistic intranuclear cascade calculations (INC). The results indicate a significant energy deposition for a class of annihilations that are shown to occur relatively deep within the nucleus. In addition, promising experimental observables and triggers are identified. The calculations are especially relevant to LEAR antiproton-nucleus experiments, particularly PS 187. This experiment is described here and possible future investigations are suggested.

MOTIVATION

There is intense interest in what happens to nuclei and nuclear matter at high densities and temperatures.[1,2] Unfortunately, the ideal laboratory for such studies has yet to be found. Indeed, the very concept of temperature for nuclei (the thermalization of highly excited collections of nucleons) has little experimental basis to date.[3] Collisions of relativistic and ultrarelativistic heavy ions (RHI) can possibly provide high local matter densities, but because of fragmentation due to conservation of longitudinal momentum, the amount of matter available to thermalize the energy may be small.

Very high energy densities in heavy nuclei might, however, cause the nucleus, or regions of the nucleus, to undergo a transition from a collection of nucleons to a quark-gluon plasma. The structure of the QCD vacuum is believed[2] to be such that at energy densities a few times that of the nucleon (∿ 360 MeV/fm^3) such a transition might occur. In addition, the simple first-order phase transition from a nuclear fluid to a hot nuclear gas (when the excitation energy E^* of the nucleus becomes greater than the disassembly energy) is quite interesting. There exist, in fact, experimental data that find a plausible interpretation in the latter scenario.[4]

We summarize here recent calculations[5] that quantitatively verify suggestions[6,7] that low-energy ($E_{\bar{p}}$ < 1 GeV) antinucleon-nucleus annihilations are possibly the best place to study nuclei at high excitation. When an antinucleon annihilates on a nucleon within a nucleus, a large number of pions (at low energies, approximately 5) are produced in a hadron-sized region and carry away approximately 2 GeV of energy. The average pion momentum is such that they are strongly absorbed by nucleons to form Δ_{33} resonances. We choose low energies to keep the longitudinal momentum (and possible fragmentation) to a minimum and to assure that the annihilation region moves rather slowly through the nucleus ($E_{\bar{p}}$ = 175 MeV implies $\beta_{\bar{N}N}$, the "fireball" velocity, is 0.29). Also, at low energy the annihilation is predominately into pions, and at 175 MeV there is no competition from inelastic pion production. One disadvantage of lower energies is the larger $\bar{N}N$ cross section and subsequent surface localization of annihilations in nuclei. Our calculations confirm earlier observations[8] that the strong antinucleon-nucleus attraction remedies this problem in part and increases significantly the antinucleon penetration of the nucleus.

METHOD

The input $\bar{N}N$ data, the INC model and the modifications for the intranuclear casade code ISABEL[9,10] are described in Ref. 5. Suffice it to say here that careful, realistic INC calculations were performed for 175 MeV $\bar{p}$ + ^{12}C, ^{238}U interactions.

RESULTS

We have calculated approximately 17,500 cascades for 175-MeV $\bar{p}$ + ^{12}C, and 19,000 for $\bar{p}$ + ^{238}U. These two target nuclei represent a compromise between cost and the desire to investigate the mass dependence of $\bar{p}$ annihilation on nuclei.

In examining the results we concern ourselves with the following questions:

A) Is there a large energy deposition E_{dep} a significant fraction of time?

Here

$$E_{dep} \equiv m_p + m_{\bar{p}} + T_{\bar{p}} - \sum_{i=1}^{N} E_{\pi_i} \quad , \tag{1}$$

where the sum includes all (N) pions that exit the nucleus. This definition has the advantage of being intuitively simple. It represents a lower limit when compared to alternate definitions which might, for example, subtract only the energies of "primordial" pions in Eq. (1).

B) Do the antiprotons penetrate a significant distance into the nucleus before annihilating? This point is necessarily related to A) and will be addressed in that context.

C) What are the general observable characteristics of antiproton annihilations in nuclei?

D) What are the characteristics of the high energy deposition events? Can they be easily distinguished from surface annihilations via an experimental trigger?

E) The INC calculations are based on the assumption that nothing unusual is occurring. Can we, then, identify experimental quantities that may reflect the presence of degrees of freedom not included in the calculations?

Energy Deposition

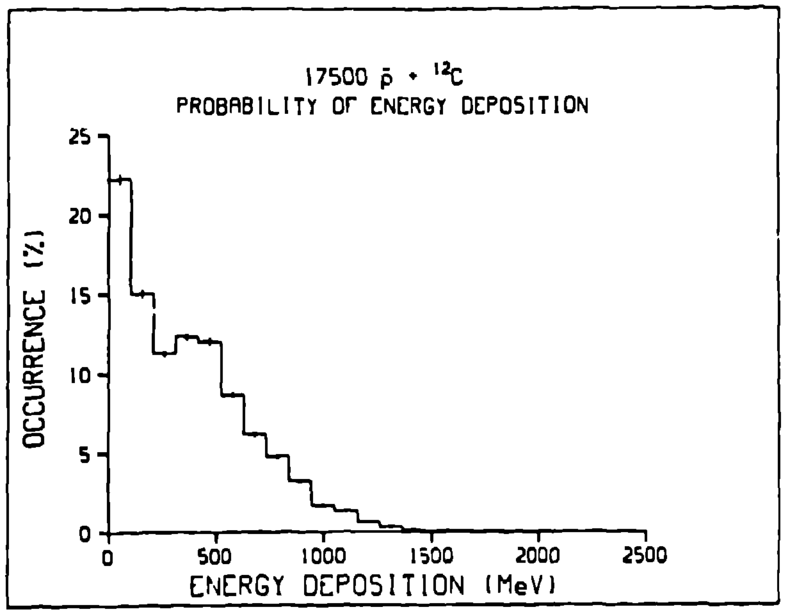
In Figs. 1a and b, we see the distribution of annihilation events versus E_{dep} for ^{12}C and ^{238}U, respectively. The error bars are statistical. To understand these results, recall that the pion can transfer energy to the nucleus in two ways:

$$\pi + N \to \Delta \quad ,$$
$$\Delta + N \to N + N + \pi \quad . \tag{2a}$$

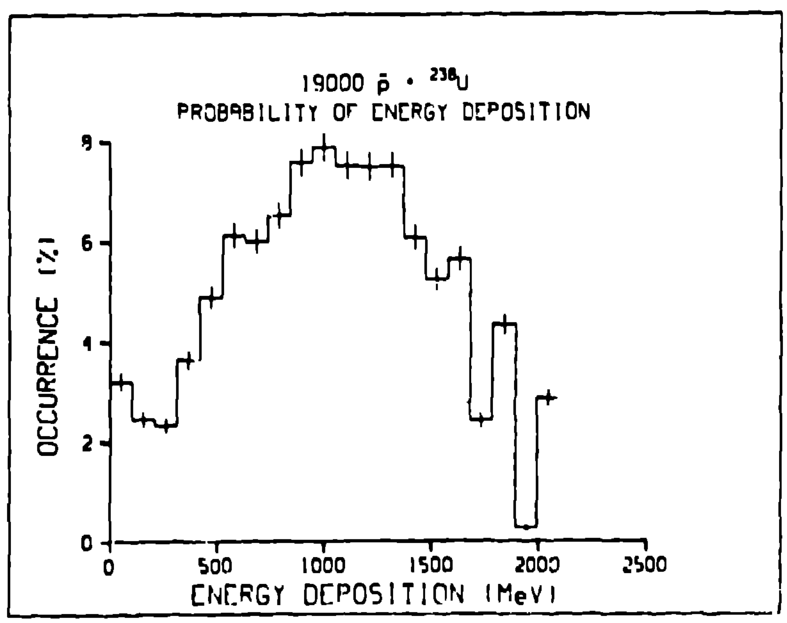
$$\pi + N \to \Delta \quad ,$$
$$\Delta + N \to N + N \quad . \tag{2b}$$

In 2a), the Δ scatters about, distributing energy to the nucleons it recoils from. In 2b), the π is "truly absorbed", i.e., the total energy of the pion ($m_\pi + T_\pi$) is given to two (or more) target nucleons. The latter process is quite efficient at depositing energy in the nucleus. The cross section for 2b) is, as noted earlier, significant and energy dependent.

The peaks in E_{dep} at 400 MeV for ^{12}C and 1000 MeV for ^{238}U indicate that the average number of pions absorbed is 1 and 2,



(a)



(b)

Fig 1. a) Probability of $\bar{p}$ annihilation in ^{12}C versus energy deposition (E_{dep}) where E_{dep} is defined in Eq. (1). b) The same quantity for ^{238}U. The error bars are statistical.

respectively. (Recall that for $\bar{N}N$ annihilations one gets on the average five pions, each with total energies of approximately 400 MeV.) The really striking result here is that for annihilations on ^{238}U, over 55% of the events result in $E_{dep} > 1$ GeV! For ^{12}C, 75% and for ^{238}U, 3% of the annihilations result in $E_{dep} > E_{bind}$ where $E_{bind} \sim 8A$ MeV.

Figure 2 shows E_{dep} versus the radius of annihilation. The bars reflect the distribution of events, not statistical errors. The crossed arrows indicate average values. As we expect, the large E_{dep} annihilations occur deeper within the nucleus.

Penetrability

The annihilation probability versus annihilation radius is given in Figs. 3a and b. The solid curves are calculations for a real $\bar{p}+A$ attractive potential of V_R = 250 MeV, while the dashed curves represent V_R = 0. The effect of the potential is to move the average annihilation radius farther into the nucleus by approximately 0.5 fm in each case. For both ^{12}C and ^{238}U, on the order of 40% of the annihilations occur inside the nuclear half-density radius. An appreciable fraction annihilate even further inside,

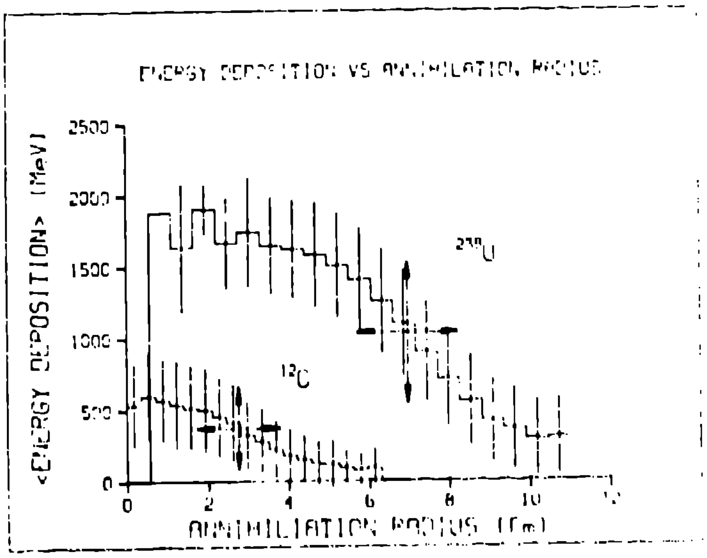
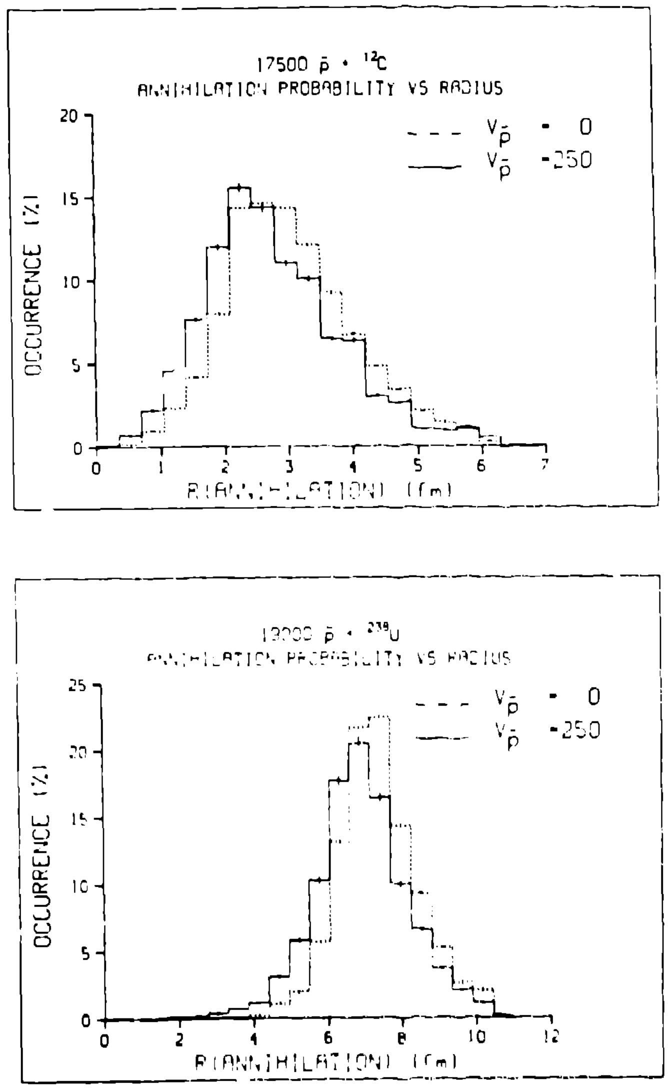


Fig. 2. Energy deposition (see Eq. 1) from $\bar{p}$ annihilation in ^{12}C and ^{238}U versus radius at which the annihilation occurs. The bars represent the distribution of events. The cross arrows indicate average values. The average annihilation radii are approximately equal to the nuclear sharp cutoff radii ($1.128\ A^{1/3}$) within 1.2 fm.



(a)

(b)

Fig. 3. a) The probability of $\bar{p}$ annihilation in ^{12}C versus radius of annihilation. The solid curve results from calculations with V_R = 250 MeV, the dashed curves with V_R = 0. b) The same for ^{238}U. The bars are statistical errors. Note that ∿ 50% of the annihilations occur within the sharp cutoff radii (7.0 fm for ^{238}U and 2.6 fm for ^{12}C). The effect of the potential in increasing the $\bar{p}$ penetrability is quite apparent.

although effectively no annihilations occur at the center (only 3% in ^{12}C and 0.01% in ^{238}U annihilate inside 1 fm). Penetration into regions of maximum density is important, however, in that

Table I

Total reaction cross sections (σ_R) for $E_{\bar{p}}$ = 175 MeV. V_R is the strength of the (attractive) real optical potential. The shape follows the matter distribution.

	$\bar{p}$ +^{12}C	$\bar{p}$ +^{238}U
σ_R (V_R = 250 MeV)	535 mb	2705 mb
σ_R (V_R = 0)	420 mb	2290 mb

interesting things are predicted to happen(2) when high energy densities occur in nuclear matter.

General Characteristics

In this section we present pion and proton angular energy and multiplicity distributions for impact parameter-averaged annihilations. Total reaction cross sections are also presented. All angles and energies are in the lab frame.

In Table I, the total reaction cross sections are presented. The reaction cross sections (σ_R) are given for V_R = 0 and 250 MeV. The σ_R are, as expected, larger for the more attractive potential and increase as $A^{2/3}$, which should be the case for strongly absorbed projectiles.

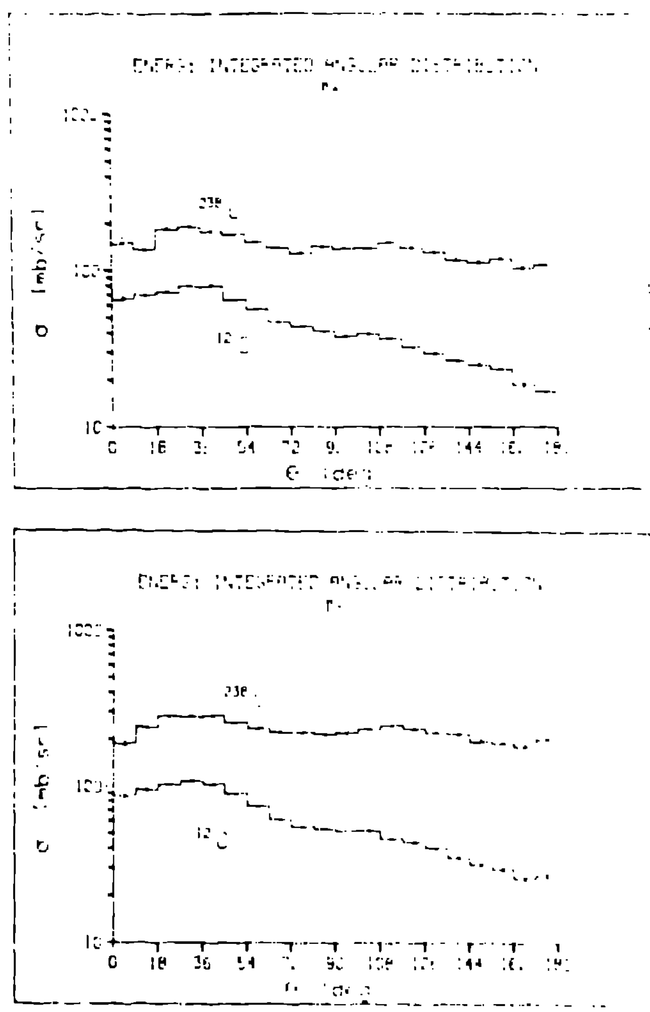
Table II gives average multiplicities for pions, protons and neutrons for $\bar{p}p$ at rest, $\bar{p}$+^{12}C, $\bar{p}$+^{238}U at 175 MeV, and $\bar{n}$-A (light nuclei) at 750 MeV. Note that on the average, one pion is totally absorbed by ^{12}C and two pions are absorbed by ^{238}U. The $\bar{n}$-A data are at a higher energy where inelastic-π production is possible, thus the $\langle n_{\pi^+}\rangle$ is slightly larger than for $\bar{p}p$ at rest. The $\bar{n}$-A $\langle n_p\rangle$ is almost twice that for $\bar{p}$+^{12}C primarily due to the fact that our calculations do not include (slow) evaporation. If one examines the data of Ref. 11 and excludes protons below $\sim$ 40 MeV, then $\langle n_p\rangle$ = 1.

Table II

Average multiplicities from $\bar{p}$-p and $\bar{p}$-A annihilations. The * indicates results of present calculations with $E_{\bar{p}}$ = 175 MeV and V_R = 250 MeV.

	$\bar{p}p$ At Rest	$\bar{p}+{}^{12}C$*	$\bar{p}+{}^{238}U$*	$\bar{n}$-A 1.4 GeV/c (Ref. 11)
$\langle n_{\pi^{\pm,0}}\rangle$	5.0	4.1	2.9	------
$\langle n_{\pi^+}\rangle$	1.5	1.1	0.7	1.59 ± .06
$\langle n_{\pi^-}\rangle$	1.5	1.4	1.1	1.23 ± .04
$\langle n_{\pi^0}\rangle$	2.0	1.6	1.1	------
$\langle n_p\rangle$	---	1.0	2.9	2.12 ± .09
$\langle n_n\rangle$	---	1.1	5.7	------

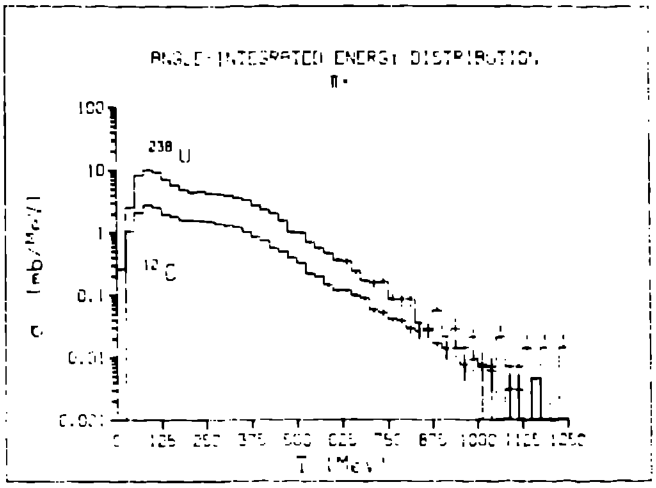
In Figs. 4a and b, the energy-integrated-angular distributions for π^+ and π^- are presented. The isotropic nature of the scattering, particularly for ^{238}U, underscores the uniqueness of the low energy $\bar{p}$+A interaction. Unlike high energy A-A collisions, there is no projectile fragmentation to carry off momentum and energy. The decrease in $d\sigma/_{d\Omega}$ at small angles is due to the attenuation of most forward-going pions by the bulk of the nucleus. The angle-integrated-energy spectra are shown in Figs. 5a and b for π^+/π^- and in Figs. 6a and b for protons and neutrons. The pion distributions have two components, a broad bump centered at about 300 MeV and a sharp peak at ≈ 100 MeV. The lowest energy pions are essentially totally absorbed.



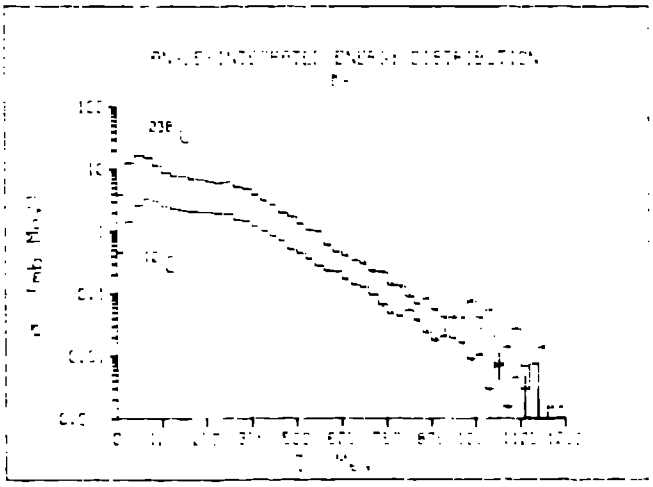
(a)

(b)

Fig. 4. a) The energy integrated angular distributions for π^+ (versus lab angle) which result from $\bar{p}$ + ^{12}C, ^{238}U annihilations. b) The same for π^-.



(a)

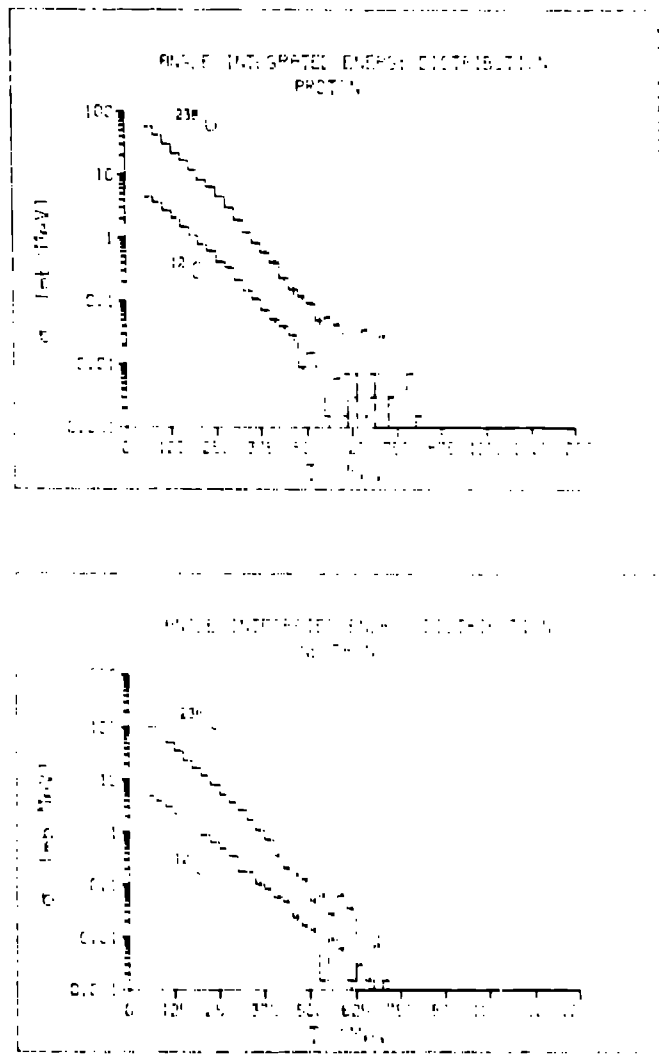


(b)

Fig. 5. a) The angle integrated energy distributions for π^+ (versus lab kinetic energy) emitted in $\bar{p}$ + ^{12}C, ^{238}U annihilations. b) The same for π^-. Note the "double bump" structure (see text) and the Coulomb effects at low T.

Proton and neutron energy spectra (Figs. 6a and b) are relatively featureless. The slopes can be associated with a "temperature" or slope parameter T_o,

$$d\sigma/_{dE} \propto \exp(-^T/_{T_o}) \quad . \qquad (12)$$



(a)

(b)

Fig. 6. a) The angle integrated energy distributions for protons (versus lab kinetic energy) emitted in $\bar{p}$ + ^{12}C, ^{238}U annihilations. b) The same for neutrons.

For ^{238}U we find T_0 (proton) = 75 MeV, while T_0 (neutron) = 68 MeV. The corresponding values for ^{12}C are T_0 (proton) = 82 MeV and T_0 (neutron) = 82 MeV. Without ascribing too much significance to such a simple parameterization, we may compare these to inclusive proton spectra slope parameters obtained from nucleus-nucleus collisions.(1) We find that $T_0 \approx 80$ MeV is observed in inclusive proton spectra from nucleus-nucleus collisions of approximately 1 GeV/nucleon lab energy.

The π^+ rapidity plots are shown in Figs. 7a and b. We see that a large component of the pion spectrum emanates from the target (y=0). There is, however, a component that has y ≈ - 0.4 from ^{12}C and y ≈ - 0.6 from ^{238}U. These correspond to "backsplash" pions, or those which move backward with little attenuation after the annihilation. These rapidity distributions are quite different from heavy ion collisions, which generally have protons, neutrons, and pions associated with fragments having projectile, target and (sometimes) center-of-mass rapidities. The lack of fragmentation in $\bar{p}$-A annihilations is quite apparent here.

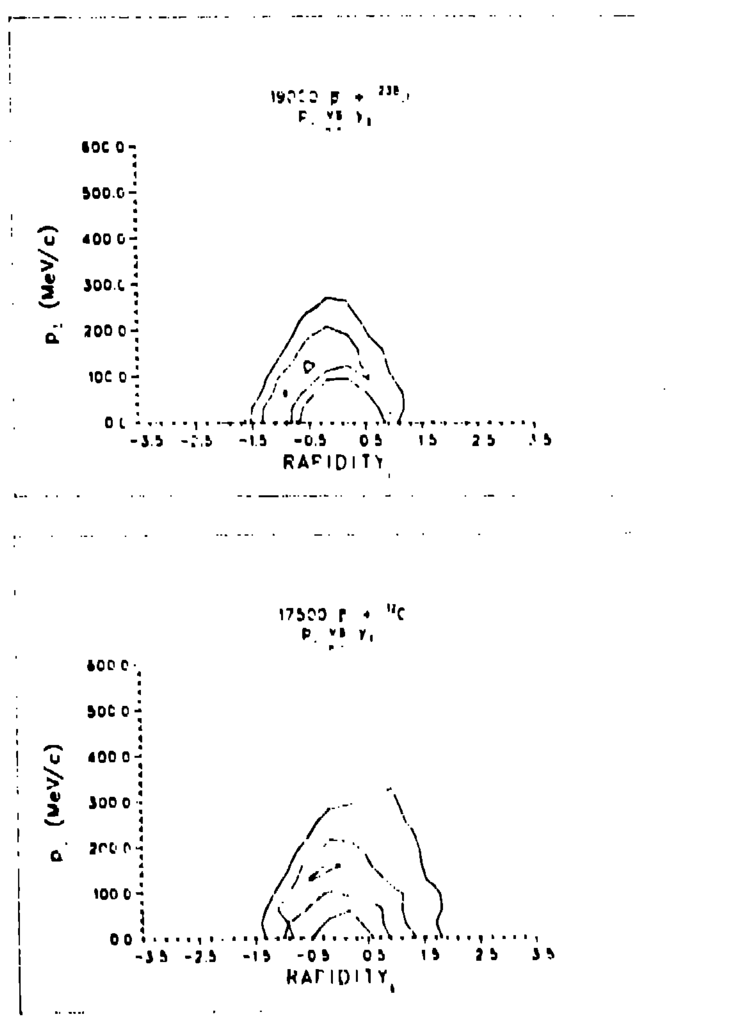
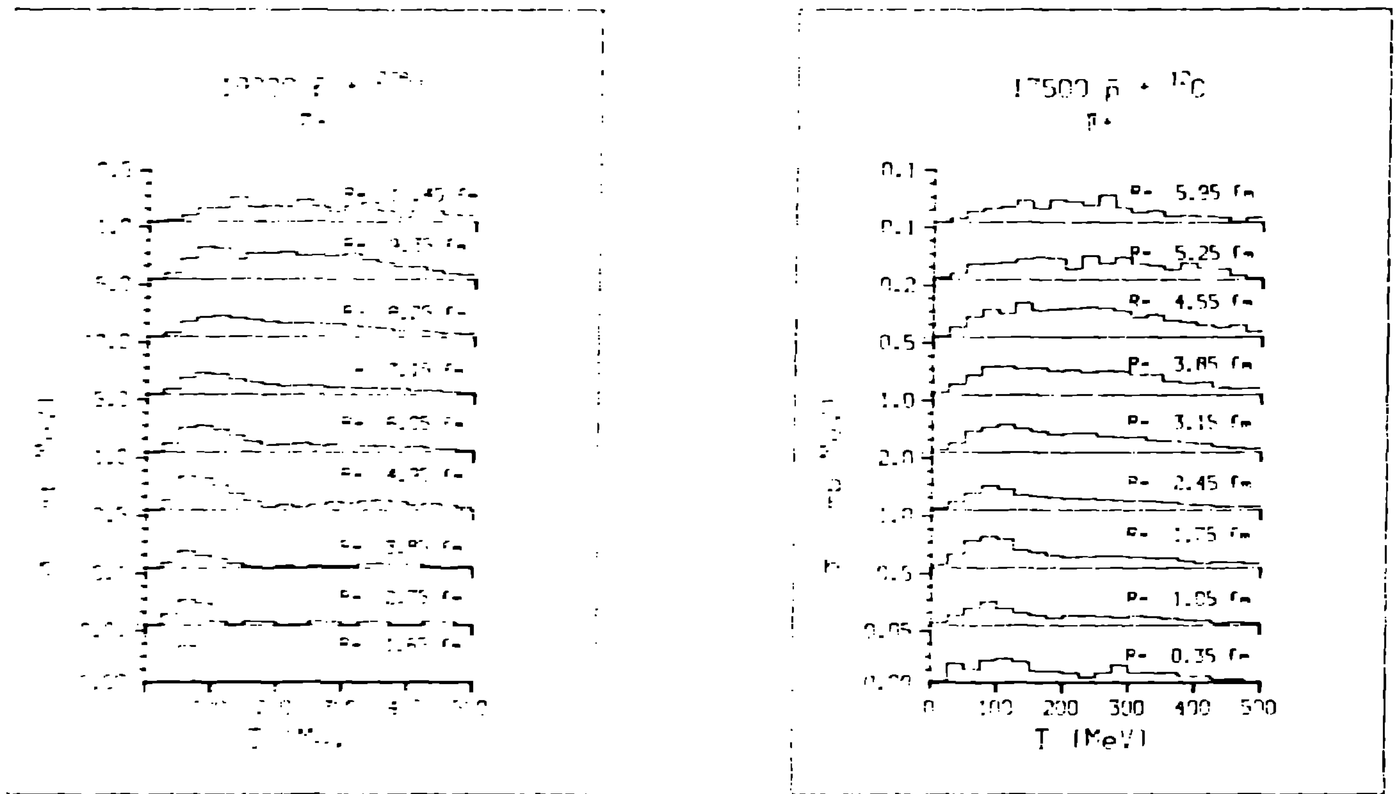


Fig. 7. a) Longitudinal rapidity (y) versus transverse momentum for π^+ emitted in $\bar{p}$ + ^{238}U, and b) $\bar{p}$ + ^{12}C annihilations. Note the "backsplash" pion peak at y ≈ -0.6 and $p_\perp$≈100 MeV/c. The contour intervals are 0.2 barns/GeV^2 for ^{12}C and 0.9 barns/GeV^2 for ^{238}U.



(a) (b)

Fig. 8. a) The angle-integrated energy distributions binned according to radius of annihilation for π^+ resulting from $\bar{p}$ + ^{238}U, and b) $\bar{p}$ + ^{12}C annihilations. Note the distinct appearance of two components in the spectra (see text).

Character of Large E_{dep} Annihilations

Assuming that nothing unusual is occurring, the method for energy deposition is pion scattering and absorption. The large E_{dep} annihilations will perforce happen deeper within the nucleus. In Fig. 8, we see the π^+ angle integrated energy spectra for various radii of annihilation. A broad distribution centered at ∿ 200 MeV corresponds to "primordial" pions, mostly from peripheral annihilations. A lower energy peak arises as annihilations occur deeper within the nucleus. These "thermalized" pions seem to result from small R_{arn}, large E_{dep} annihilations. Thus examination of those events with an excess of low-energy pions should prove interesting.

Another large E_{dep} indicator is the pion and proton multiplicity. These can be seen in Fig. 9. There is, as one might expect, a particularly strong correlation between the number of protons ejected and the energy transferred to the nucleus. Similarly, there is an inverse correlation for the pions. Note that the bars in Fig. 9 indicate the distribution of events, not statistical errors.

Another possibility centers on the observation, made earlier with reference to Fig. 7, concerning "backsplash" pions. The lack of such pions could indicate a relatively deep annihilation.

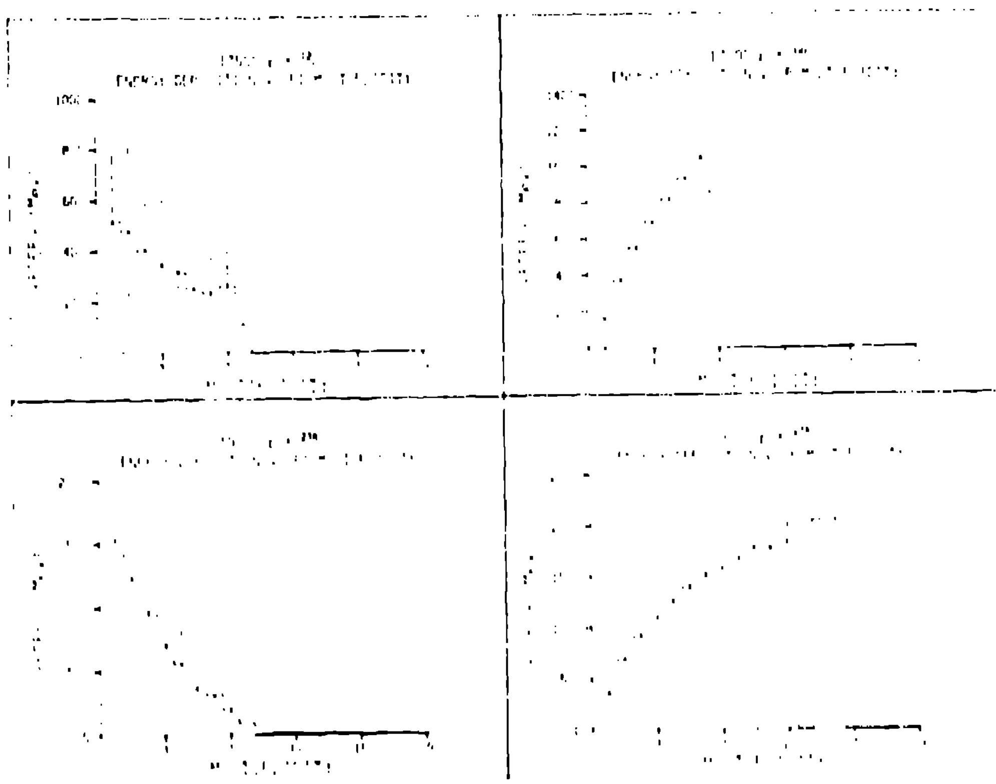
Deviations From INC Behavior

It would be somewhat disappointing if the data agreed quite well with these calculations. One might hope that a significant number of annihilations would lead to new phenomena such as those envisioned by Rafelski,[12] where the annihilation fireball "melts" nearby nucleons to form a quark/gluon plasma. If such degrees of freedom are indeed open, how might these new channels be reflected in the observables discussed here?

Any answer depends, unfortunately, on the decay characteristics of the unknown "state". A rapid decay into pions would be difficult to distinguish, while decay into gamma rays would definitely upset the (assumed INC) energy balance. The most optimistic scenario would have the quark blob living for > 10^{-10} sec and being detected as a strange Q/M particle. In addition the decay of a quark-gluon plasma into strange particles has been suggested.[12]

One might, then, look for a kaon yield over and above that expected simply from known $\bar{p}+p \rightarrow$ kaons and pions. We are in the process of calculating $\bar{p}+A$ kaon production for this purpose. Significant deviations from the INC predictions could indicate the presence of other degrees of freedom. The isotropy might be upset if jet-like behavior occurred. Broad range proton and pion inclusive data are necessary for such comparisons. The shape of multiplicity distributions might also be affected.

(a) (c)



(b) (d)

Fig. 9. Energy disposition (E_{dep}) as defined in Eq. (5) versus charged pion multiplicity for a) $\bar{p}$ + ^{12}C, and b) $\bar{p}$ + ^{238}U annihilations. c) E_{dep} versus proton multiplicity for $\bar{p}$ + ^{12}C, and d) $\bar{p}$ + ^{238}U annihilations.

EXPERIMENTAL ASPECTS

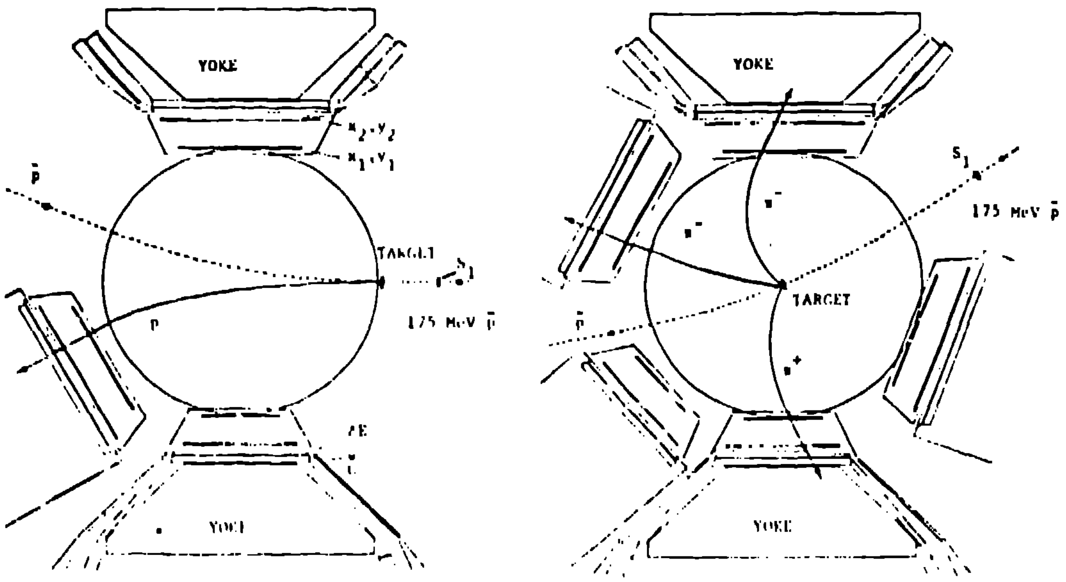
Our experimental arrangement for PS 187 is very similar to the system with which we have been taking data on proton and heavy-ion induced pion production on nuclei.[13] This system is designed to be as broad ranged as possible as one never knows "a priori" where new (i.e., non-INC predicted) phenomena will show up. Thus we have aimed to cover the angular region $0° \leq \Theta \leq 180°$ and energy region $50 < T_\pi < 500$ MeV, with similar momentum ranges for protons and kaons. Since we are particularly interested in observing correlations between particles (especially like pions) we require a reasonably large, solid angle and multiparticle detection capability.

The "Calliope" device is illustrated in Fig. 10b. A beam passes through the target at the center of the (81-cm diam, 7.5-cm gap) circular magnetic field operated at two different magnetic field settings. Produced particles are deflected and detected in six arrays placed at the edge of the pole faces. Each detector array consists of two X-Y position-determining planes followed by a 1/2-in-thick scintillation detector and a novel Cherenkov detector.[14] This array provides particle momentum (assuming charge of $\pm e$) energy loss, times of flight, and Cherenkov light yield (particularly useful as a pion trigger). Thus, redundant particle indentification occurs. An effective solid angle of about 1 steradian in a planar geometry allows us to perform the inclusive and exclusive measurements of interest and to compare the results directly with the INC calculations.

Our Phase II measurements [search for $\bar{p}$+ nucleus "bound" states via the $\bar{p}+A \rightarrow p + (\bar{p}+A-1)$] require a very broad range of acceptance in proton energy, since the Q value of this reaction is completely unknown. In addition an angular acceptance of about $\pm 15°$ around 0° is desirable along with the best possible proton energy resolution. These objectives can be accomplished by slightly modifying the Calliope system as shown in Fig. 10a. Placing the target in front of the magnet provides better separation of the $\bar{p}$ beam from the protons of interest, better energy resolution, and allows us to look at other reaction products simultaneously.

Our future experimental plans depend on the results from our first experiment. Specifically if we can define kinematic regions where production yields deviate significantly from INC calculations, then second generation exclusive measurements should yield additional information as to what new physics is occuring.

We are, however, studying one specific measurement that has not yet been proposed for LEAR. This is the measurement of heavy fragments in $\bar{p}$+A collisions. The use of a Bragg curve spectrometer[15] should allow a wide variety of normal and abnormal fragments to be



(a) (b)

Fig. 10. EXPERIMENT 187 a) The reaction $\bar{p} + A \rightarrow p + A^*$. b) pion production and correlations in 175 MeV antiproton-nucleus interactions. The system can be configured with as many as six detector systems (five are shown here).

observed in a thin target experiment. Such a detector is under development at Los Alamos.

CONCLUSIONS

We have performed realistic calculations of $\bar{p}$+A interactions at low energies within the intranuclear cascade model. Results indicate that a large amount of energy can be transferred to the nucleus in a unique way. The characteristics of the annihilations of $\bar{p}$'s within nuclei are quite unlike anything seen in conventional hadron-nucleus and nucleus-nucleus collisions.

These calculations should provide important background for comparison with data from LEAR PS 187 and lend insight into the nature of this fascinating and exciting arena of nuclear physics.

ACKNOWLEDGEMENTS

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