Dynamics of Low-Energy Antiproton Annihilation in Nuclei as Inferred from Inclusive Proton and Pion Measurements

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The cross sections for the production of charged pions and protons from the annihilation of 608-MeV/c antiprotons on ^{12}C, ^{89}Y, and ^{238}U are presented. The sources of pion and proton emission are inferred from the rapidity distributions of the data. The results are compared to and seen to be in good agreement with intranuclear-cascade calculations.

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The behavior of nuclei at extremes of density and temperature is, despite much recent effort, still relatively unknown. The best means of inducing such extremes and the most reliable signals from which to infer the nature of the excited system are still hotly debated. Intermediate- and high-energy nucleus-nucleus collisions,[1,2] though quite complex, deservedly attract much attention in this context.

We report here the first results from a series of measurements undertaken to explore another possibility, namely, the annihilation of low-energy antiprotons in nuclei.[3,4] The antinucleon-nucleon annihilation process is well localized in space and time, and generally results in the production of five pions, each with an average momentum near that of the Δ resonance. Annihilation studies on nuclei at modest incident antiproton momenta assure that the nucleus is not fragmented by the transfer of linear momentum, and that only the annihilation energy is given to the nucleus. Measurements of antiproton annihilation in nuclei thus offer a way to study the response of the nucleus to the deposition of 2 GeV of well-defined and localized energy. In addition, one can ask if the presence of nuclear matter itself modifies the free antinucleon-nucleon annihilation mechanism in any way. Recent evidence for a change in confinement scale in nuclei[5] indicates that the latter is not totally unlikely.

The measurements were made with a beam of 608-MeV/c antiprotons from the CERN Low-Energy Antiproton Ring (LEAR), using the CALLIOPE magnetic spectrometer. The CALLIOPE spectrometer, the design and performance of which are described elsewhere,[6,7] is operated with a pole gap of 12.7 cm and a field of 1.2 T. The target sits at the center of the magnet. Six detector modules, each containing two planes of (x,y) position-sensitive gas proportional chambers, a ΔE/time-of-flight scintillator, and a threshold Cherenkov detector,[8] surround the pole at radii of 48 to 55 cm. The total angular acceptance is approximately 400 msr, distributed rather uniformly from 0° to ±180°. Light charged particles can be identified and momentum analyzed over a range from 120 to 1200 MeV/c with a resolution of $dp/p^2 = 15\%/(\mathrm{GeV}/c)$. The rather continuous angular acceptance of CALLIOPE allows reliable extraction of total cross sections for relatively isotropic processes such as low-energy antiproton-nucleus annihilation and is particularly important for the construction of complete invariant cross section versus rapidity plots (in contrast to a limited number of fixed-angle measurements).

Given the inherent complexity of antiproton annihilation on nuclei, we undertook to calculate it within the intranuclear-cascade (INC) framework; i.e., following annihilation on a single nucleon, the interaction is assumed to proceed as a series of incoherent πN, NN, and ΔN interactions. Pion-nucleon interactions are treated in the isobar model with use of an energy-dependent width for the delta. The calculations presented here are described in detail by Clover *et al.*[9] We note only that, in light of recent antiproton-nucleus elastic-scattering measurements,[10] the present calculations have been done with a value of 75 MeV for the real part of the antiproton-nucleus optical potential as opposed to 250 MeV in Ref. 9.

In Fig. 1 the angle-integrated pion momentum distributions $(d\sigma/dp)$ are presented versus laboratory momentum. To obtain these data, the double-differential cross sections are interpolated over the small angular regions missed as a result of the mechanical spaces between detectors and then in-

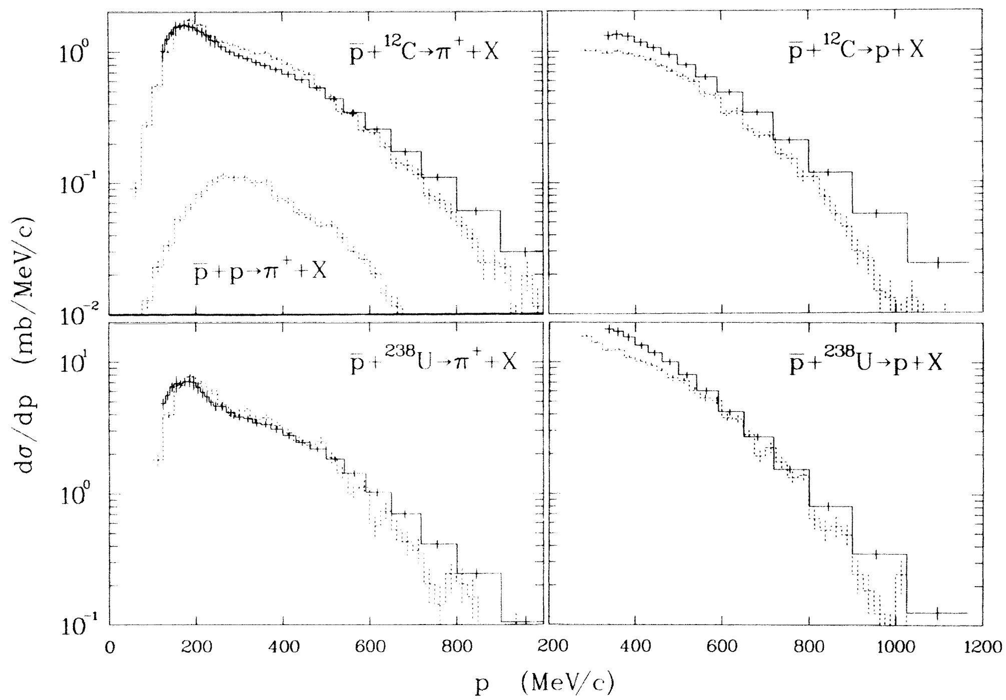

FIG. 1. The angle-integrated inclusive momentum distributions for π^+ and protons from 608-MeV/c antiproton annihilation on ^{12}C and ^{238}U. The solid histograms are the data and the dashed histograms represent the INC calculations. The second dashed curve in the upper left frame represents the momentum distribution of pions from antiproton-proton annihilation at the same momentum.

tegrated over angle. The solid histograms are the data, while the dashed histograms represent the INC calculations. Also shown is the free $\bar{p}+p\rightarrow\pi^++X$ momentum distribution at the same incident antiproton momentum.[9] One notes that, above 300 MeV/c, the antiproton-nucleus data are similar in shape to the free antiproton-nucleon distribution, reflecting noninteracting pions from peripheral annihilations (these we will call "primordial" pions). Also present is a yield of lower-momentum pions containing both the pions that have interacted, formed deltas, and reappeared with lower energies, and the backward going (in the $\bar{N}$-N center-of-mass frame) primordial pions that appear in the laboratory at lower momenta as a result of the Lorentz factor ($\beta_{\bar{p}}=0.54$). The INC calculations reproduce this structure quite well for all target masses for both π^+ and π^-. The pion spectra versus target mass show a slight increase in yield of the lower-momentum pions as A increases, due simply to a larger interaction probability for the primordial pions. The π^- spectra exhibit similar agreement with the INC calculations. In Table I, the integrated total cross sections for π^+ and π^- production are given along with the predictions of the INC calculations.

The angle-integrated proton momentum distributions are also shown in Fig. 1. The slope parameters T_0 (MeV) obtained by a fit of the momentum distribution in the region of momentum greater than 500 MeV/c with an exponential of the form $d\sigma/dE=C_0\exp(-E/T_0)$ are given in Table I. We note a slight increase in the slope parameter with decreasing A, reproduced by the INC calculations, which we interpret as resulting from an increase in interaction probability in heavier nuclei for faster protons in the first stages of the cascade after the annihilation. We observe also that the proton slope parameters are similar to those obtained in 1-GeV/u heavy-ion collisions.[1] The deviation between the experimental and INC cross sections at high momenta is attributed to the fact that the phase-space model used in the INC calculations underpredicts the yields of high-momentum pions from the annihilation.[9]

TABLE I. Total pion-production cross sections and proton slope parameters T_0 $[d\sigma/dE=C_0\exp(-E/T_0)]$ for 608-MeV/c antiproton annihilation on ^{12}C, ^{89}Y, and ^{238}U. The INC calculations of these quantities (in parentheses) are also given for comparison.

	σ_{π^+} (mb)	σ_{π^-} (mb)	T_0 (MeV)
^{12}C	488 ± 31	637 ± 41	88 ± 5
	(494)	(664)	(74)
^{89}Y	1240 ± 80	1760 ± 110	80 ± 5
	(1250)	(1820)	(69)
^{238}U	2000 ± 130	3000 ± 190	77 ± 4
	(1920)	(3050)	(68)

The errors shown in all figures reflect statistical errors, estimated systematic uncertainties due to the interpolation of the double-differential cross sections over regions where the spectrometer acceptance is zero, as well as uncertainties in the detector efficiencies, solid angles, etc. The overall systematic normalization uncertainties are less than 10%. The data are presented with a momentum binning that reflects the resolution contributions from uncertainties in beam position on target and inherent wire-chamber resolution. The lower-momentum cutoffs for pions are determined by detector acceptance and for protons by target-energy-loss considerations. The errors shown for the total pion cross sections include, in addition to those mentioned above, small uncertainties due to extrapolation to pion energies below those measured, following the prescription used by us in Ref. 7.

In Fig. 2 the positive-pion and proton invariant cross sections from ^{12}C and ^{238}U are presented versus rapidity (y) for different ranges of transverse momentum (p_T), in order to allow a more precise identification of the kinematical sources of the ejectiles. For an antiproton of given incident momentum, for example, one might expect fast pion emission following peripheral annihilation to be isotropic in the center-of-mass frame of a system moving with the incident momentum but with a mass of $2m_N$ (i.e., the antinucleon-nucleon system). Similarly, if the antiproton stops in a heavy nucleus, emission of protons would be rather isotropic in the target frame. Such behavior manifests itself as the symmetry of the cross section about $y=0$ in the proton case and about $y=0.31$ in the pion case (for incident 608-MeV/c antiprotons). This technique has been successfully used to identify the kinematic origin of ejectiles after pion and high-energy antiproton absorption on nuclei,[11,12] and can be utilized in the present case to help determine how many nucleons participate in the annihilation process and subsequent cascade in nuclei.

The pion rapidity spectra in Fig. 2, shown for $p_T \geq 120$ MeV/c and $p_T > 500$ MeV/c, clearly reveal different kinematical sources; i.e., the latter originate from the quasifree $\bar{N}$-N system ($y \approx 0.3$) while the former come from a system involving many more neucleons ($y \approx 0$) for both light and heavy nuclei. The INC calculations reproduce this behavior, supporting the interpretation that the high-p_T pions are primordial (in the sense defined earlier) while the slower pions result from the transfer of energy to the nucleus via Δ formation, scattering, and decay, losing memory of their quasifree $\bar{N}N$ origin in the process.

The proton data are presented in a similar manner in

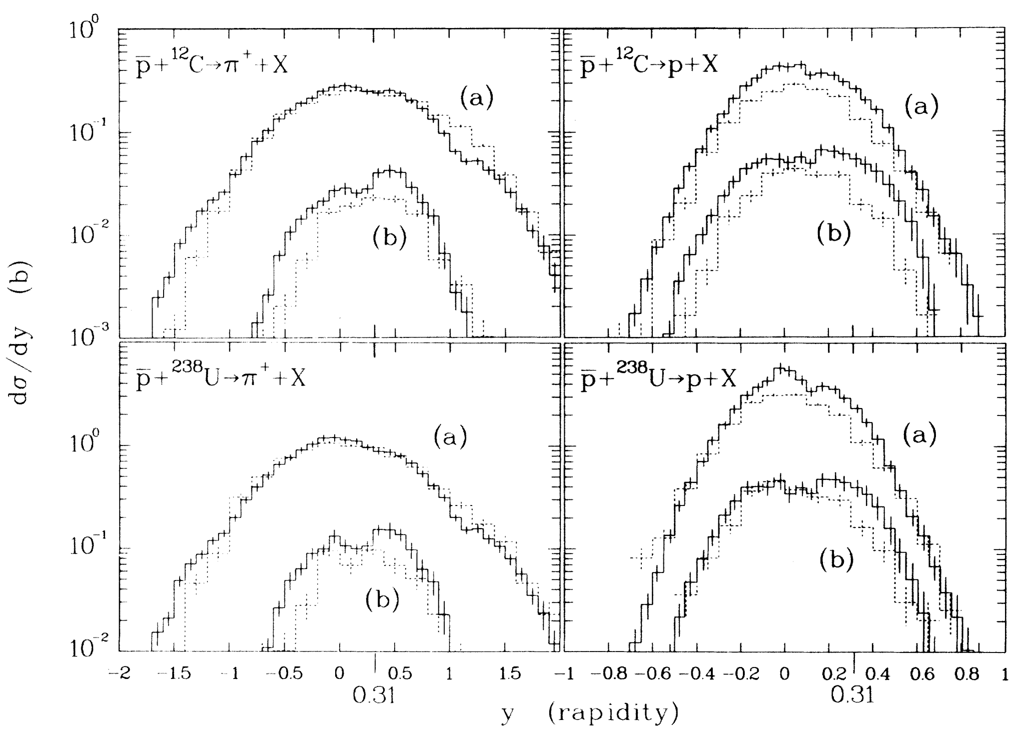

FIG. 2. The measured invariant cross section vs rapidity for positive pions with $p_T \geq 120$ MeV/c (histograms a) and $p_T \geq 500$ MeV/c (histograms b) and protons with $p_T \geq 330$ MeV/c (histograms a) and $p_T \geq 600$ MeV/c (histograms b) from 608-MeV/c antiproton annihilation on ^{12}C and ^{238}U. The symmetry of invariant cross sections about $y=0$ or $y=0.31$ indicates isotropic pion emission from the target or quasifree antinucleon-nucleon frames, respectively. The dashed curves represent the INC calculations.

Fig. 2, but for $p_T \geqslant 330$ MeV/c and $p_T \geqslant 600$ MeV/c (the beam momentum). The low-p_T protons clearly originate from the target system. The high-p_T data show, in addition, some structure at positive y, not well reproduced by the INC calculations, which could be due to fast protons from $\pi + N \rightarrow \pi + N$ very early in the post-annihilation cascade or perhaps from annihilation occurring on more than one nucleon.[13]

Multinucleon annihilation is perhaps unlikely to manifest itself in the inclusive spectra as a result of the strong peripheral localization of the annihilation. The average annihilation occurs near the nuclear surface[9] where the probability of antiproton overlap with a number of nucleons is small. Of course, the final-state distributions of particles and momenta following a multinucleon annihilation are a matter of speculation. Recent statistical-model calculations[14] predict enhanced strangeness production and a tail of high-momentum protons from annihilation on two nucleons [something we may see a hint of in the inclusive spectra (Fig. 2)], but a serious attempt at answering this question awaits an experimental means to bias against peripheral annihilations and study the few that remain.

In conclusion, the first high-statistics data for pion and proton emission following 608-MeV/c antiproton annihilation on nuclei are presented. The results are consistent with the view, made quantitative via the INC calculations, that inclusive proton and pion emission result primarily from annihilation on a single nucleon followed by a series of cascades similar to those which occur in pion-nucleus interactions.

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[1]Proceedings of the International Conference on Nucleus-Nucleus Collisions, Michigan State University, edited by G. F. Bertsch, C. K. Gelbke, and K. D. Scott, Nucl. Phys. **A400** (1983).

[2]Proceedings of the Third International Conference on Ultrarelativistic Nucleus-Nucleus Collisions, edited by T. Ludlam and H. Wegner, Nucl. Phys. **A418** (1980).

[3]J. Rafelski, Phys. Lett. **91B**, 281 (1980).

[4]R. M. DeVries and N. J. DiGiacomo, in Proceedings of the Workshop on Nuclear and Particle Physics at Energies up to 31 GeV: New and Future Aspects, edited by J. D. Bowman, L. S. Kisslinger, and R. R. Silbar, Los Alamos National Laboratory Report No. LA-8775-C, 1981 (unpublished), p. 541.

[5]F. E. Close, R. L. Jaffe, R. G. Roberts, and G. Gross, Phys. Rev. D **31**, 1004 (1985).

[6]J. W. Sunier *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **241**, 139 (1985).

[7]N. J. DiGiacomo *et al.*, Phys. Rev. C **31**, 292 (1985).

[8]W. E. Sondheim *et al.*, Nucl. Instrum. Methods **219**, 97 (1984).

[9]M. R. Clover, R. M. DeVries, N. J. DiGiacomo, and Y. Yariv, Phys. Rev. C **26**, 2138 (1982).

[10]D. Garetta *et al.*, Phys. Lett. **135B**, 266 (1984), and **149B**, 64 (1984).

[11]R. D. McKeown *et al.*, Phys. Rev. Lett. **44**, 1033 (1980).

[12]K. Miyano *et al.*, Phys. Rev. Lett. **53**, 1725 (1984).

[13]J. P. Schiffer, Comments Nucl. Part. Phys. **14**, 15 (1985).

[14]J. Cugnon and J. Vandermeulen, Phys. Lett. **146B**, 16 (1984).