Prowse and A. Lou, Bull. Am. Phys. Soc. 10, 114 (1965).

[12]Using potentials without hard core and a method of calculation which is considerably cruder than what we use here, H. Nakumura, Progr. Theoret. Phys. (Kyoto) 30, 84 (1963), has come to similar conclusions.

PRODUCTION OF ANTIPROTONS VIA NUCLEAR MOTION*

D. E. Dorfan, J. Eades, L. M. Lederman, W. Lee, and C. C. Ting

Columbia University, New York, New York

and

P. Piroué and Stuart Smith

Princeton University, Princeton, New Jersey

and

J. L. Brown, J. A. Kadyk, and G. H. Trilling

Physics Department and Lawrence Radiation Laboratory, University of California, Berkeley, California

(Received 4 May 1965)

Since the very first observation of meson production at an accelerator,[1] it has been recognized that "Fermi motion" provides large assistance in making extra energy available in the c.m. system. Present experimental techniques permit the observation of reactions having exceedingly small partial cross sections; these techniques could be applied to the question of just how much energy this complex nuclear effect could provide. For example, a 30-BeV proton collision in which the entire laboratory recoiled coherently would yield 30 BeV in the c.m. system, equivalent to the collision of a 450-BeV proton with a nucleon at rest. If a copper nucleus could take up the recoil, the available energy would be ~20 BeV (200-BeV accelerator). One can then ask whether the probability for similar events is large enough to be detected, in view of the great sensitivity of present techniques. Since no conservation laws are violated, it is safe to say that the question must be answered experimentally. The existence of such (very improbable) correlations is a problem which may perhaps be of interest to nuclear-structure theorists.

Although an extensive literature exists on nuclear internal motions, there is no "well-known" prescription for describing these results in a useful way from the viewpoint of a high-energy collision. We have, therefore, made a series of measurements on the reaction

$$p + \mathrm{Cu} \rightarrow \bar{p} + \text{residue}, \tag{1}$$

using protons of energies near and below threshold for antiproton production via the free-particle reaction

$$p + \binom{n}{p} \rightarrow p + p + \binom{n}{p} + \bar{p}. \tag{2}$$

For collisions below the threshold of the above reaction, some complex nuclear effect is necessary for $\bar{p}$ production. The observed $\bar{p}$ yield will then be a measure of the relative probability of such effects. More precisely, the observation of $\bar{p}$ at a bombarding energy T represents the existence of an interaction in which more than $4m_p$ is available in the c.m. system. Although the detailed mechanism for providing this energy is not known (it could be provided by intermediate pions, or by the coherent recoil of clusters), the main objective of this work is to find the distribution function

$$P_T(W_0)dW_0, \tag{3}$$

i.e., the probability of observing a c.m. total energy W_0 when the bombarding energy in the laboratory system is T. We assume that dynamics enters simply via a threshold function $(W-4m_p)^n$, although a careful investigation of $\bar{p}$ production by free protons above threshold would

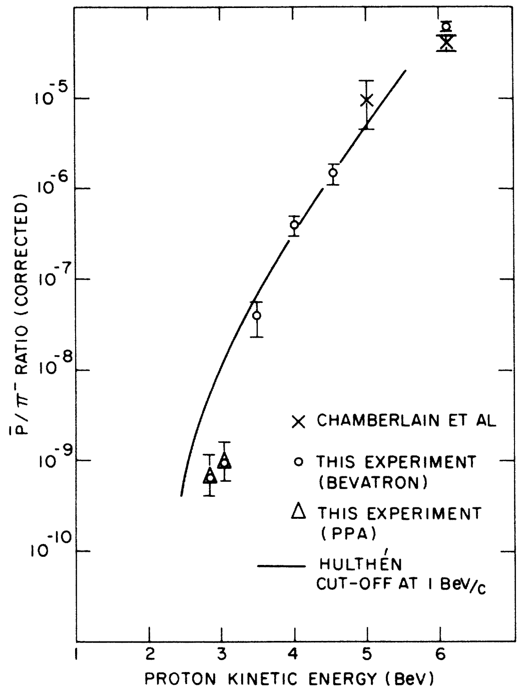

FIG. 1. Maximum $\bar{p}/\pi^-$ yields for each proton energy. We plotted 2-BeV/c $\bar{p}$ yield[6] at 6.1-BeV proton energy, 1360-MeV/c $\bar{p}$ at 4.55 BeV, 1200-MeV/c $\bar{p}$ at 4 BeV, 960-MeV/c $\bar{p}$ at 3.5 BeV, and 760-MeV/c $\bar{p}$ at 3.05 and 2.88 BeV.

be required to confirm this. We also assume that a nucleon momentum distribution, $f(k)dk$, is a satisfactory (although perhaps not unique) model for the mechanism by which the nuclear energy is contributed to the reaction.[2] Thus our results on $\bar{p}$ production may be applied to other experiments[3] via the $f(k)$ which is deduced. The results, in the form of the ratio $\bar{p}/\pi$ as a function of incident proton energy, are presented in Fig. 1 and Table I.

The data points at 6.1, 4.5, 4.0, and 3.5 BeV were obtained in the separated beam designed for the Bevatron 25-in. bubble chamber.[4] A slow extracted proton beam impinged on a Cu target one interaction length thick. Secondary particles were accepted at 0°. The two-stage separator, when tuned to antiprotons, achieved a pion rejection of $\sim 10^5$. Additional rejection was achieved by velocity selection using time of flight and a threshold Čerenkov counter which provided a veto of $\beta \approx 1$ particles.

At the higher bombarding energies the yield was sufficient to do a momentum survey of the $\bar{p}$. At each momentum we swept the separator currents to find the maximum yield of pions and antiprotons. This also provided a calibration of the Čerenkov counter, which was found to reject pions by a factor ~20 and have a 75% efficiency for $\bar{p}$, insensitive to $\bar{p}$ momentum in our interval. The peak yields are shown in Fig. 1 along with the data of Chamberlain et al.[5] Similarly, at lower bombarding energies, where the $\bar{p}$ yields are small and tuning became impractical, the separator currents for the desired secondary momenta were set by peaking on pions and using the ratio of separator currents at 6.1 BeV for the corresponding $\bar{p}$ settings.

Table I. Summary of the antiproton data taken at the Bevatron and the Princeton-Penn accelerator.

Proton energy (BeV)	$\bar{p}$ momentum (MeV/c)	No. of counts	$\bar{p}/\pi$ (corrected)
6.1 Cu	870	241	$(0.66\pm 0.1)\times 10^{-5}$
	970	113	$(1.1\ \pm 0.2)\times 10^{-5}$
	1200	398	$(2.0\ \pm 0.4)\times 10^{-5}$
	1370	394	$(3.0\ \pm 0.6)\times 10^{-5}$
4.55 Cu	870	70	$(5.4\ \pm 1)\times 10^{-6}$
	970	77	$(9.3\ \pm 2)\times 10^{-6}$
	1200	82	$(11.0\ \pm 2)\times 10^{-6}$
	1370	161	$(16\ \pm 3)\times 10^{-6}$
4.0 Cu	870	35	$(2\ \pm 0.5)\times 10^{-7}$
	970	37	$(2.3\ \pm 0.5)\times 10^{-7}$
	1200	99	$(4\ \pm 0.8)\times 10^{-7}$
	1370	30	$(2.8\ \pm 0.7)\times 10^{-7}$
3.5 Cu	970	12	$(4\ \pm 1.5)\times 10^{-8}$
3.05 Cu	760	5	$(9\ \pm 4)\times 10^{-10}$
2.88 Cu	760	4	$(6\ \pm 3)\times 10^{-10}$
2.88 Be	760	0	$<2\times 10^{-10}$

For very low $\bar{p}$ counting rates, stability was checked every two to three hours by repeaking on pions. As a check on background we set the separator currents away from pions and antiprotons. The counts in the $\beta \cong 1$ channels remained the same (presumably mostly muons), but no counts were observed in the $\bar{p}$ channels, i.e., zero background correction in all the yield curves.

Corrections to the $\bar{p}/\pi^-$ data come from π-μ decay and from target reabsorption. The errors quoted include effects due to calibration uncertainties such as drifts in the separator currents, efficiencies, etc.

The two lowest points (at 3.04 and 2.88 BeV) were obtained at the Princeton-Penn accelerator. These measurements were made at 13° relative to the incident proton beam, the most forward angle available. At this angle the laboratory momentum of antiprotons produced at threshold by 3-BeV protons colliding with backward-moving target nucleons is 760 MeV/c. Accordingly, a beam of this momentum was transported via a quadrupole (Q) and dipole (D) arrangement $Q_1Q_2D_1(14°)S_1D_2(14°)Q_3Q_4S_2S_3$-$D_3(-8°)S_4$, where $S_1, \cdots, S_4$ are scintillation counters located at 42, 57, 68, and 81 ft from the target, respectively. The interspersed bending magnets swept out particles produced by interactions in the counters. The beam was tuned to positive protons, and pions were rejected on the basis of their time of flight through the entire telescope. For particles triggering the logic, times of flight were measured between S_2 and S_3, and also between S_3 and S_4. Both of these times of flight were displayed on a two-dimensional pulse-height analyzer where particles of proton mass defined a specific region. With the polarity of all magnets reversed the trigger rate fell to a few counts per 10^8 π^-. This low background could be obtained because of the fine structure of the Princeton-Penn accelerator internal proton beam (1.4-nsec-wide bunches, 33 nsec apart). This makes accidental coincidences coherent and, if proper distances are chosen between counters, far removed in time from the region of interest. A shorter run with a Be target failed to show $\bar{p}$ events in 5×10^9 pions, i.e., $\bar{p}/\pi^- \lesssim 2\times 10^{-10}$. Corrections were made for π-μ decay and target reabsorption. In addition, a 12% correction was made to reduce the data to 0° (for comparison with the Bevatron data), assuming isotropy in the c.m. system and fitting of the results as discussed below.

As an aid in interpreting the results from the point of view of high-energy collisions we plot, in Fig. 2, the total energy in the c.m. system, W_0, for a head-on collision of a 30-BeV proton and a target nucleon as a function of the internal momentum. Also plotted is the minimum laboratory energy required to produce $\bar{p}p$ pairs versus the same nucleon momentum. Thus the detection of $\bar{p}$ at 3 BeV implies a finite probability for the observation of collisions at the AGS ($T = 30$ BeV) corresponding to $W_0 = 10$ BeV.

Elioff et al.[6] calculated the antiproton yield for incident proton energies down to 4.5 BeV using a statistical model. Agreement between their data and the calculation was very good. In their calculation the particles inside a nucleus were considered to constitute a completely degenerate Fermi gas with a maximum energy of 25 MeV.

We have considered various nucleon momentum distributions inside a nucleus and calculated $\bar{p}$ yields using the model of Elioff et al. In what follows we assume that nucleons inside a nucleus can be treated nonrelativistically.

We will use the same notation as in reference 6, and hereafter use $\hbar = c = m_p = 1$. Then

$$P_T(W_0)\Delta W_0 = \int_{W_0}^{W_0+\Delta W_0}(2t)^{1/2}g(t)\,dt\,d\mu, \qquad (4)$$

where $g(t)$ is the nucleon kinetic-energy dis-

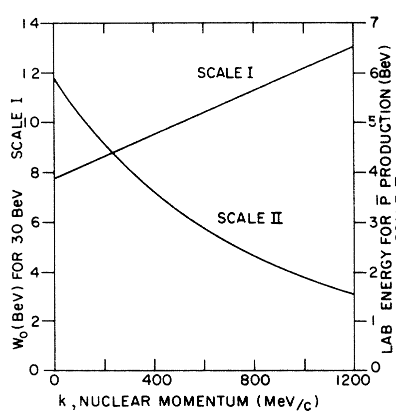

FIG. 2. Energy available in the c.m. system for a collision of a 30-BeV proton with a target proton moving in the opposite direction with nuclear internal momentum (scale I). In scale II, we take the c.m. energy to be 4 BeV (threshold for $\bar{p}$ production), and present the corresponding laboratory energy required to achieve this value of W_0. This curve would automatically be cut off below 2 BeV by the phase-space factor.

tribution function inside a nucleus, corresponding to a momentum distribution $f(k)$; μ is the cosine of the angle between an incident proton and a target nucleon; and t is the energy of the target nucleon. We get Elioff's result if we use

$$g(t) = 1 \text{ for } 0 \leq t \leq 0.025,$$
$$= 0 \text{ for } t \geq 0.025.$$

Assuming the nucleon kinetic energy can be represented by a Gaussian or Hulthén distribution, i.e.,

$$g_g(t) \propto \exp[-(t/t_0)^2], \quad (5)$$

or

$$g_h(t) \propto \left(\frac{1}{2t+\alpha^2} - \frac{1}{2t+\beta^2}\right)^2, \quad (6)$$

we have calculated $P_T(W_0)\Delta W_0$ in the manner of Elioff.

$\bar{p}$ yields were obtained for various values of n in the threshold function $(W_0-4)^n$, and for different cutoffs on t. We find that for the Gaussian distribution we cannot fit our data for $t_0 = 20$ MeV, a value preferred from lower energy experiments. In order to fit our data we would need $t_0 = 60$ MeV. For the Hulthén distribution we show the results of our calculation in Fig. 1. For this calculation we used $\alpha = 0.0486$, $\beta = 0.340$, $t_{\max} = 0.41$, and $n = \frac{7}{2}$. Agreement between data and calculation is fair.

We found that the calculated results do not depend very much on n. One can make an additional modification by noting that the nucleon with Fermi momentum k does not have a total energy of $(m_p^2 + k^2)^{1/2}$ because the total energy of the nucleus has to remain the mass of Cu. For this reason we used $(W_0-4-\epsilon)^n$ instead of $(W-4)^n$ and calculated the yield for various values of ϵ: $\epsilon = 0, 0.2, 0.5$. We found that $\epsilon = 0$ fitted our data best.

No exhaustive search for better solutions has been undertaken. However, the significance of the "fit" obtained may be illustrated by Fig. 3 in which the resulting probability distribution (3) is shown. Also shown are some arbitrary but possible extrapolations. Within the large uncertainties of these extrapolations one sees that the AGS, with 10^{12} protons, can provide $\sim 10^5$ collisions per pulse which have ~14-20 BeV available in the c.m. system. An application of these results to AGS experiments is described in an accompanying Letter.[3]

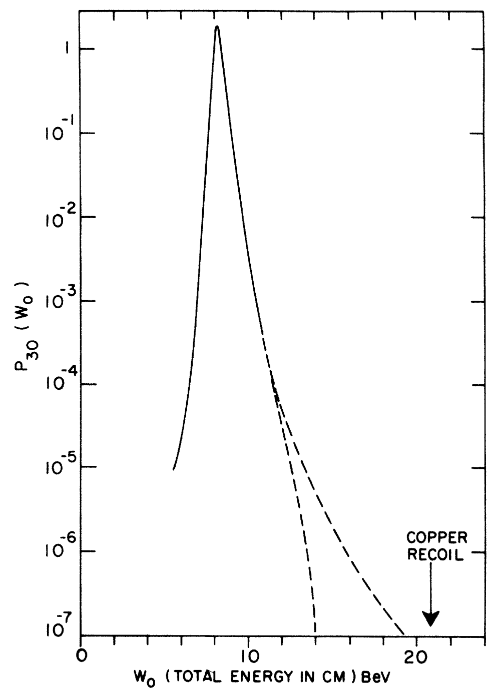

FIG. 3. Distribution in W_0 for a 30-BeV proton incident upon nuclear matter with the internal motion given by (6). The dotted lines are possible extrapolations, e.g. 21 BeV represents the maximum nuclear momentum allowed in a copper nucleus.

We would like to thank Dr. E. Lofgren and the operating crew of the Bevatron, and also Dr. M. White and the staff of the Princeton-Penn accelerator, for enthusiastic and effective cooperation. We would also like to thank Mr. E. Barnes for computer programming, and Dr. M. Bowler for assistance in the Bevatron data taking.

---

*Work supported in part by the U. S. Atomic Energy Commission.

[1]E. Gardner and C. M. G. Lattes, Science 107, 270 (1948).

[2]Although we used a simple picture involving independent particle motion, we suspect that many diverse phenomena, ignored in our treatment, are, in fact, partially included, e.g. intermediate real pion production, recoil of clusters, etc.

[3]D. E. Dorfan, J. Eades, L. M. Lederman, W. Lee, and C. C. Ting, following Letter [Phys. Rev. Letters 14, 999 (1965)].

[4]R. B. Bell, R. W. Bland, M. G. Bowler, J. L. Brown, R. P. Ely, S. Y. Fung, G. Goldhaber, A. A. Hirata, J. A. Kadyk, J. Louce, C. T. Murphy, J. S. Sahouria, V. H. Seeger, W. M. Smart, and G. H. Trilling, University of California Radiation Laboratory

Report No. UCRL-11527 (unpublished).
[5]O. Chamberlain, E. Segrè, C. Wiegand, and T. Ypsilantis, Phys. Rev. 100, 947 (1955).
[6]T. Elioff, L. Agnew, O. Chamberlain, H. M. Steiner, C. Wiegand, and T. Ypsilantis, Phys. Rev. 128, 869 (1962).

SEARCH FOR MASSIVE PARTICLE*

D. E. Dorfan, J. Eades, L. M. Lederman, W. Lee, and C. C. Ting
Columbia University, New York, New York
(Received 4 May 1965)

Recent developments in strong-interaction theory have led to the speculation that there may exist particles associated with the basic representations of SU(3) and higher symmetry schemes.[1-3] In this picture mesons, baryons, and resonances are composite systems built up of these fundamental elements. The theoretical considerations indicate variously that these triplets could be fractionally charged,[1,2] could be stable, and are probably relatively massive.[3] This has provoked the purely experimental question: Are there metastable particles in nature which, because of their high mass and consequently low production probability, have to date escaped detection?

We report here the negative results of a search for particles of mass $3 \lesssim m \lesssim 7$ BeV produced by collisions of 30-BeV/c protons with Be and Fe nuclei. We depend on knowledge of the nuclear internal motion, studied in the preceding Letter,[4] to evaluate the relative probability of achieving c.m. energies sufficient to produce such particles. The essential signature we seek is mass, as defined by momentum and velocity. This differs from other experiments[5-7] which are based on the low ionization deposited by particles of charge $\frac{1}{3}e$ (quarks). Our experiment is also sensitive to quarks or, in fact, particles of any charge $q \geq \frac{2}{3}e$. The total flight path from the target is ~120 m, and this requires a stability which, although mass- and charge-dependent, is roughly $\tau \geq 10^{-7}$ sec.

A high intensity negative beam was defined at 4.5° from the G-10 target of the AGS. The beam layout is illustrated in Fig. 1. The momentum was defined to ±1% by dipole magnets D_1 and D_2 separated by a 4-ft by $\frac{1}{2}$-in. by $\frac{1}{2}$-in. collimator. Three additional momentum determinations were made by counter-defined trajectories through magnets D_3, D_4D_5, and D_6D_7. A set of quadrupoles (not shown) held the beam together for its ~100-m flight path to S_{10}. Vacuum pipes and helium bags were used whereever possible. Since the center of the mass range to which we were sensitive is ~4 to 5 BeV, we set the beam momentum for 10 BeV/c in order to be near the peak in the laboratory spectrum expected at 5° on the basis of simple

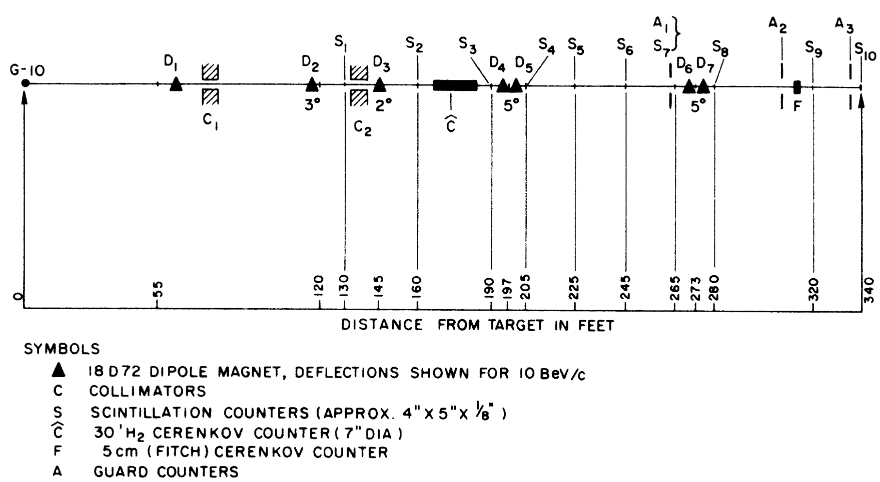

FIG. 1. Schematic beam layout.