EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/80-98
11 June 1980

OBSERVATION OF THE FERMI PLATEAU IN THE IONIZATION ENERGY LOSS OF HIGH-ENERGY PROTONS AND PIONS IN HYDROGEN GAS

J.P. Burq[*)], M. Chemarin[*)], M. Chevallier[*)], A.S. Denisov[**)], T. Ekelöf[***,†)], P. Grafström[***,†)], E. Hagberg[†)], B. Ille[*)], A.P. Kashchuk[**)], A.V. Kulikov[**)], M. Lambert[*)], J.P. Martin[***,*)], S. Maury[***,††)], M. Querrou[††)], V.A. Schegelsky[**)], I.I. Tkach[**)] and A.A. Vorobyov[**)]

ABSTRACT

We have measured the ionization loss of highly relativistic protons and pions passing through an ionization chamber filled with hydrogen at 10 atm pressure. The Lorentz factor of the particles ranged from $\gamma = 100$ to $\gamma = 1800$. The ionization loss was found to be constant in the measured γ interval within ±0.5%, in agreement with the predictions of the classical Fermi theory. In particular, our results disagree with the theoretical predictions of Tsytovich, according to which radiative corrections lead to a decrease in the ionization loss at higher energies.

(Submitted to Physics Letters B)

*) Institut de Physique nucléaire, IN2P3, Université de Lyon-Villeurbanne, France.
**) Leningrad Nuclear Physics Institute, Gatchina, USSR.
***) At present CERN, Geneva, Switzerland.
†) The Gustaf Werner Institute, University of Uppsala, Sweden.
††) Laboratoire de Physique corpusculaire, IN2P3, Université de Clermont-Ferrand, Aubière, France.

1. INTRODUCTION

The Bethe-Bloch theory for energy loss of relativistic particles predicts a logarithmic increase of the energy loss with the Lorentz factor γ of the ionizing particles. Fermi was the first to show [1] that the electric polarization of the material through which the particles pass affects the amount of the energy loss considerably. As a result, the energy loss should, after some increase, reach a constant level -- the Fermi plateau -- the height of which is a function of the density of the material. The asymptotic region, in which the ionization is γ-independent, is reached when $\gamma >> \omega_s/\omega_0$, where ω_s represents the oscillation frequency of the atomic electrons ($\hbar\omega_s = I$, where I is the mean excitation potential of the material), and ω_0 is the plasma frequency of the material [$\omega_0^2 = 4\pi n(e^2/m)$; here, n is the number of electrons in 1 cm^3, m and e are the mass and the charge of the electron, respectively].

In his theory, Fermi used the classical electrodynamic equations of Maxwell to calculate the energy loss in distant collisions, while the close distance impacts were treated using the theory of Bethe and Bloch, assuming that the effects of the polarization of the medium are negligible in such collisions. The results obtained by Fermi were confirmed at a later stage by calculations based on first-order QED [2]. Also, higher-order QED corrections to the energy loss were estimated [3,4], and it was found that these corrections change the height of the Fermi plateau by only $\sim$ 1%. On the other hand, Tsytovich [5] has found that radiative corrections should have a considerable effect on the energy loss at high energy. According to Tsytovich, the energy loss, after having reached the level of the Fermi plateau, starts to decrease again with increasing γ and finally approaches from above a new asymptotic value at

$$\gamma >> \frac{1}{|\lambda|} = \frac{1}{\alpha} \cdot \frac{\omega_s}{\omega_0} \frac{1}{\ln (c/\langle v \rangle)} ,$$

where $\langle v \rangle$ is the averaged velocity of the atomic electrons in the material, and α is the fine-structure constant. In this theory the asymptotic radiative correction to the energy loss is given by

$$\Delta W = -\frac{2\alpha}{\pi} \ln^2 \frac{1}{|\lambda|} .$$

This correction may be of the order of 10%.

No clear conclusion can be drawn from experimental data available until now concerning the existence of such a decrease in ionization at high energies. One group [6] has reported a decrease in the ionization produced by high-energy electrons in photoemulsions in the γ-region $50 \leq \gamma \leq 2000$, which is in agreement with Tsytovich's predictions. In other experiments [7,8] with high-energy electrons, this effect has not been observed. However, in these experiments, the absorption of bremsstrahlung radiation in the detectors required substantial corrections to be applied to the data, and the results were not conclusive for this reason. Investigations with high-energy cosmic muons [9] have shown no evidence for the Tsytovich effect. In this case the limited statistics in the experiment again made the conclusion uncertain. A recent experiment performed at Fermilab [10], using a thin semiconductor detector and ultra-relativistic electrons with values of the Lorentz factor in the range $10^4 < \gamma < 10^5$, has shown an absolute ionization loss that is $(7 \pm 2)\%$ smaller than that of the Fermi plateau. Two possible reasons for such a result have been suggested by the authors: the Tsytovich effect, and the influence of the finite thickness of the employed detector.

Here we report on the results of an experiment at the CERN Super Proton Synchrotron (SPS) in which the ionization loss of protons and pions was measured in H_2 at 10 atm pressure and at Lorentz factors between $\gamma = 100$ and $\gamma = 1800$. For such an absorption medium $\omega_s/\omega_0 = 22$ and $1/|\lambda| \simeq 600$, and in consequence the measured γ-interval is in the region where, according to Tsytovich, one should expect a decrease in the ionization loss approaching a new asymptotic level some 19% below the Fermi plateau.

2. MEASUREMENTS AND RESULTS

The present measurements were made using the existing set-up of an experiment, the primary purpose of which was to measure elastic scattering of hadrons in the

Coulomb interference region [11]. The ionization loss was measured with an ionization chamber IKAR (Fig. 1) filled with hydrogen gas at 10 atm pressure. The secondary beam derived from a 400 GeV proton beam was focused onto IKAR, and the dimensions of the beam spot were about 10 × 10 mm^2. The width of the momentum bite in the beam line was $\Delta p/p = 0.1\%$. The incident particles were identified using Čerenkov counters, a muon detector, and an electromagnetic calorimeter. Also, the scattering angle and the momentum of the outgoing particle were measured. These measurements were useful for the rejection of particles that produced nuclear reactions in the walls of IKAR and in the other material in the beam. The relative amount of such particles was about 1%.

The ionization chamber consists of six modular cells, all contained in a cylindrical pressure vessel. Two of these cells are shown in Fig. 1. Each cell contains an anode plate and a cathode plate, 12 cm apart, mounted perpendicularly to the beam direction. An earthed wire grid is placed 2 cm from the anode. The beam enters and leaves the pressure vessel through steel windows that are 270 μm thick and 80 mm in diameter. In the region where the beam traverses the chamber electrodes, these are made of 20 μm thick aluminium foil. The energy left in the hydrogen gas by a relativistic particle is about 40 keV in each ionization chamber cell. The electrons created in the gas were collected during 22 μs onto the anode plates A_i. In order to avoid pile-up of the signals during the electron collection time, a 100 μs dead-time was introduced in the trigger. For the same reason, the beam intensity was kept at a level of only $\sim 10^3$ particles per 1 s burst.

The signals from all six anodes A_i were summed, amplified, and strobed by two 0.1 μs strobes. The first strobe was synchronized with the start of the signal, and the second was sent when the ionization signal reached its maximum value (Fig. 1). For each particle, two amplitudes V_0 and V were thus measured. The amount of the ionization loss was determined by V, and the amplitude V_0 served as a reference in this determination.

The maximum energy T_0 transferred to a single δ-electron which could be detected in the chamber was determined by the radius of the anode A (100 mm) and the pressure of the gas. In the present case, T_0 = 120 keV. Figure 2 shows the V_0 and V distributions for a sample of measurements obtained with 100 GeV/c protons. Zero on the abscissa corresponds to the position of the pedestal used to shift the spectra into the linear region of the ADC. The mean value of the V_0-distribution $\langle V_0 \rangle$ was found to be close to zero, which means that there were no systematic shifts due to, for example, pile up of the ionization signals in the measurements. The V_0 spectrum was well fitted by a symmetric Gaussian distribution shown by the solid line in Fig. 2a, while the V spectrum had a tail on the high-amplitude side, similar in shape to that of a Landau distribution. From such distributions we obtained the average amplitudes $\langle V \rangle$. In this experiment only the relative amount of the ionization loss was determined, the aim being to measure the ratio of the ionization loss produced by protons and positive pions of the same momentum. These measurements were performed simultaneously and thus under identical experimental conditions, thereby reducing further the effect of systematic errors. The measurements were made at two beam momenta: 100 GeV/c and 250 GeV/c. The results are presented in Table 1.

3. DISCUSSION

From the results shown in Table 1 it follows that the ionization loss of relativistic particles is constant within ±0.5% in the Lorentz factor interval $100 < \gamma < 1800$. Our data are plotted in Fig. 3 together with the data of Barber [12], which were obtained using electrons of energy between 1 and 34 MeV. Our data were normalized to the last points of Barber's data. In their turn, Barber's data were normalized in the γ-region $5 < \gamma < 20$ to the theoretical curve $W_I(\gamma)$ in Fig. 3. This curve was calculated according to the Bethe-Bloch formula, applying as upper limit for the detectable energy loss T_0 = 0.12 MeV. The curve $W_{II}(\gamma)$ in Fig. 9 represents the energy loss corrected for the density effect according to Sternheimer [13,14], who has extended the classical method introduced by Fermi, and the curve $W_{III}(\gamma)$ is the asymptotic value for the energy loss with

Tsytovich's radiative correction. Our experimental points show that there is no variation in the height of the Fermi plateau up to $\gamma = 1800$, in close agreement with the predictions of the classical theory of ionization loss and in contradiction to the predictions of Tsytovich. As to the difference in the absolute values of $W_{II}(\gamma)$ and $W_{expt}(\gamma)$, it could be [12,15] attributed to Čerenkov radiation that escapes from the sensitive volume of the ionization chamber or is absorbed without producing ions.

REFERENCES

[1] E. Fermi, Phys. Rev. 57 (1940) 485.

[2] U. Fano, Ann. Rev. Nucl. Sci. 13 (1963) 1.

[3] A. Crispin and G.N. Fowler, Rev. Mod. Phys. 42 (1970) 290.

[4] J.D. Jackson and R.L. McCarthy, Phys. Rev. B 6 (1972) 4131.

[5] V.N. Tsytovich, Sov. Phys. JETP 16 (1963) 1260; Zh. Eksp. Teor. Fiz. 43 (1962) 1782.

[6] G.B. Zhdanov et al., Sov. Phys. JETP 16 (1963) 245; Zh. Eksp. Teor. Fiz. 43 (1962) 342.

R.I. Alekseeva et al., Sov. Phys. JETP 17 (1963) 1254; Zh. Eksp. Teor. Fiz. 44 (1963) 1864.

[7] E.H. Bellamy et al., Phys. Rev. 164 (1967) 417.

[8] D.W. Aitken et al., Phys. Rev. 179 (1969) 393.

[9] F. Ashton and D.A. Simpson, Phys. Lett. 16 (1965) 78.

[10] W. Ogle et al., Phys. Rev. Lett. 40 (1978) 1242.

[11] J.P. Burq et al., Phys. Lett. 77B (1978) 438.

[12] W.C. Barber, Phys. Rev. 103 (1956) 1281.

[13] R.M. Sternheimer, Phys. Rev. 91 (1953) 256.

[14] R.M. Sternheimer, Phys. Rev. 103 (1956) 511.

[15] R.M. Sternheimer, Phys. Rev. 93 (1954) 1434.

Table 1

Beam momentum (GeV/c)	Lorentz factor		Number of events		$\frac{\langle V\rangle_p - \langle V\rangle_\pi}{\langle V\rangle_p}$ (%)
	p	π^+	p	π^+	
100	106	716	31025	24435	-0.08 ± 0.25
250	266	1791	20210	12174	$+0.19 \pm 0.40$

APPENDIX

The energy loss including the density effect correction was calculated using the Sternheimer formula [13]. This formula is given below in a somewhat modified form that can be used for direct evaluation at any value of the gas pressure:

$$W(\gamma) \equiv -\frac{1}{\rho}\left(\frac{dE}{dx}\right)_{T_0} = \frac{A}{\beta^2}\left[B + \ln 2T_0 - \beta^2 + 2\ln\gamma - \delta_P(\gamma)\right] ,$$

$$A \equiv \frac{2\pi n\ e^4 z^2}{mc^2 \rho} ,$$

$$B \equiv \ln\left[\frac{mc^2\ (10^6\ \mathrm{eV})}{I^2}\right] ,$$

where

z and β are the charge and the velocity of the incident particle;

ρ is the density of the material;

T_0 (MeV) is the maximum energy transfer detected by the apparatus;

$\delta_P(\gamma)$ is the density effect correction which we determine as follows:

$$\begin{cases} \delta_P(\gamma) = 2\ln\gamma + C_P + a\left[(x_1)_P - x\right]^s , & (x_0)_P < x < (x_1)_P \\ \delta_P(\gamma) = 2\ln\gamma + C_P , & x > (x_1)_P \end{cases}$$

where

$$x = \log_{10}\gamma ,$$

$$\begin{cases} (x_1)_P \equiv (x_1)_1 - \frac{1}{2}\log_{10} P , \\ (x_0)_P \equiv (x_0)_1 - \frac{1}{2}\log_{10} P , \\ C_P \equiv C_1 + \ln P , \end{cases}$$

$$C_1 \equiv 2\ln\left(\frac{I}{\hbar\omega_{01}}\right) - 1 .$$

Here, P is the gas pressure in atm, ω_{01} is the plasma frequency in H_2 at 1 atm pressure, $(x_0)_P$ is the value of x below which $\delta_P(\gamma) = 0$, and $(x_1)_P$ is the value of x above which the energy loss is constant. For hydrogen gas $A = 0.1536$ MeV/g$\cdot$cm^{-2}; $B = 21.07$ ($I = 19$ eV), and $C_1 = -9.5$. The other parameters were taken from Ref. 14: $a = 0.505$, $s = 4.72$, $(x_1)_1 = 3$, and $(x_0)_1 = 1.85$. As was explained in the text, in our case T_0 = 0.12 MeV. With these constants, the energy loss was calculated using the above formulae, and the results are shown in Fig. 2 [curve $W_{II}(\gamma)$]. The curve $W_I(\gamma)$ was calculated using the same formulae, but with $\delta_P(\gamma) = 0$.

Figure captions

Fig. 1 : The upper picture shows schematically the construction of two cells of the ionization chamber IKAR. The lower diagram illustrates the timing of the two strobe signals with respect to the rise of the anode pulse.

Fig. 2 : The upper figure shows the amplitude distribution for the reference signal V_0 (strobe 1); the lower figure shows the same distribution for the ionization signal V (strobe 2).

Fig. 3 : Plot showing the ionization energy loss versus the Lorentz factor γ. Data points are from the present experiment and from that of Barber. The full-line curves are calculations according to Bethe and Bloch (W_I), Sternheimer (W_{II}) and Tsytovich (W_{III}). The dashed curve is a line drawn through the experimental points.

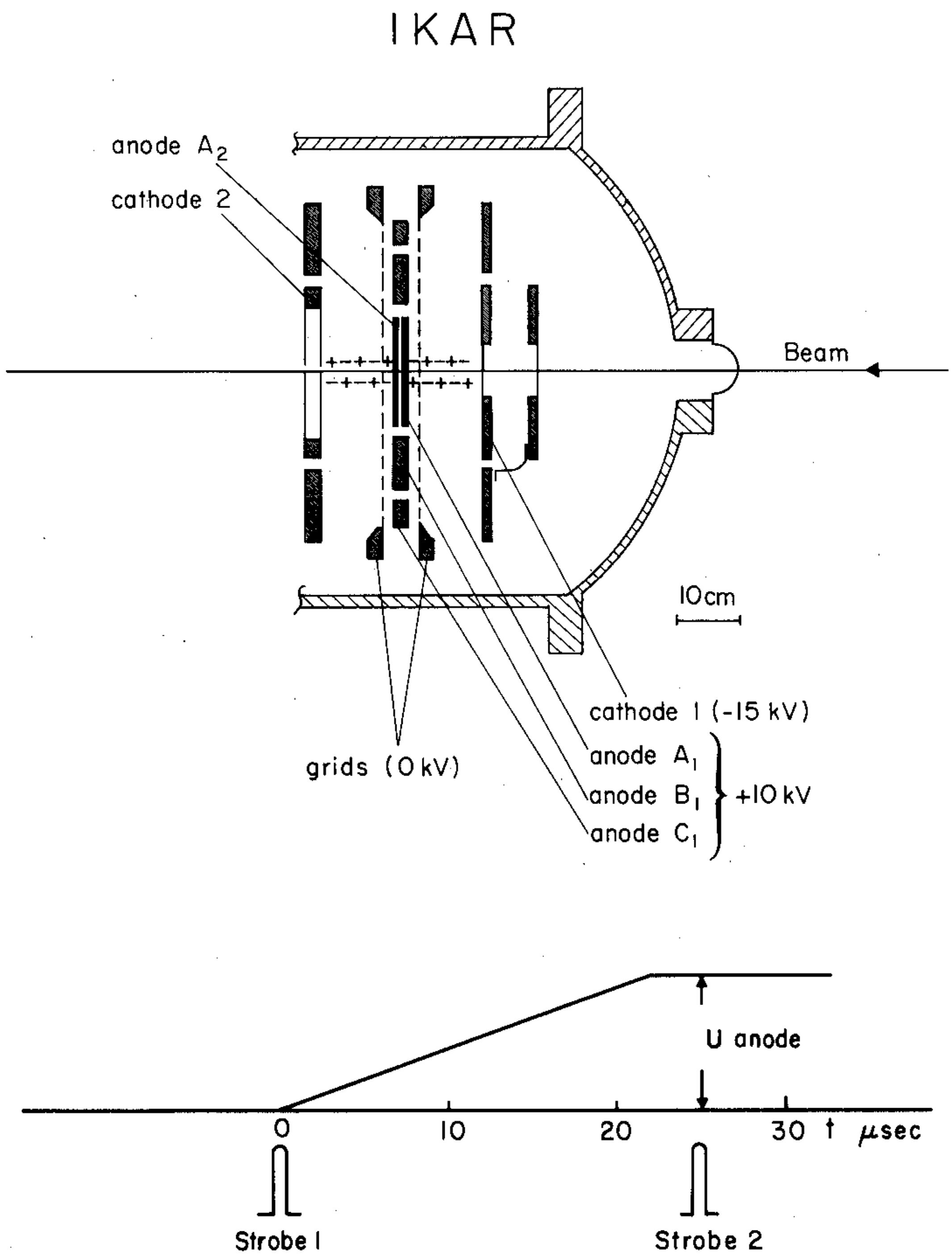
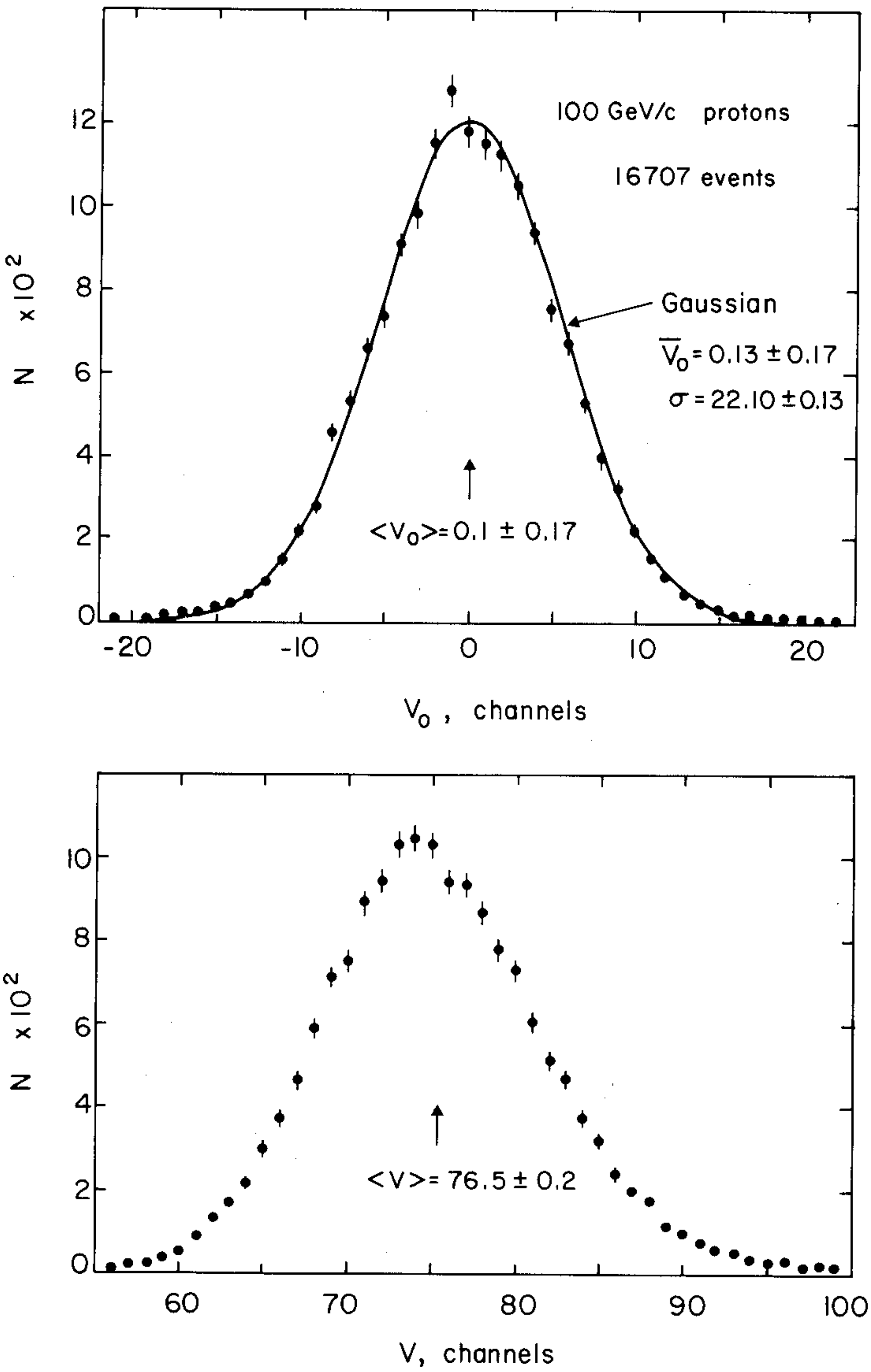
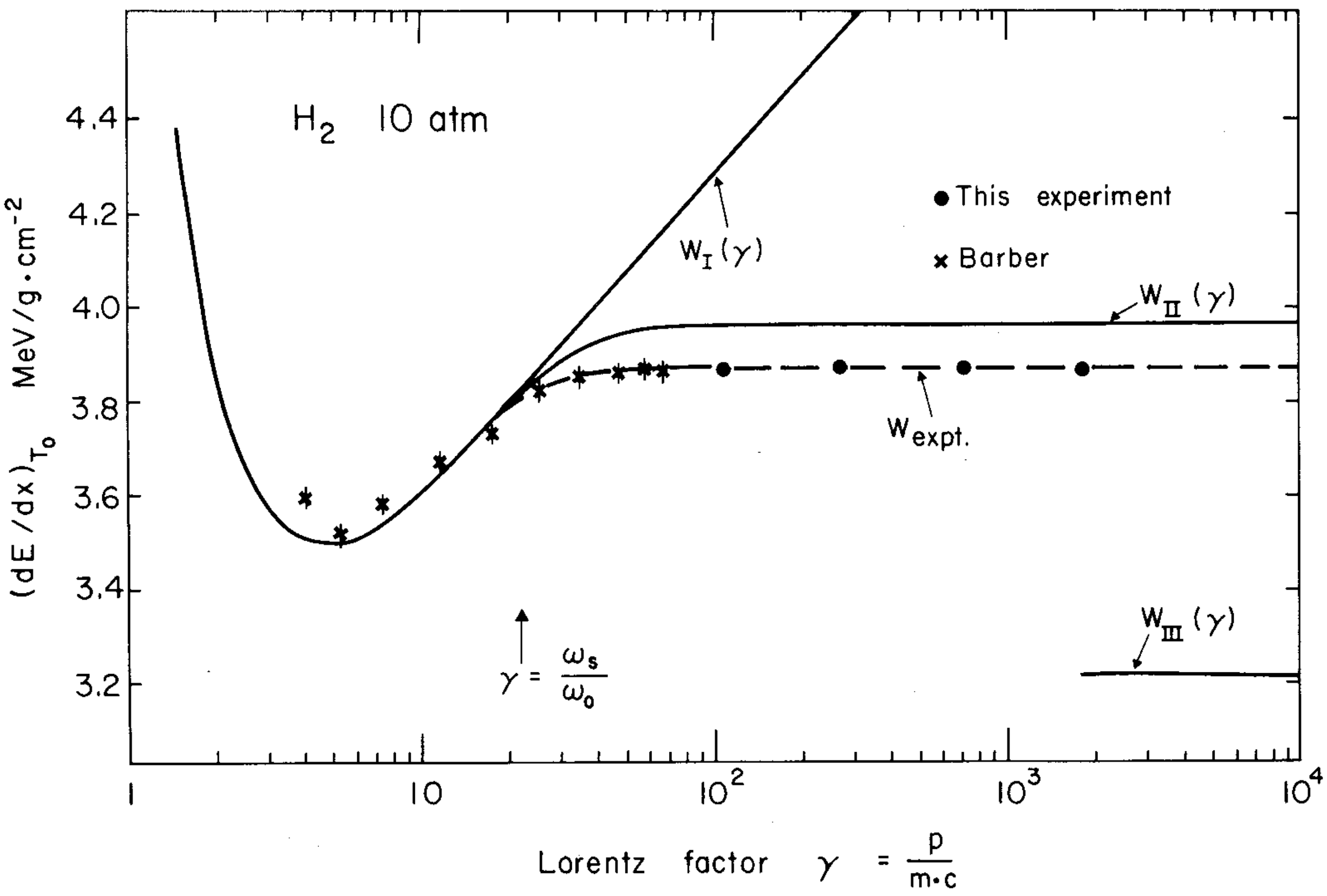

IKAR
anode A2
cathode 2
Beam
10cm
cathode 1 (-15 kV)
grids (0 kV)
anode A1
anode B1
anode C1
+10 kV
U anode
0
10
20
30
t μsec
Strobe 1
Strobe 2

Fig. 1



100 GeV/c protons
16707 events
Gaussian
$\overline{V_0}$ = 0.13 ± 0.17
σ = 22.10 ± 0.13
<V_0> = 0.1 ± 0.17
N x10^2
V_0, channels
<V> = 76.5 ± 0.2
V, channels

Fig. 2



H2 10 atm
● This experiment
× Barber
W_I (γ)
W_II (γ)
W_expt.
W_III (γ)
γ = ωs/ω0
4.4
4.2
4.0
3.8
3.6
3.4
3.2
(dE/dx)To MeV/g·cm-2
1
10
10^2
10^3
10^4
Lorentz factor γ = p/m·c

Fig. 3