Experimental Comparison of the Velocities of eV (Visible) and GeV Electromagnetic Radiation*†

B. C. Brown, G. E. Masek, T. Maung, E. S. Miller, H. Ruderman, and W. Vernon
Department of Physics, University of California, San Diego, La Jolla, California 92037
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An experiment has been carried out employing time-of-flight techniques to compare the velocity of propagation of short pulses of eV (visible) and GeV electromagnetic radiation. The results give a relative velocity difference $[c(\mathrm{GeV})-c(\mathrm{eV})]/c(\mathrm{eV})=(1.8\pm6)\times10^{-6}$. The velocity of 11-GeV energy electrons v_e is measured and found to be approximately equal to the velocity of visible light: $(c-v_e)/c=(-1.3\pm2.7)\times10^{-6}$.

We report here on an experiment[1] which compares directly the velocity of visible light to the velocity of 7-GeV γ rays.[2] The basic concept of this experiment was to use the Stanford Linear Accelerator Center (SLAC) electron beam to produce short (5-psec) pulses of both 7-GeV γ rays (generated by *bremsstrahlung*) and visible light (generated by synchrotron radiation) at a point midway down the accelerator length. The remaining part of the accelerator was then used as a high-vacuum flight path for both radiations; their times of flight over this path were compared using standard photomultiplier-electronics techniques.

The physical arrangement is schematically shown in Fig. 1. The SLAC electron beam (11 GeV energy) was directed onto a 0.015-in. (0.03 radiation length) copper target (T_1) located in the beam monitor can at Sector 19.[3] This was the *bremsstrahlung* production target. After passing through T_1, the beam was deflected by a magnet (B_1) which served both to dump the electron beam and to produce the synchrotron radiation.[4] Optically opaque shutters at Sector 18 (S_1), up-beam of the B_1 magnet, and at Sector 22 (S_2), down-beam of the magnet, could be inserted into the

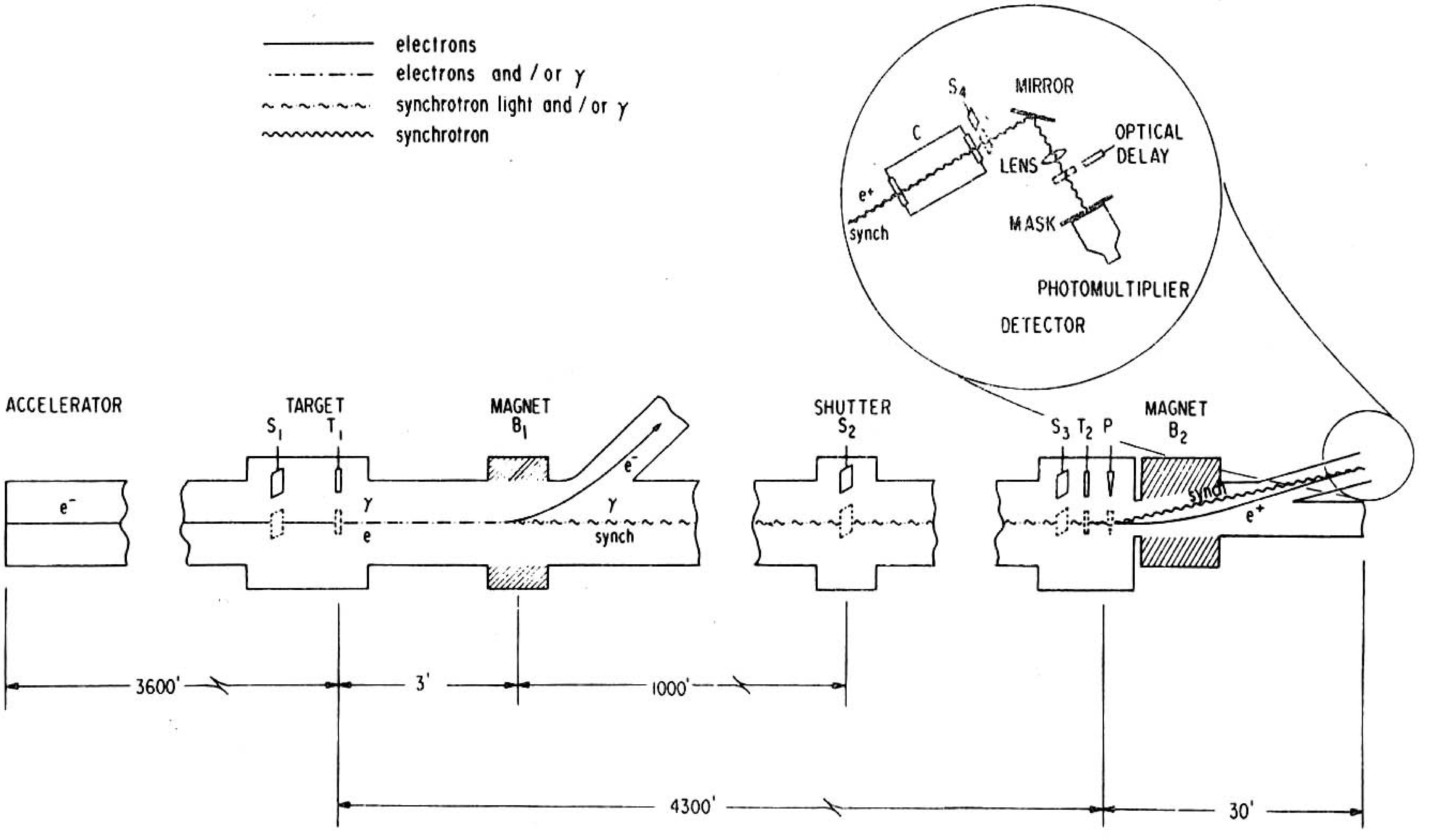

FIG. 1. Schematic diagram of the experimental arrangement (see discussion in the text). The setup for the synchrotron signal was S_1B_1P, and for the γ-ray signal, $S_1T_1B_1S_2S_3T_2B_2C$, where the symbol means the device is inserted or activated.

beam to test the localization of the synchrotron light production. Both radiations then travel a distance of approximately 4300 ft to the analysis region where each is detected on separate runs.

For the γ-ray detection, a second target (T_2) consisting of 0.5 in. of copper (0.9 radiation length) was inserted to produce electron-positron pairs from the γ rays. The high-energy positrons ($E = 7.5 \pm 0.5$ GeV) were selected by the magnet B_2 and directed to the detector, insuring that the γ rays observed through positron conversions had energies ≥ 7 GeV. At the detector, a gas Cherenkov counter[5] (C) observed by a mirror-lens-photomultiplier system (Fig. 1, inset) was used to detect the positrons. For the synchrotron radiation detection, a prism (P) in the analyzing region directed the optical light towards the detector. A third optically opaque shutter (S_3) could be used to test for visible light. At the detector the synchrotron light passed through the Cherenkov counter and was detected by the mirror-lens-photomultiplier system. The shutter (S_4) provided a final check for optical light—either synchrotron light or Cherenkov light.

The operation of the experiment consisted of alternating runs in which the γ radiation or the synchrotron radiation was detected. The various elements (shutters, targets, prism, Cherenkov counter) could be remotely inserted or activated. Various combinations of these could be used to produce a γ-ray signal and check its background, and similarly for the synchrotron light. The logic for the signals is given in the caption of Fig. 1. Typically, synchrotron signals were detected with signal:noise better than 1000:1 and photomultiplier (PM) pulses corresponding to twenty photoelectrons.[6] The γ-ray signal out of the PM was of similar magnitude, but with a signal:noise of 4:1. As discussed below, this background was the principal factor limiting the accuracy of the experiment.[7] The γ-ray spectrum was verified by varying the B_2 magnet current.

The time of flight (TOF) of both radiations was measured relative to a timing pulse derived from the microwave phase reference for the accelerator. Each accelerator pulse gave a PM (Amperex XP-1210) signal from which the TOF measurement was derived. This was digitized and stored, along with the PM pulse height (actually pulse integral), on a two-dimensional pulse-height analyzer. Thus one could compare the times of the two radiation signals at the same pulse height (integral). The results of one (typical) set of runs on synchrotron radiation and γ rays are shown in Figs. 2(a)–2(d). To analyze the data the peaks of the time distributions [e.g., Figs. 2(c) and 2(d)] were determined using a Gaussian fit to the eleven channels nearest the peak. Figure 2(e) shows the result of plotting the fitted mean versus pulse height for four runs—two normal runs and two runs using an optical delay.[8] We

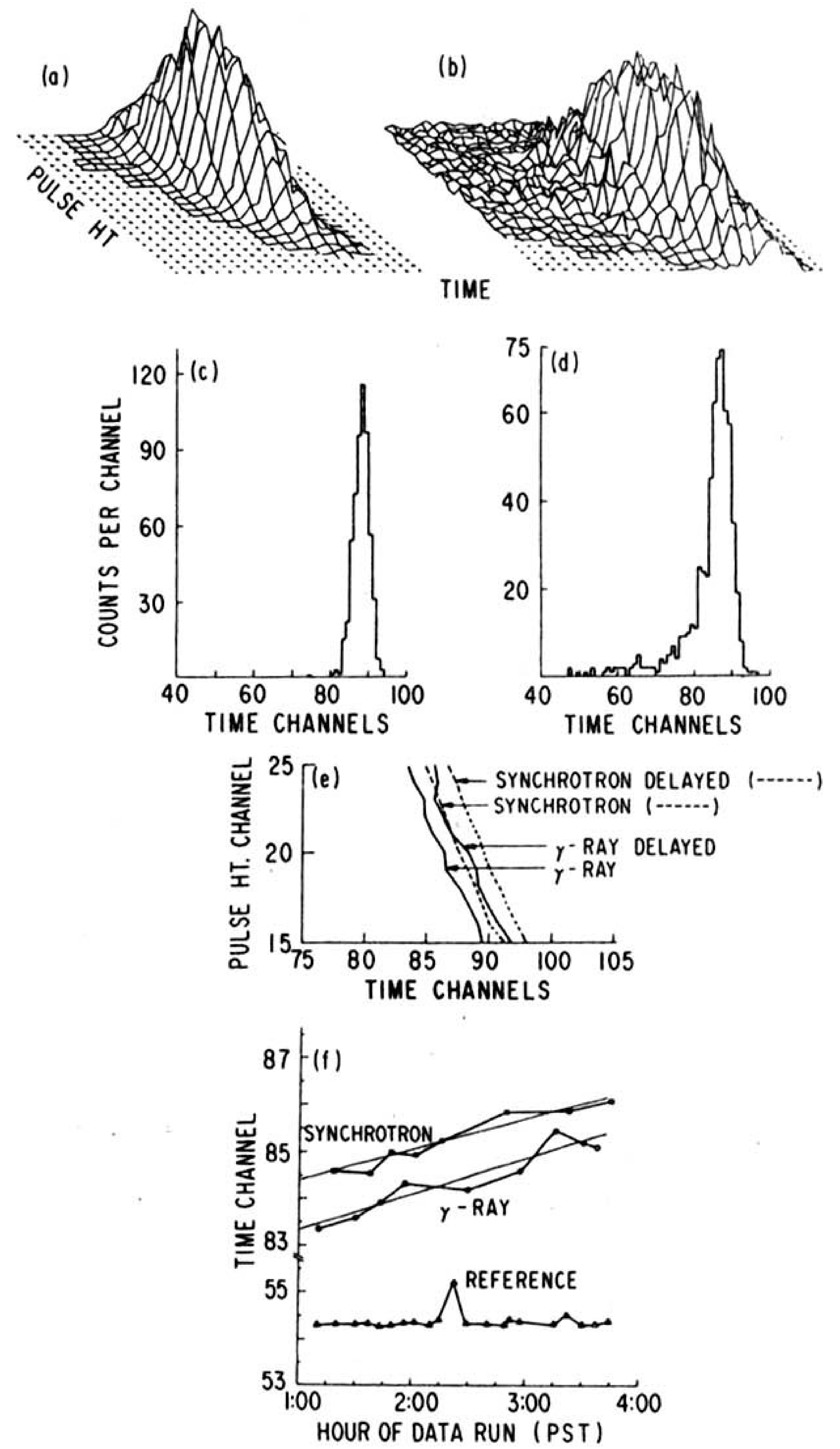

FIG. 2. (a) Two-dimensional pulse height versus time distribution for a typical synchrotron light run; and (b) for a γ-ray run. (c) and (d) are time distributions resulting from cuts on the two-dimensional distribution at the same pulse height. The calibration was 19.3 psec/channel, thus the synchrotron peak has a full width at half-maximum of ~95 psec. Note the early tail on the γ-ray distribution due to the background discussed in the text. (e) and (f) are discussed in the text. In (f), the straight lines are the best straight-line fits to the data; the reference is a check on the stability of the electronic system.

see that the synchrotron and γ-ray curves are parallel and that the delay shifts both curves in time by the same amount. To summarize the data for each run, we fitted the time-pulse height curve for pulse height channels 15 to 25 with a straight line and extracted the fitted time for pulse height channel 24. For the main series of runs this fitted time is plotted in Fig. 2(f).

In order to extract a velocity comparison from this data we must compensate for the drift of the TOF system, correct for known optical path differences, and determine the effects of the background on the time-of-flight peak. The latter were studied using a computer model for the PM-electronics system. We concluded that the time distributions were adequately explained (by the model), that no correction need be applied to the measured time difference, and that an error of 25 psec should allow for uncertainties in the simulation.[9] The net time difference is calculated as follows:

$$\Delta t = t_{eV} - t_{GeV} = (\text{observed difference}) + (\text{optical path corrections}) + (\text{background effects})$$
$$= (17.6 \pm 5)\ \text{psec} + (-9.8 \pm 3)\ \text{psec} + (0 \pm 25)\ \text{psec} = (7.8 \pm 25)\ \text{psec}.$$

Since the flight path was 4300 ft, the flight time was 4.3 μsec, giving

$$\frac{c(\text{GeV}) - c(\text{eV})}{c(\text{eV})} \equiv \frac{\Delta c}{c} = \frac{\Delta t}{t} = \frac{(7.8 \pm 25)\times 10^{-12}}{4.3 \times 10^{-6}} = (1.8 \pm 6)\times 10^{-6}.$$

Thus, we see no evidence for a vacuum dispersion in this experiment. Using γ rays from π^0 mesons, previous workers[2] had determined the velocity of 6-GeV γ rays. Their result agreed with optical and microwave determinations with errors of ~130 parts per million. Studies of pulsar data also allow one to set stringent limits on vacuum dispersion,[10] but reports of observations of γ rays above a few MeV energy have been controversial.[11] Although models for a vacuum dispersion have been proposed and discussed,[12] all existing data support the constancy of the velocity of light.

With the same detection apparatus we also compared the velocity of 11-GeV electrons to the velocity of visible light. This was carried out by alternating the usual synchrotron light runs in which the electron beam produced light at Sector 19 with runs in which the electrons traveled the additional 3600 ft to the beam switch yard (BSY). Bending the electrons at this point with the usual BSY magnets also produced synchrotron light. Comparing the synchrotron light arrival time from these two different source points allows one to compare the velocities of electrons and light. The result of this measurement gives a time difference $\Delta t = -4.6 \pm 9.6$ psec. The flight time, t, was 3.6 μsec giving $(c - v_e)/c = \Delta t/t = (-1.3 \pm 2.7) \times 10^{-6}$. Since special relativity would predict $(c - v_e)/c \simeq m_e^2/2E_e^2 \approx 10^{-9}$, we have in effect shown that the limiting (asymptotic) velocity for electrons is approximately the velocity of light.

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[1]Further details are available in B. C. Brown, thesis, University of California at San Diego, 1973 (unpublished).

[2]An excellent review of the determinations of the velocity of light is available in L. Essen and K. D. Froome, *The Velocity of Light and Radio Waves*, (Academic, New York, 1969). The most recent determinations using laser techniques are reported in Z. Bay *et al.*, Phys. Rev. Lett. 29, 189 (1973); K. M. Evenson *et al.*, Phys. Rev. Lett. 29, 1346 (1972). A measurement with 6-GeV photons is reported by T. Alväger *et al.*, Ark. Fys. 31, 145 (1966).

[3]For a description of the Stanford Linear Accelerator, see *The Stanford Two-Mile Accelerator*, edited by R. B. Neal (Benjamin, New York, 1968).

[4]Although the production of the synchrotron and γ radiation does not occur at precisely the same point, this introduces a negligible correction ($< 10^{-14}$ sec) in the time-of-flight difference since the electrons (which produce both radiations) are moving at nearly c.

[5]The pressure of the gas Cherenkov counter was remotely controlled. For detection of positrons, it was pressurized to 15 atm of N_2. For synchrotron detection it was filled with 1 atm of He—ensuring that charged particles would not produce Cherenkov radiation.

[6]For this experiment, the accelerator was operated in the beam knockout mode in which a single rf bunch of approximately 10^9 electrons (and a time spread ~5 psec) are accelerated every 1/360 sec.

[7]The presence of a γ-ray background was evidenced by the fact that 20% of the total signal remained when S_4 was inserted (see Fig. 1). Removal of T_1 demonstrated that both signal and background were produced from

the primary target. The reason the synchrotron signal had so little background is that T_1 was retracted for synchrotron runs. Tests indicated that the background was probably caused by bremsstrahlung radiation directly exciting the photocathode. The PM was masked so that the signal could excite only the central portion of the photocathode, whereas the background could excite all parts of the photocathode resulting in early background pulses due to transit time differences.

[8]The optical delay consisted of a 1-in. Lucite window which could be inserted after S_4, delaying optical light by 40 psec.

[9]The background limitations on the present experiment could perhaps be eliminated by better shielding or by adding a 10-nsec delay to the optical signal path to allow the PM to recover from the background radiations. Limitations due to resolution and drift of perhaps 5 psec with the present data system seem reasonable.

[10]Z. Bay and J. P. White, Phys. Rev. D 5, 796 (1972); G. Feinberg, Science 166, 879 (1969); J. M. Rawls, Phys. Rev. D 5, 487 (1972).

[11]J. E. Grindlay, Astrophys. J. 174, L9 (1972); J. V. Jelley, in *The Crab Nebula*, edited by R. D. Davies and F. G. Smith (Springer, Berlin, 1971), p. 32; T. C. Weeks *et al.*, Astrophys. J. 174, 165 (1972).

[12]B. C. Brown, Nature (London) 224, 1189 (1969); T. C. Pavlopoulos, Phys. Rev. 159, 1106 (1967), and Nuovo Cimento 60B, 93 (1969).

Study of the Inclusive Reaction $p+p \to p+X$ between 40 and 260 GeV/c Using an Internal H_2 Jet Target*†

F. Sannes, T. De Lillo, M. Lieberman, J. Mueller, and B. Robinson
Rutgers University, New Brunswick, New Jersey 08903

and

I. Siotis‡
Imperial College of Science, London SW7, United Kingdom

and

G. Cvijanovich
Upsala College, East Orange, New Jersey 07019

and

A. Pagnamenta and R. Stanek
University of Illinois, Chicago, Illinois 60680
(Received 26 December 1972)

We have measured the relative energy dependence of the invariant cross section for the inclusive reaction $p+p \to p+X$ for $0.05 \leq M_X^2/s \leq 0.22$ at $t=-0.33$ and -0.45 GeV^2. The energy range from $s=80$ to 480 GeV^2 was covered continuously by taking data during the acceleration ramp of the National Accelerator Laboratory machine. The data are compared with the diffractive-excitation and Regge models.

We have measured the s and M_X^2 dependence of the invariant cross section for the single-particle inclusive reaction

$$p+p \to p+X \quad (1+2 \to 3+X) \tag{1}$$

(X = anything) at the National Accelerator Laboratory (NAL) using the acceleration ramp from $P_{\text{lab}} = 40$ to 260 GeV/c and the internal H_2 jet[1] target. Recoil protons from Reaction (1), with $55° < \theta_3 < 65°$ in the lab, exit the main accelerator beam pipe through a 3-mil Ti window and are detected in a counter-range telescope (Fig. 1). Two recoil momentum bites are selected simultaneously by means of three Al absorbers, the trigger logic being $C_1C_2C_3C_4C_5\overline{C}_6$ and $C_1C_2C_3C_4C_5C_6\overline{C}_7$. The protons of interest have $560 < P_3 < 660$ MeV/c and $660 < P_3 < 780$ MeV/c and are $\simeq 2.5$ and $\simeq 2.0$ times minimum ionizing, respectively. They are distinguished from π's of the same ranges by means of time of flight between counters C_1 and C_4 and pulse height in counters C_1–C_5.

The H_2 jet target is essentially a vertical cylinder of ~10 mm diameter. It is pulsed for 250 msec twice during the 2.5-sec acceleration ramp of the machine. The H_2 jet density is roughly 2×10^{-7} g/cm^3, and may vary up to a factor of 2 over a period of a few hours. Above 40 GeV/c the circulating beam profile is an ellipse with ap-