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Relative Velocity Measurements of Electrons and Gamma Rays at 15 GeV

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Measurements were made to detect differences in the velocity of propagation of γ rays and electrons in the energy range 15–20 GeV, by using a time-of-flight technique with 1-psec sensitivity and a flight path of ~ 1 km. A relative velocity difference larger than $1-\beta_e$ ($\sim 5\times10^{-10}$) would imply a breakdown of special relativity. No significant difference in the velocities of light and electrons was observed to within ~ 2 parts in 10^7.

Previous efforts have been made to detect a frequency-dependent shift in the velocity of light from visible wavelengths up to GeV energies. All such experiments are in essence attempts to detect some departure from the predictions of special relativity.

The most recent contribution preceding the present work was made by Brown *et al.*[1] Using a time-of-flight (TOF) technique, they compared the velocities of short pulses of visible light and 7-GeV γ rays. The results gave a relative velocity difference of $(1.8\pm6)\times10^{-6}$. An additional measurement using 11-GeV electrons and visible light gave a relative velocity difference of $(-1.2\pm2.7)\times10^{-6}$. The precision of these measurements was limited in part by the time resolution of photomultiplier detectors.

In the present experiment at the Stanford Linear Accelerator Center the relative velocities of ~ 15-GeV γ rays and electrons with energies ranging from 15 to 20.5 GeV were measured by using an rf separator (RFS) synchronized with the accelerator's rf system as the timing element. Ultimate time resolution was limited, in part, by the characteristic bunch length of the Stanford Linear Accelerator Center beams, ~ 5 psec or 5 deg of rf phase. Results more than 1 order of magnitude smaller in $\Delta v/c$ at energies higher than the previous best measurements were achieved.

Electrons accelerated to 15 GeV in about $\frac{2}{3}$ of the full length of the accelerator strike a thin, annular target at the end of sector 22, scatter, and produce bremsstrahlung photons [Fig. 1(a)]. Measurements were made both with and without further acceleration. With acceleration, electron energy increased continuously to 20.5 GeV at the end of the accelerator. After a common flight path of 1015 m a small fraction of the photons and scattered electrons strike two thin targets which serve as positron sources for the beam transport system [Fig. 1(b)]. The upstream (downstream) target fills the upper (lower) half of the beam aperture. Their axial displacement within the field of vertical bending magnet B60, in conjunction with subsequent collimation and momentum analysis, is such that only 13.5-GeV positrons produced by electrons (photons) in the upper (lower) target are retained in the transport

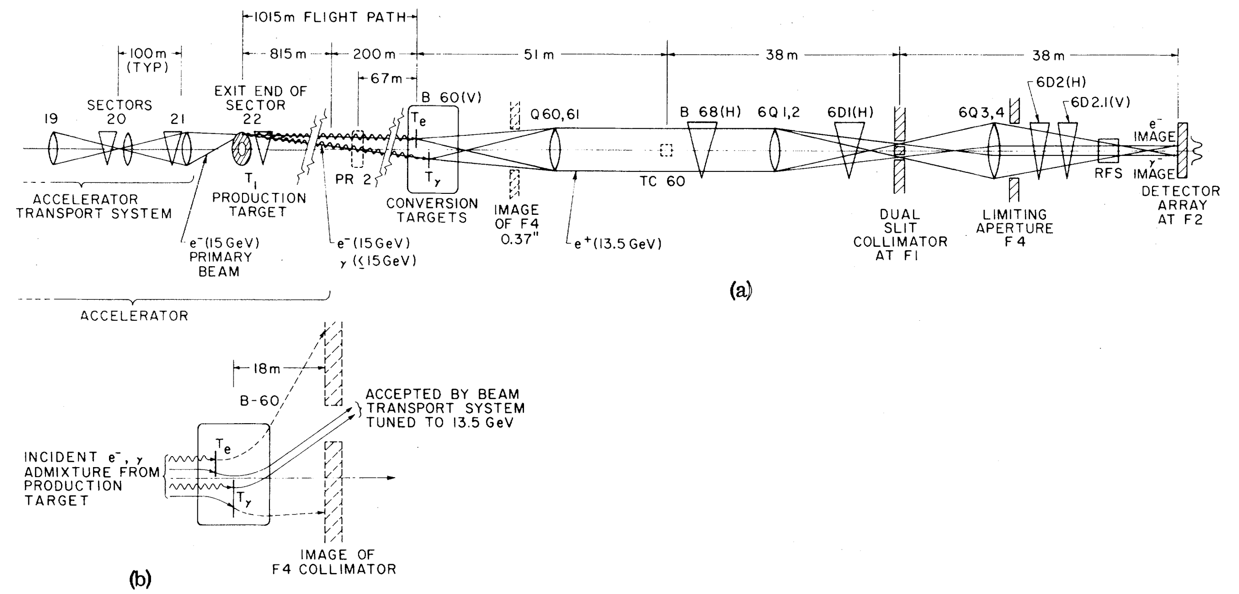

FIG. 1. (a) Accelerator and beam transport systems (vertical plane). (b) Separation of e^- and γ beams and rejection of background at the conversion targets within the magnetic field of B60 (vertical plane).

system. Images of the upper (lower) target cover the lower (upper) slits of a dual-slit collimator located at F1. This collimator is in turn imaged on the detector at the second focus of the secondary beam just downstream of the RFS. The final images consist of two horizontal strips where positrons comprising the upper (lower) image were produced by electrons (photons). The RFS provides an effective transverse deflecting field uniform over the wave-guide aperture,[2] imparting a transverse momentum to an extremely relativistic particle dependent only upon the particle's arrival time relative to the RFS phase. With the phase set for null deflection, the maximum deflection sensitivity at 13.5 GeV/c is 0.0070 in. per degree of phase, or 0.0068 in./psec.

Thus, an e^--γ TOF difference would be manifested as a change in the separation of the e^- and γ images when the RFS is turned on. The typical full width at half-maximum of the images was 0.070 in. with approximately equal contributions from random phase spread, finite image size, and miscellaneous aberrations. This width corresponds to $\Delta v/c \sim 1.5\times10^{-6}$ for a drift length of 1015 m. Random TOF differences between e^- and γ positrons within the secondary beam transport system (due mainly to horizontal dispersion) have an rms value ~1 psec. The correlated TOF difference (due to the fact that e^- and γ positrons occupy different regions of phase space in the vertical plane) was < 0.1 psec and would simulate the effect of a true $(v_e - v_\gamma)/c \sim -3\times10^{-8}$.

It is an important fact that the beam striking the target at sector 22 is scattered by angles large compared with the acceptance angle of the B60 targets and consequently that the time phase of both the electrons and the γ's at B60 is statistically representative of the average time phase of the incident electron beam with negligible uncertainty. We believe that on one occasion we experienced an effect due to anomalous electron flux from a portion of the beam passing through the center of the annular target, but on most occasions we are also certain that such an effect could not have occurred because electron beam steering at sector 22 was such that an unscattered beam could not have been transmitted to the B60 targets. No other systematic effects known to us could have affected the measurements significantly.

Background photons produced beyond the sector-22 target could not be identified during a measurement. But an attempt was made to estimate the highest possible background contamination before and after each run by steering the beam into the walls of the accelerator downstream of sector 22 with the target removed. Under these conditions, the electron rate was negligible, while the γ rate fell to about 15% of normal. We have made the conservative assumption that the worst-case background (15%) prevailed in all measurements and have corrected our timing sensitivity accordingly.

A multiwire proportional chamber located at the second focus measured the vertical coordinate of each positron on an event-by-event basis. The differential linearity of the device is measured to be about 40 μm (0.0016 in.). The resolution for a single event can be estimated to be 100 μm (0.0040 in.) from the intrinsic signal-to-noise limitation of the position encoding electronics. More detailed discussions of the beam line and the multiwire proportional chamber as well as theoretical implications of the results can be found elsewhere.[3,4]

Figure 2 shows the profile obtained with an ^{55}Fe double-slit test source (0.020-in. slits with a mean separation of 0.2998 in.). Figures 2(b) and 2(c) show the typical γ (e^-) profile obtained with the γ (e^-) targets separately, demonstrating that crosstalk between images is negligible.

A large number of independent measurements were made each consisting of three sets of e^--γ profiles, one with RFS off, and two with RFS on, one at each of the two maximally sensitive phases. The data were analyzed by two methods.

Method 1.—The coordinates of all events are histogrammed and the separation of the γ and e^- images is determined for each RFS phase by fitting the double-peaked profiles [Fig. 2(d)] with convenient line shapes parametrized in terms of the amplitude, mean, and width of the two images. The relative e^--γ velocity difference deduced from such a measurement can be expressed as

$$\Delta v/c = \pm A^{-1} f (S^{\pm} - S^0)/Lc = A^{-1} f (S^+ - S^-)/2Lc. \quad (1)$$

where $S^{\pm}$ is the e^--γ peak separation in each of the two maximally sensitive RFS phase settings, S^0 is the RFS-off peak separation, A is the deflection sensitivity of the RFS, L is the drift length, and $1 < f < 1.6$ is a correction factor that accounts for the assumed 15% γ background and losses in timing sensitivity due to incomplete temporal overlap of the RFS gating (on occasion part of the beam spill was accidentally allowed to fall outside the RFS pulse). For each complete set of data $S^+ - S^- = \Delta S$ and $\Delta v/c$ are determined.

Method 2.—From the same data as above, the difference of coordinates of electron and γ events that occur only in temporal succession, at constant RFS phase, is histogrammed. This yields a single-peak profile [Fig. 2(e)] with a well-de-

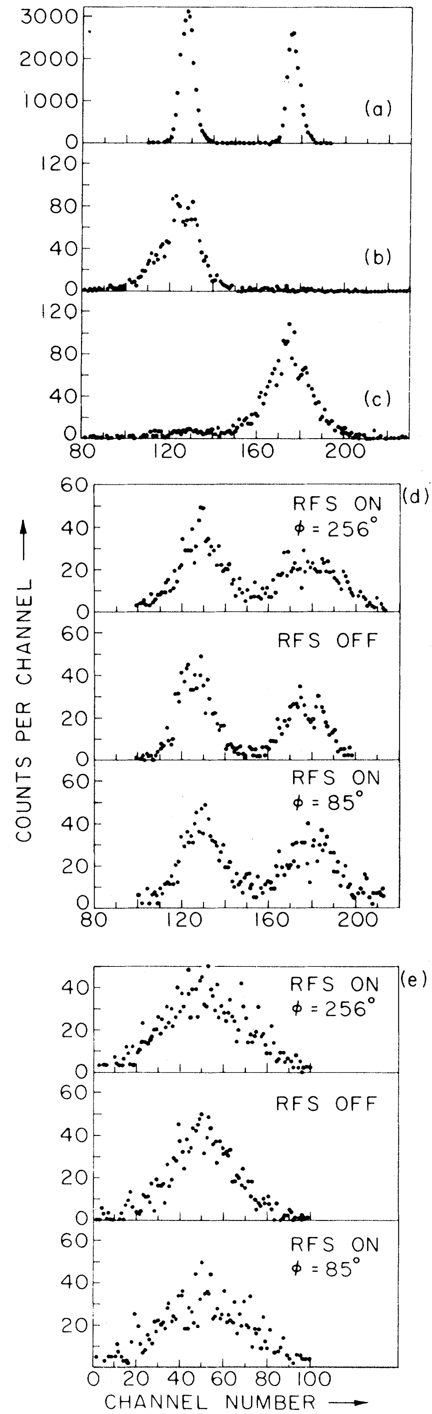

FIG. 2. Detector performance and typical experimental data. One channel represents 6.4×10^{-3} in. (a) ^{55}Fe double-slit position spectrum. (b) γ image alone (e^- conversion target removed). (c) e^- image alone (γ conversion target removed). (d) Typical experimental spectra of e^- and γ images. (e) Difference spectra of above data (in this example, one channel represents 0.55 psec).

TABLE I. Experimental results: difference of the high-phase and low-phase e^--γ peak separations, arrival-time difference corrected for timing sensitivity, and the relative e^--γ velocity difference inferred therefrom. Uncertainties are observed standard deviations for the number of measurements indicated.

Experiment	No. of measurements	No. of events	Analysis method	Mean gamma energy (GeV)	E_{e^-} (GeV)	L (m)	$S^+ - S^-$ (10^{-3} in.)	Δt[a] (psec)	$\Delta v/c$ (10^{-7})
1	2	10 266	1	⋯	⋯	⋯	-1.3 ± 3.1	-0.17 ± 0.40	⋯
2	4	13 176	1	14.2	15	67	4.6 ± 3.4	0.60 ± 0.44	13 ± 10
3	8	28 887	2	14.2	15	1015	-2.29 ± 3.12	-0.37 ± 0.32	-1.22 ± 1.05
4	3	11 828	2	14.2	15–20.5	1015	4.70 ± 4.65	0.38 ± 0.58	1.25 ± 1.91
4′	5	19 756	2	14.2	15–20.5	1015	-15.7 ± 13.7	-1.63 ± 1.75	-5.36 ± 5.75

[a]The relationship of Δt and ΔS and their uncertainties is not proportional because the timing sensitivity f varies from measurement to measurement.

fined mean that does not require fitting, and is entirely independent of RFS phase and steering changes occurring over times long compared with the time between events.

Averages and standard deviations of $\Delta v/c$ for all independent measurements in each of several different experimental conditions are then calculated with statistical weighting. For method 1, the observed spread of ΔS_t was typically the order of twice the expected statistical fluctuation whereas for method 2, the observed and statistical standard deviations agree. This indicates that time-dependent fluctuations of unknown origin in the separation of the images (comparable in magnitude with our statistical uncertainties) did occur, but that by comparison only of events that are temporal neighbors the effects of these fluctuations are entirely removed.

In Table I results obtained in each of the experimental configurations are given. The first row in the table is the result of a test in which the B60 targets are removed and a conventional target [TC60 in Fig. 1(a)] is used instead to illuminate uniformly the dual-slit collimator at F1. This simulates the "e^--γ" beams in the last stage of the system and was done primarily to demonstrate the potential precision of the experiment.

The second row is the result of another test where a thin target [PR2 in Fig. 1(a)] located a short distance upstream of B60 is used instead of the sector-22 production target. This was done to check e^--γ identification, isochronism of the positron beam line, and mechanics of data taking.

The remaining results shown in the table are obtained in the final experimental configuration with the sector-22 production target in place, and with use of the full drift length of 1015 m. In experiment No. 3, electrons drift the last third of the accelerator, while in No. 4 and No. 4′ they are accelerated to 20.5 GeV. In No. 4 anomalous data obtained on one occasion as a result of targeting difficulties at sector 22 are omitted, while in No. 4′ all data are included.

Taken as a whole, we interpret these results to indicate equality of the velocities of propagation of γ rays and electrons in the energy range 15–20 GeV to within ~2 parts in 10^7, where a relative difference greater than $1 - \beta_e = 5 \times 10^{-10}$ would be significant.

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