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ELECTRON-POSITRON ANNIHILATION IN FLIGHT

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ABSTRACT

The positron-electron annihilation cross section has been measured for 50, 100, and 200 Mev incident positron energies. Three small proportional counters in a magnetic field determined the incident electron or positron momentum and a large scintillation counter immediately behind the absorber indicated the disappearance of a particle. The positron annihilation cross section was determined by subtracting the electron loss rate (due mainly to bremsstrahlung energy losses) from the positron loss rate. The cross sections obtained at 50, 100 and 200 Mev were, respectively, 11.0 ± 2.5, 6.3 ± 1.2, and 3.7 ± 0.6 millibarns per electron in a beryllium absorber, in good agreement with Dirac's two quantum annihilation cross section. The presence of annihilation radiation was detected in coincidence with the disappearance of a positron within a small cone in the forward direction.

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During the course of searching nuclear plates for electron-electron scattering events with 200 Mev incident electrons, Barkas, Deutsch, Gilbert and Violet[1] observed two events that corresponded to the disappearance in flight of a high energy electron. These two events appeared quite real with no plausible explanation.

The following experiment was done to gain more information about electron and positron disappearances in general and if possible to explain the two disappearance events observed above[2*].

At the outset it was well recognized that positrons should disappear in flight by annihilating with an electron at rest giving rise to two gamma rays. This is a second order process in electrodynamics and the theoretical cross section was known with some confidence[3]. It was therefore proposed at the beginning to try to observe the annihilation in flight of positrons by a balance type experiment comparing the "disappearance" cross section of positrons to that of electrons.

A thin radiator (placed in the magnetic field of the pair spectrometer) in the path of the bremsstrahlung beam of the synchrotron is an excellent symmetric source of high energy positrons and electrons. Reversing the direction of the magnetic field changes only the sign of the particles observed in

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* After the initiation of this work, a further search of plates exposed at the same time but at lower energy was made which showed more disappearances of one sign of particles and none of the other. The conclusion drawn in the erratum (ref. 2) above is that the magnetic field was somehow reversed and that the disappearances observed were annihilations of positrons in flight.

a given direction. The number and direction of the particles relative to the background should stay the same. With this symmetric type source a comparison could be made of the "poor geometry" adsorption of positrons versus electrons.

At this point it is necessary to consider the absorption processes involved when a 200 Mev electron or positron passes through matter. The known processes are:

1. Ionization loss
2. Bremsstrahlung or radiation loss
3. Multiple scattering
4. Single large angle scattering
5. Annihilation in flight (positrons only).

Inverse beta decay is theoretically too small to be considered a competing process. The first four processes should be essentially the same for positrons and electrons*. Therefore if we are looking for a difference in the absorption between positrons and electrons, the loss due to these processes should be made small, i.e. the absorber should be thin compared to the range and of low Z. Processes 2, 3, and 4 are proportional to the square of the nuclear charge Z of the absorber, while the annihilation cross section is proportional to Z. For the experimental conditions of a low Z absorber ($Z < 10$), a solid angle of the absorber to the detector of 2π, and 50 to 200 Mev incident particles, processes 1, 3, and 4 are small compared to 2 and 5. Bremsstrahlung gives rise to an apparent absorption in the following manner. The incident electron or positron radiates a large fraction of its energy in one event leaving the primary particle with a small energy, say less than 5 Mev. If this residual energy is less than what is required for the particle to get

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* Electron-electron and positron-electron scattering are different but at high energy both processes cause only a very small angular deviation of the incident particle and so are not observed as an absorption.

out of the absorber into the detector, then the event appears as an absorption. The absorber thickness then had to be chosen so that the probability of bremsstrahlung loss by this process was smaller than the annihilation cross section. It turned out that 2 cm of Be gave a bremsstrahlung loss about 1/4 that of annihilation. Annihilation in flight would occur once in every 300 traversals of the absorber so that an extremely small loss had to be detected.

The apparatus used is schematically shown in Fig. 1. A, B, and C are three thin walled proportional counters* in triple coincidence that defined the presence of a particle of a given momentum. Counter D is a stilbene scintillation crystal 4 inches in diameter by 4 inches thick with a cylindrical well in it 2 cm deep to hold the absorber. With no absorber in place, every time a triple coincidence occurs showing that a particle has passed through A, B, C, a fourth pulse should be observed from counter D. The loss of particles between counter C and D is the triple coincidence rate minus the quadruple coincidence rate.

The sensitive volume of counters A, B, and C was roughly a sphere 1/4 inch in diameter. The alignment was performed both by maximizing the triples to singles ratio, and by accurately locating the counters on a circle, i.e. the orbit of a particle in the uniform magnetic field. Both methods agreed. The ratio of triples to counter C singles rate was roughly 40 percent, showing that the electrons or positrons had small deviation from their calculated orbits. Counter D was required to be extremely efficient if it was to introduce no additional loss factor. The efficiency of a scintillation counter is determined by both the bias setting of the pulse detector and by the number of photoelectrons ejected in the photo tube per incident particle. The

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* These were Victoreen geiger tubes cut down in length and refilled.

counter used had to have a long light pipe to remove the photo tube from the effects of the magnetic field, but in spite of this gave approximately 150 photoelectrons per incident particle. With the electronic bias set at a pulse height corresponding 10 to 15 photoelectrons, the statistical efficiency was better by many orders of magnitude than what was needed. The effective pulse size from a small gamma source was unchanged for +, 0, and - magnetic field showing that the photo tube was sufficiently shielded. The coincidence circuits and gate generators for each counter were standard in design with the exception that the gate generator for counter D had to have zero dead time. In order to record the triples minus the quadruple coincidence, it was felt at the beginning that a more reliable result could be obtained by recording both the triple and quadruple coincidences separately and then subtracting rather than using an anticoincidence circuit. In order to record reliably the large numbers associated with the triples and quadruples rates, three or more scalers were used in parallel for each.

The reduction of the background loss rate was the major problem in the success of the experiment. This turned out to be principally a counting rate problem, not just a chance coincidence one, but also dependent upon such effects as overloading amplifier D with a resulting change of bias and after pulsing of the small proportional counters. During normal running conditions a run of 3000 triples took 15 minutes with a background loss rate of 1 to 3 counts. Both the triples rate and loss rate were essentially entirely due to particles from the radiator. When the radiator was removed the triples rate was reduced by a factor of 800 and the loss rate relative to the primary synchrotron beam was reduced by approximately a factor of 4, so that background from surrounding objects did not have to be considered.

Results

Table I displays the results on disappearances. Many short runs of background and absorber were used to balance out the effects of changing background. Also the experiment was set up at three different times with at least a month's interval in between, and with different counters. The results were always consistent. The direction of the magnetic field was determined by the force on a current carrying wire and for no run with a low Z absorber was the electron loss rate as large as the positron loss rate.

The Be absorber was used the most to get statistically meaningful cross sections for the positron annihilation in flight process. LiH was used to check the Z dependence of disappearances at 100 and 200 Mev, but counting times were much longer due to its low density. Aluminum and silver absorbers showed too much bremsstrahlung loss at 200 Mev to get meaningful answers for the positron annihilation cross section, but the total loss for electrons was less by a factor of 5 than the cross section that could be ascribed to the two disappearances in nuclear plates. Similarly the electron loss cross section in beryllium and LiH at 200 Mev was less by a factor of 40 than the two disappearances in nuclear plates.

It was felt then that it had been reasonably established that electrons do not disappear in flight in low Z materials by a substantially large factor less than the two events observed in nuclear emulsion. Also, if the electron loss rate is subtracted from the positron loss rate, the remainder loss rate equals the theoretical annihilation cross section at 200, 100, and 50 Mev within statistical accuracy. There remained, however, the need for additional proof that the disappearances of positrons was associated with the annihilation in flight process.

Confirmation of Annihilation in Flight

When a high energy positron annihilates with an electron at rest, two high energy gamma rays are given off which are strongly correlated in the forward and backward direction in the center of mass system. In the laboratory system then, there is one gamma ray with nearly all the energy directed forward and another low energy gamma at large angle. It was attempted then to observe the high energy gamma ray going forward in coincidence with the disappearance of a positron in the beryllium absorber.

The disappearance or annihilation of the positrons in beryllium was observed essentially the same as before; namely, three counters A, B, and C in coincidence proved the presence of a high energy positron, while a fourth counter D monitored its passage through the absorber. However, instead of determining disappearances by the difference between two large coincidence rates (triples minus quadruples), an anticoincidence circuit was used which finally worked as reliably as the subtraction method. The anticoincidence pulse was then used in coincidence with a fifth counter, E. Counter E could be placed in two general positions: (1) the extrapolated positron trajectory in the magnetic field, and (2) the extrapolated gamma ray trajectory (namely, the tangent to the positron trajectory at the point of the absorber). With counter E in position (1), an efficiency was determined for counting 200 Mev positrons to be $\frac{\text{triples + counter E}}{\text{triples}} = 70$ percent. This efficiency dropped to less than one percent when counter E was moved to position (2), saying that position (2) was essentially outside the positron orbit. With counter E in position (2) in coincidence with the anticoincidence disappearance pulse, i.e., with counter E looking at the gamma ray trajectory in coincidence with annihilations, the ratio $\left(\frac{\text{anticoincidence and counter E}}{\text{anticoincidence}}\right)$ was less than 5 percent. Counter E was a thin wall proportional counter, and should not detect high energy gamma rays alone.

However, when 2-1/2 radiation lengths of lead (the maximum of the shower curve for 200 Mev gamma rays) was put in front of counter E in position (2), then the ratio $\left(\frac{\text{anticoincidence and counter E}}{\text{anticoincidence}}\right)$ increased to 50 ± 8 percent. This says that with counter E made sensitive to gamma rays we see a gamma pulse in coincidence with the positron annihilation. The half width of the positron curve for this ratio was approximately the width of the counter showing that the gamma rays were directly forward. When electrons were used, these ratios were essentially the same except that the disappearance rate for electrons was 1/4 that of positrons. The disappearance of electrons is due to high energy bremsstrahlung loss, which should give one high energy gamma going forward. These facts support the concept of positron annihilation in flight giving rise to at least one high energy gamma ray.

Acknowledgments

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References

1. W. Barkas, R. Deutsch, W. Gilbert, and C. Violet, "High Energy Electron-Electron Scattering", Phys. Rev. 86, 1, 59-63, (1952).
2. W. Barkas, R. Deutsch, W. Gilbert and C. Violet, Erratum, Phys. Rev. 86.
3. P. A. M. Dirac, Proc. Camb. Phil. Soc. 26, 361, (1930).

TABLE I

Particle	Energy	Absorber	Observed loss per 1000 traversals	Net loss minus background
positrons	200	Be	5.1	3.75 ± 0.5
positrons	200	none	1.4	
electrons	200	Be	0.77	0.1 ± 0.3
electrons	200	none	0.65	
positrons	100 Mev	Be	10.5	9.5 ± 1.0
positrons	100 Mev	none	1.0	
electrons	100 Mev	Be	3.7	3.2 ± 0.6
electrons	100 Mev	none	0.5	
positrons	50 Mev	Be	21.0	20.4 ± 2.0
positrons	50 Mev	none	0.6	
electrons	50 Mev	Be	10.0	9.4 ± 1.0
electrons	50 Mev	none	0.6	
positrons	200 Mev	2 inch LiH	2.8	2.0 ± 0.4
positrons	200 Mev	none	0.8	
electrons	200 Mev	2 inch LiH	1.0	0.7 ± 0.3
electrons	200 Mev	none	0.3	
electrons	200 Mev	2 inch Al	4.5	3.8 ± 0.6
electrons	200 Mev	none	0.7	
electrons	200 Mev	3.7 g/cm^2 Ag	4.2	3.0 ± 0.6
electrons	200 Mev	none	0.7	

TABLE I (cont.)

Positron loss minus electron loss per 1000 traversals	Energy	Absorber	Experimental cross section per electron of absorber in millibarns	Theoretical positron annihilation cross section per electron of absorber in millibarns
3.65 ± 0.6	200 Mev	Be	3.7 ± 0.6	3.53
6.3 ± 1.2	100 Mev	Be	6.3 ± 1.2	6.35
11.0 ± 2.5	50 Mev	Be	11.0 ± 2.5	10.8
1.3 ± 0.5	200 Mev	LiH	2.6 ± 1.0	3.53

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EXPERIMENTAL ARRANGEMENT

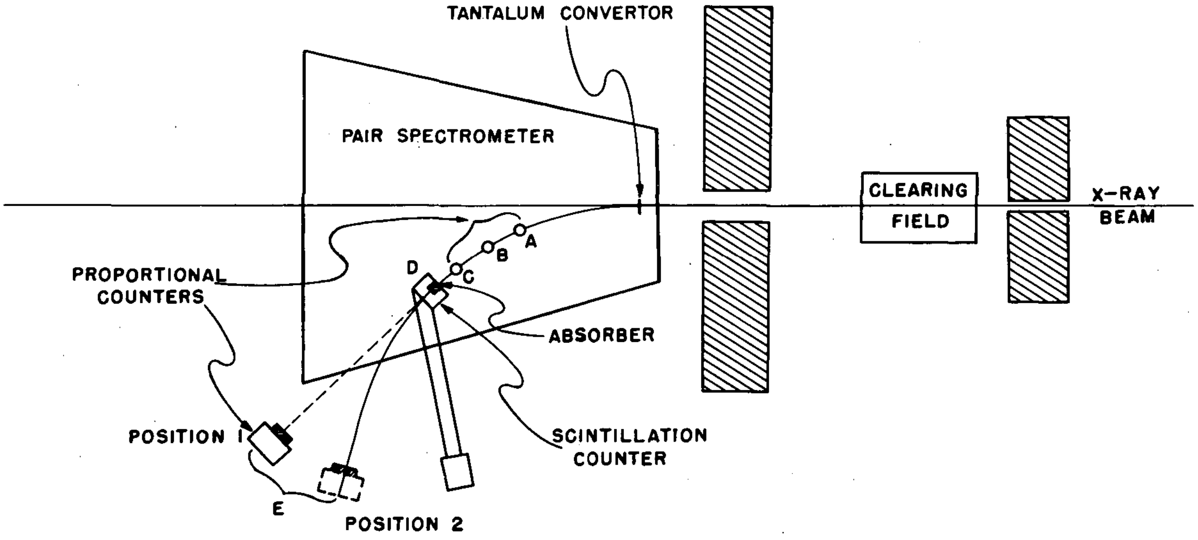

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Fig.1