Measurement of Electron Pairs for the Determination of a 65-Mev X-Ray Spectrum*

RICHARD H. STOKES†
Institute for Atomic Research and Department of Physics, Iowa State College, Ames, Iowa
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A magnetic cloud chamber has been used to observe electron pairs produced by the beam of a synchrotron operating at 65 Mev. The cross section for pair production given by the Bethe-Heitler theory was used to obtain the x-ray energy spectrum. The observed spectrum was in agreement with that expected theoretically. Values of the quantum and energy flux are given in terms of the reading of a Victoreen thimble ionization chamber.

INTRODUCTOIN

SEVERAL recent investigations[1-3] have measured the x-radiation produced by extreme relativistic electrons that are decelerated in heavy materials. These experiments show substantial agreement with the Bethe-Heitler theory at electron energies of 19.5, 309, and 322 Mev. The present investigation was undertaken at a peak energy of 65 Mev to study the energy spectrum and the quantum flux of the Iowa State College synchrotron operated with a tungsten target 0.005 inch thick. This information is of interest for a comparison with the results of the Bethe-Heitler theory and furnishes a basis for future studies of gamma-interactions with nuclei.

The experimental method consisted of the observation of electron pairs produced by the x-ray beam in the gas of a magnetic cloud chamber. The pairs were observed under conditions which allowed good curvature measurements to be made on both the electron and positron. The information thus obtained was used, together with the theoretical values of pair production cross section, to obtain the energy spectrum of the quanta. Two experimental investigations[4,5] at high energy indicate the reliability of the theoretical cross section for pair production.

APPARATUS

A 12-inch diameter cloud chamber and magnetic coils were used in the experiment. Air was used as the noncondensible component and a mixture of 1 part water and 2 parts ethyl alcohol was introduced into the chamber to provide the condensible vapor. Accurately regulated air pressure, admitted below a rubber diaphragm whose motion was not constrained, was used to compress the chamber. Expansion of the chamber was effected by opening a large capacity valve which rapidly reduced the chamber to atmospheric pressure. Line air pressure was used and was regulated by two stages of pressure reducers. A modified Hoke reducer designed for low pressures was used to achieve accurate regulation of expansion ratio. A three-dimensional description of the tracks was obtained by use of a stereoscopic attachment on the 35-mm camera lens. To obtain curvature measurements the tracks were projected through the optical system of the camera used to record them. A translucent screen arrangement similar to the one used by Brueckner *et al.*[6] allowed the radii of curvature to be measured.

A magnetic field was produced in the chamber by a pair of coils similar to the Helmholtz type. The mean radius of the coils was 30 cm and the cross section of the windings was 14.25 cm, radially, by 15.25 cm, axially. These are approximately in the ratio of the square root of 31 over 36, a uniformity condition suggested by the field expansions of Ruark and Peters.[7] Ference, Shaw, and Stephenson[8] have shown that a separation between coils less than that given by the Helmholtz condition is useful in producing a field of great uniformity over a considerable volume. With the measurements of Ference as a guide, calculations were made using the expansions of Ruark. This procedure showed that a 5 percent reduction of the separation was best for uniformity over the useful volume of the chamber. The field used in the experiment was uniform to one-half percent and had a value of 2500 gauss.

Each magnetic coil was constructed of 550 turns of 0.25-inch diameter copper tubing with a 0.065-inch wall thickness. The tubing had glass fiber insulation bonded with silicone varnish and was wound on brass coil forms. DC 996 silicone varnish was applied between successive layers and after the winding was completed the coils were baked in an oven to cure the varnish. Cooling of the coils was accomplished by passing soft water at 500 psi through the hollow conductors in 12 parallel paths. The paths were electrically separated by rubber hose sections.

The control system of the cloud chamber is shown in block diagram form in Fig. 1. This circuit synchronized the cloud-chamber expansion with a single x-ray pulse and provided the various delays necessary

* Contribution No. 151 from the Ames Laboratory of the AEC.
† Present address: Box 1663, Los Alamos, New Mexico.
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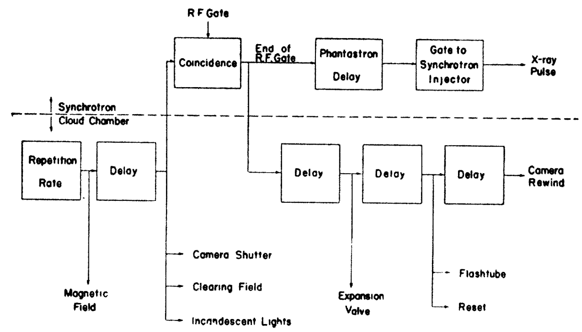

FIG. 1. Cloud-chamber control circuit—block diagram.

for cloud-chamber operation. As shown in the block diagram, after the magnetic field had been turned on, the cloud chamber interrogated the synchrotron and received an answer in the form of a pulse that was in definite phase relationship with the time of the x-radiation. This pulse, after delays in both the synchrotron and the cloud-chamber circuits, enabled the chamber to be expanded immediately prior to the x-ray pulse.

To eliminate difficulties with a high background of pair electrons, a collimated beam of radiation was allowed to enter the chamber through a beryllium window 0.005 inch thick. The collimator was a stack of lead bricks 18 inches thick with a hole five-eighths inch in diameter.

PROCEDURE

About 4000 photographs were recorded in obtaining the x-ray energy spectrum. The x-ray pulse intensity of the synchrotron was reduced by a factor of 50 to 100 from its peak value and was monitored by the ballistic deflection of an ionization chamber monitor. For monitoring that part of the data used to determine the number of quanta, a Victoreen thimble ionization chamber was used in a single-ended cylinder of lead one-eighth inch thick. Since the Victoreen chamber measures only large dosages of radiation, it was exposed with the synchrotron operating continuously and at high pulse intensity. The ionization chamber monitor was used, over a portion of its range known to be linear, to determine the ratio between the x-ray beam intensity at the high level of continuous operation and the low level beam intensity used to produce pairs in the cloud chamber.

From the reprojected tracks the radius of curvature was deduced from a measurement of the following quantities: the apparent radius of curvature, r', of a segment of the helical electron track as determined by matching a circle at each end and the midpoint, the length of the chord of this helical segment, K, and the angle, a, between the chord and a plane normal to the magnetic field. By use of the relation,

$$r/r'=\tfrac{1}{2}[1+\{1-(\tfrac{1}{2}K/r')^2\}^{\frac{1}{2}}]\cos^2 a +\tfrac{1}{2}[1-\{1-(\tfrac{1}{2}K/r')^2\}^{\frac{1}{2}}],$$

the radius of curvature, r, of the helix projected onto a plane normal to the magnetic field was computed. From the relation

$$\frac{\tan a'}{\tan a}=\frac{K\cos a/2r}{\sin^{-1}(K\cos a/2r)},$$

the pitch angle, a', of the helix was computed. The correction factor by which one multiplies the measured radius of curvature, r', to obtain the radius of curvature corresponding to the magnitude of the electron momentum, is

$$F=r/(r'\cos a').$$

For small values of $\frac{1}{2}K/r'$ this correction factor reduces to $\cos a$.

Due to the high energy of the quanta and the consequent strong forward-directed characteristic of the pairs, most of the electron tracks lay nearly in a plane normal to the magnetic field. A portion of the chamber near the window, 15.3 cm long, was used to detect pairs and all pairs that originated in this portion were measured. Under these conditions it was possible to observe sufficient length of track so that the percentage relative error of the radii of curvature would be limited. The criterion used was that all tracks have a ratio of chord length squared over radius of curvature greater than one centimeter. Of all observed pairs from 5–65 Mev, less than one percent failed to satisfy this requirement and thus no appreciable energy discrimination arose through accuracy requirements on the radius of curvature measurements. Measurements indicate that the maximum error in the radius of curvature measurement was about 15 percent and that most of the data had errors in the range 5–10 percent.

RESULTS

The number of pairs, N, and the corresponding energy interval are shown in Table I. For the mid-energy, E, of each of these intervals the relative cross section, σ, for pair production was read from the curve given by Bethe and Heitler.[9] The curve used was the

TABLE I. Energy spectrum.

Total energy of pairs in Mev	N	σ	$\frac{NE}{\sigma}$	$\Delta\% =\frac{100}{\sqrt{N}}$
5– 9.9	123	2.90	318	9
10–14.9	119	4.35	344	9
15–19.9	90	5.20	303	10
20–24.9	67	5.90	255	12
25–29.9	64	6.50	270	12
30–34.9	59	7.10	270	13
35–39.9	44	7.50	220	15
40–44.9	52	7.80	283	14
45–49.9	46	8.10	270	15
50–54.9	36	8.30	227	17
55–59.9	32	8.55	215	18
60–64.9	20	8.80	142	22
65–67.4	3	9.00	22.1	58

[9] H. Bethe and W. Heitler, Proc. Roy. Soc. (London) A146, 83 (1934).

one for H_2O, which is slightly different from the unscreened case at the highest energies. In each energy interval the number of pairs is multiplied by the total energy, E, and divided by σ. These relative values of the x-ray energy spectrum are shown in Fig. 2. The solid curve is the Bethe-Heitler bremsstrahlung energy spectrum for air as obtained from Rossi and Greisen.[10] An upper limit of 65 Mev was used for this curve, corresponding to the operating conditions of the synchrotron as given by a calibration chart which has as a basis the measurement of the synchrotron field strength at the time the electron beam strikes the target.

All data were taken with the cloud-chamber magnetic field at nearly the same value. This situation causes some discrimation at the lowest energies due mainly to a decreasing ability to identify pairs. When pronounced inequalities in the energy division between members of a pair occur, the low energy positron, a small circle, can be missed, either due to overlapping with other tracks or because it makes a large angle with a plane normal to the magnetic field. The lowest energy experimental point is affected appreciably in this way.

The data were observed by observing a portion of the center of the synchrotron beam having an angular width small with respect to the total beam width. Schiff[11] has shown that the x-ray beam width of electron accelerators usually is determined not entirely by the characteristics of the radiation process, but also by the multiple scattering of the electrons in the target before the radiation occurs. This latter effect produces an effective integration over the angles of quantum emission and makes it reasonable to compare the experimental data with the Bethe-Heitler curve which represents values of cross section integrated over all angles. In the present case calculations and measurements indicate that the over-all beam width is due at least as much to multiple scattering as to the inherent nature of the bremsstrahlung process in an infinitely thin target.

When a comparison of the experimental points with the curve of Fig. 2 is made, two facts should be recognized. First, it is clear that one should compare the experimental points with the average value of the curve over the 5-Mev interval. The difference between the averaged value and the value of the curve at the center of the interval is small, however, except for the interval 60–65 Mev. In this case the averaged value is about 15 percent lower then the value at the center, but still falls within the statistical accuracy of the experimental point. The second point to be considered is the distortion that arises from the finite energy resolution of the cloud chamber. The general magnitude of this resolution has been indicated, but an exact determination has not been attempted due to the variety of track lengths

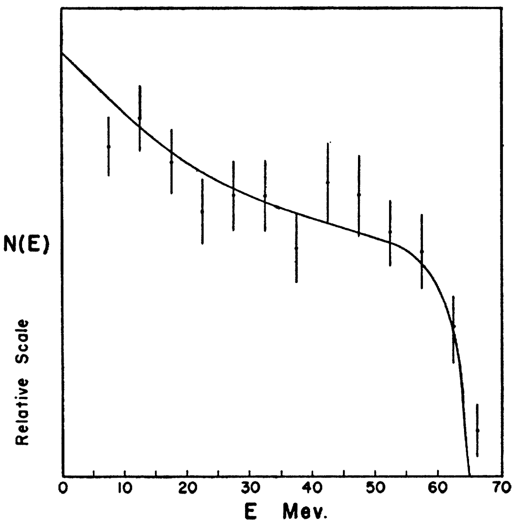

FIG. 2. Synchrotron energy spectrum.

contributing to each energy interval. The energy resolution effect causes the greatest distortion at the upper end of the spectrum and, if corrected for, would tend to raise slightly the experimental point at 62.5 Mev. The effect of both these corrections would be in the direction of making the spectrum fall off more sharply at the upper limit. This agrees with the suggestions of Heitler[12] and of Guth,[13] that if the correct wave functions were used in the theory, the upper end of the bremsstrahlung spectrum would probably tend to a finite limit.

The value for the quantum flux obtained was 6.6×10^7 quanta per square cm per r unit of the Victoreen chamber for the energy range 10–65 Mev. Corresponding to this value the energy flux is found to be 2.2×10^9 Mev per square cm per r unit for the energy range 0–65 Mev. These values have a statistical error of 20 percent. McMillan, Blocker, and Kenney[14] recently obtained results from the Berkeley synchrotron which can be used for a general comparison with the above value of the energy flux. McMillan's Victoreen chamber was in an open-ended cylinder one-eighth inch thick while our value was obtained with a single-ended cylinder of the same wall thickness. For the peak energies of 320 and 160 Mev, McMillan's values are, respectively, 3.3 and 2.2×10^9 Mev per square cm per r unit.

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