Spectral Analysis of 10-Mev Betatron Radiation by Nuclear Emulsion

P. K. S. WANG AND M. WIENER
National Bureau of Standards, Washington, D. C.
October 21, 1949

An attempt to determine the spectrum of the 10-Mev betatron at the Naval Ordnance Laboratory has been made. We recorded and measured the proton tracks from the photo-disintegration of deuterium absorbed into the nuclear emulsions.[1,2]

The emulsions were Ilford C_2, 100μ thick. After eradication of accumulated background,[3] the plates were soaked in D_2O for 20 minutes at 25°C, before exposure. Tests indicate that D_2O is reproducibly absorbed to the extent of 80 percent of the weight of emulsion before soaking and is uniformly distributed in the various layers of the emulsion. These plates along with a control plate similarly soaked in H_2O were then exposed perpendicularly to the axis of the x-ray beam for an exposure of approximately 0.3 roentgens as measured by a Victoreen thimble chamber without external cap. The distance of the plates from the target was about 1.5 meters. The exposure lasted for 12 seconds. Along with another blank control plate, these plates were immediately developed in a mild hydroquinone developer perfected by Yagoda.[4] The fog background of the exposed plates was very slight. This facilitated the scanning of the plates and the measurement of the tracks. There were about 2000 tracks on each of the D_2O loaded plates and very few ($\sim$30) on an H_2O loaded plate. The blank control plate showed the usual background of accumulated stars and tracks.

We measured 500 tracks on the D_2O plates and selected those tracks (312) which had a slope $\leq 45°$ in the wet emulsion. On an equal area of an H_2O loaded plate, only 7 tracks were found. Since the 100μ emulsion swelled to 380μ after soaking and then shrank to 40μ after processing, the depth component, d, of the measured track length was multiplied by a factor, 9.5, in order to determine the original slope of the track in the wet emulsion. The uncorrected data on these 312 tracks are shown in Fig. 1, along with the control plate data.

The probability of a track starting and ending within the emulsion depends on its length and slope. This probability is equal to the ratio $(t-d)/t$, where t is the emulsion thickness after development (40μ). To correct for this, each track was given a statistical weight $t/(t-d)$. As we have limited our acceptable track angles to $\leq 45°$, this is a small correction in most instances. The weighted histogram is shown in Fig. 2.

The range-energy relationship was calculated from the variation of stopping power with energy[5] for the wet plate. This relationship was checked experimentally with recoils from D$-$D neutrons obtained using 0.75-Mev deuterons from the 3-Mev Van de Graaf machine at the Department of Terrestrial Magnetism of the Carnegie Institution. Our relationship is good to ± 5 percent within the ranges we are considering. The rated maximum energy of the betatron is 10 Mev while the photon energy corresponding to the longest track is 11 Mev. According to information received, this is a reasonable value. In the following comparison with theory we assume the actual maximum energy to be 11.0 Mev.

The number of proton tracks, N_p, to be expected in our experiment within the range limits R_w and $R_w+\Delta R_w$ is related to the x-ray spectral intensity $I(E)\Delta E$ by the equation:

$$N_p = \frac{I(2E_p+2.2)}{2E_p+2.2}\sigma_{45°}{}^{135°}(2E_p+2.2)N_D 2(dE_p/dR_w)\Delta R_w A t,$$

where

E_p = energy of proton in Mev,

N_D = number of deuterons per cm² emulsion,

$$= 2\times 6.0\times 10^{23}\times\frac{(\text{g of } D_2O \text{ per cm}^2 \text{ emulsion})}{20},$$

dE_p/dR_w = stopping power of emulsion (Mev/μ),

$\sigma_{45°}{}^{135°}(E)$ = the cross section for photo-disintegration by a photon of energy E within our angular limits,

A = area of the emulsion examined,

t = time of exposure.

The theoretical histogram obtained using $I(E)\Delta E$ according to Schiff[6] with a suitable normalization and with the assumed maximum energy of 11.0 Mev is shown as a dotted line in Fig. 2 for comparison with the experimental data. The discrepancy at the low energies (<4.0 Mev) is at least partially due to the difficulty in finding all the short tracks. The excess over theory at

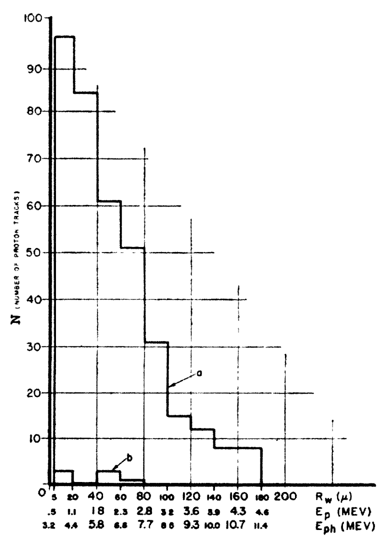

FIG. 1. (a) Histogram of data on D_2O loaded plates. Number of tracks, N, *vs.* range in wet emulsion, R_w, converted to energy of protons. E_p, and energy of incident photons, E_{ph}. (b) Histogram of data in H_2O loaded plate, equivalent area.

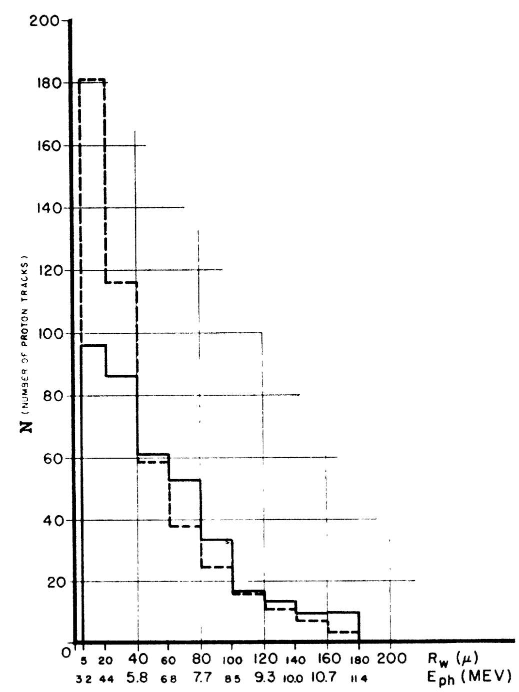

FIG. 2. Solid curve: Experimental histograms weighted for geometry. Dotted curve: Theoretical histogram from Schiff's calculations based on Bethe-Heitler theory and an assumed maximum energy of 11.0 Mev.

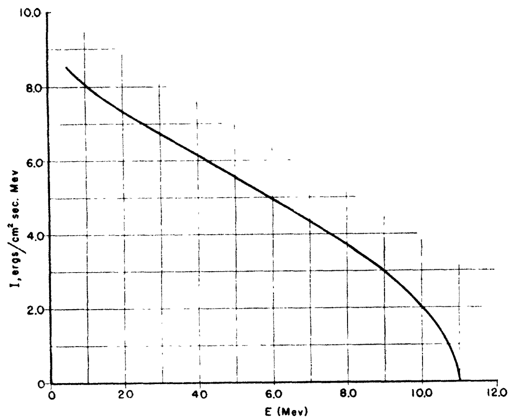

FIG. 3. Approximate intensity spectrum of the Naval Ordnance Laboratory betatron when run at "10 r/min. at 1 m," at 1.5 m from the target.

the high energies parallels results obtained at Illinois[7] at somewhat higher energies (20 Mev). If we assume the fit with Schiff's theory to be good enough, the comparison of the theoretical distribution with our experiment determines the approximate normalization factor. The intensity spectrum under the stated conditions in absolute units is given in Fig. 3.

We appreciate the kindness of Mr. D. T. O'Connor of the Naval Ordnance Laboratory for making the betatron available for our use. We wish also to extend our appreciation to Dr. U. Fano for several discussions and to Drs. N. P. Heydenburg and W. D. Whitehead for providing the D−D neutrons.

[1] W. Bosley, D. T. Cragg, *et al.*, Nature **161**, 1022 (1948).
[2] G. Goldhaber, Phys. Rev. **75**, 1725 (1949).
[3] M. Wiener and H. Yagoda, Phys. Rev. **76**, 469 (1949).
[4] H. Yagoda, Nucleonics **4**, 135 (1949).
[5] E.g., J. H. Webb, Phys. Rev. **74**, 511 (1948).
[6] L. I. Schiff, as reported by G. D. Adams, Phys. Rev. **74**, 1710 (1948).
[7] E. G. Fuller, Phys. Rev. **76**, 576 (1949).

The Excess of Negative over Positive Mesons Produced by High Energy Photons

K. A. BRUECKNER AND M. L. GOLDBERGER*
Radiation Laboratory, University of California, Berkeley, California
October 20, 1949

MESONS produced by the high energy photon beam from the University of California Radiation Laboratory 330 Mev synchrotron are found to show an excess of negatives over positives.[1] With a carbon target, observing mesons in the energy range 30–130 Mev at 90° to the photon beam, the ratio of negative to positive mesons is 1.7 ± 0.2 with no significant energy dependence.

A simple classical argument can be made to give an understanding of the reason for the negative excess. The photon can interact directly with the meson and proton through the current coupling

$$(\mathbf{j}\cdot\mathbf{A})(\text{meson})+(\mathbf{j}\cdot\mathbf{A})(\text{proton}).$$

The meson contribution is symmetrical for the production of positive and negative mesons. However, when positive mesons are produced, the proton is the initial nucleon at rest, and its current is zero. When negative mesons are produced, the proton is the final recoil nucleon giving a current contribution. Therefore, the cross sections for the production of positive and negative mesons are in the ratio

$$\frac{\sigma(\text{positives})}{\sigma(\text{negatives})}=\left[\frac{(\mathbf{j}\cdot\mathbf{A})(\text{meson})}{(\mathbf{j}\cdot\mathbf{A})(\text{meson})+(\mathbf{j}\cdot\mathbf{A})(\text{recoil proton})}\right]. \quad (1)$$

The current interaction is

$$\mathbf{j}\cdot\mathbf{A}=\frac{e\mathbf{v}\cdot\mathbf{A}}{1-(v/c)\cos\theta},$$

where

$\mathbf{v}$ = velocity of particle
$\mathbf{A}$ = vector potential
$\cos\theta$ = angle between direction of particle and photon.

This differs from the non-relativistic expression, $e\mathbf{v}\cdot\mathbf{A}$, the factor $1-v/c\cos$ in the denominator taking account of the retardation effects in the interaction of charge with the electromagnetic field. Inserting this current expression and using over-all energy and momentum conservation, the positive to negative ratio can be written

$$\frac{\sigma(\text{positives})}{\sigma(\text{negatives})}=\left[1-\frac{\epsilon}{\text{mc}^2}\left(1-\frac{v}{c}\cos\theta\right)\right]^2, \quad (2)$$

where

ϵ = meson energy including rest energy
v = meson velocity
θ = angle between direction of meson and photon
m = nucleon rest mass.

Further calculations have been carried out using standard perturbation theory for scalar and pseudoscalar mesons to the lowest order in the coupling constants g and e, treating the nucleons as Dirac particles and taking into account the effects of the nucleon recoil. The result of these calculations, for the ratio of the cross sections for positive and negative mesons, is exactly the same as that derived by the above simple considerations. Similar calculations for vector mesons with vector coupling to the nucleon field are complicated by the strong magnetic moment interaction of the vector particle with the e.m. field. The ratio of negative to positive mesons is similar to that for the scalar meson fields but is somewhat larger.

The effects of the Coulomb field of the nucleus on the production of mesons have also been investigated and found to be less than 5 percent for mesons with energies above 30 Mev.

The ratio of the cross sections for the production of negative and positive mesons given by (1) varies from 1.55 at 40 Mev to 1.83 at 100 Mev, at 90° to the photon beam. This agrees, within the probable error with the experimentally observed ratio. Since the positive-negative ratio depends in a quite direct way on the currents carried by the mesons and nucleons, a more accurate determination of the ratio and its energy dependence could provide valuable evidence concerning the magnetic moments of the particles.

* Now at Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts.
[1] McMillan, Peterson, and White (to be published in Science).

The Beta-Spectra of Cu^{64}

L. M. LANGER, R. D. MOFFAT, AND H. C. PRICE, JR.
Indiana University, Bloomington, Indiana
October 21, 1949

IN a previous paper,[1] results were reported which indicated that the negatron and positron spectra of Cu^{64} have more particles at low energy than is predicted by the Fermi theory of beta-decay. It was later reported by Wu and Albert[2] that this deviation appeared to be a function of the source thickness over the same range of values for which no such effect had been observed in the earlier work. Subsequently, we made a study of autoradiographs of sources prepared from chemical solutions. It was found that in general such sources, though appearing to be uniform, may in many cases have variations in intensity of as much as 100 to 1. Under these circumstances, the *average* thickness of a source as reported by different investigators does not have much meaning.

In order to remove this difficulty, we have attempted to remeasure the Cu^{64} spectra using sources prepared by thermal evaporation of metallic Cu in vacuum. Two sources were used.