PHYSICAL REVIEW VOLUME 98, NUMBER 5 JUNE 1, 1955

Measurement of the Čerenkov Radiation from Positive and Negative Pi Mesons*

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(Received February 16, 1955)

Čerenkov light pulses from individual π^+ and π^- mesons from the Chicago cyclotron have been measured by using photomultipliers and Lucite radiators. An analysis of the pulse-height distributions has been made for comparing the velocity dependence of the radiation with the predictions of classical theory. Theory and experiment are in substantial agreement. However, saturation was found to set in at a somewhat lower energy than theory predicts for an end-window type tube (Dumont type 6363). A search was made for a difference in the photoeffect produced by positive and negative particles radiating Čerenkov light. The effect was found to be less than about 3 percent, the limit of resolution being determined by magnetic effects on photomultiplier gain.

I. INTRODUCTION

A THEORETICAL treatment of Čerenkov radiation proceeds by the straightforward application of Maxwell's equations to a charge moving in a dielectric. The problem, treated originally by Frank and Tamm,[1] is now found in textbooks on electromagnetic theory and quantum mechanics.[2] Experiments have shown very close agreement with the predictions of theory on the angle of emission of the radiation.[3] Classical theory also predicts the radiation intensity as a function of the refractive index and velocity of the moving charge. This aspect of the theory is more difficult to test experimentally because of the problems associated with quantitative light intensity measurements at very low level.

Interest in the present measurements arose because Čerenkov counters have proven to be very useful tools in research on the primary cosmic radiation. The advantages include:

(a) Preferential response to fast particles: Below a certain cut-off velocity (e.g., $\beta=0.75$ for water) no radiation is emitted. This property discriminates against secondary effects, such as evaporation stars, which cause trouble in ionization-type measurements of primary cosmic rays.

(b) Like ionization effects (but for a different reason) the radiation intensity is proportional to Z^2, the atomic charge of the particle or nucleus, provided β is constant. This effect has been used to study protons and α particles in the primary cosmic radiation.[4,5]

(c) The correlation of direction of emission of the radiation with the direction of motion of the charged particle enables one to sense the direction of motion of particles of light velocity, and is a useful tool in measurements of cosmic-ray albedo.[6–8]

(d) Over a certain range of velocities (e.g., for water $0.75<\beta<1$) Čerenkov counters may be used as velocity spectrometers. Because of the low light intensity and limitations of present phototubes, the velocity analysis can be made in a statistical sense only.[9]

(e) Identification of the mass of the charged particle may be made in certain energy regions by auxiliary knowledge of its range. If a particle passes through the detector without a detectable Čerenkov signal, an upper limit may be set on its velocity from the relation $\beta n=1$, where $n=$ the refractive index. If the range, or the minimum range through the equipment is known, one may then bracket, or at least place a lower limit on the mass value.[6]

(f) Čerenkov counters may easily be adapted to balloon or rocket equipment for very high altitude observations.

An excellent summary of many uses of Čerenkov counters is contained in a paper by Marshall.[10]

One object of the present investigation was to examine under controlled conditions several Čerenkov detectors used in high-altitude measurements. In one of these measurements[9] the detector was to be used as a velocity spectrometer. It was therefore important to investigate (d) above, i.e., to determine how closely the velocity response of the counter matched the dependence predicted by classical theory. Measurements of slow protons and alpha particles in another experiment[7] could be improved by a more exact knowledge of the behavior of the Čerenkov counter near velocity cutoff. Thirdly, it was desired to investigate the response of Čerenkov detectors to the polarity of charge of the moving particle. It is known that the photoelectric effect is sensitive to the angle of incidence of the electric radiation vector, because the amount of absorbed radiation depends on this angle. It was thought possible that the orientation of the electric

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* This research supported in part by the joint program of the U. S. Atomic Energy Commission and the Office of Naval Research.

[1] I. Frank and I. Tamm, Compt. rend. **14**, 109 (1937).

[2] See, for example, L. I. Schiff, *Quantum Mechanics* (McGraw-Hill Book Company, Inc., New York, 1949), p. 261, and J. M. Jauch and K. M. Watson, Phys. Rev. **75**, 1249 (1949).

[3] R. L. Mather, Phys. Rev. **84**, 181 (1951).

[4] N. Horwitz, thesis, Minnesota, 1954 (unpublished); also Phys. Rev. **96**, 834(A) (1954). W. R. Weber, thesis, State University of Iowa, 1955 (unpublished).

[5] J. Linsley, Phys. Rev. **96**, 829(A) (1954).

[6] J. R. Winckler and K. Anderson, Phys. Rev. **93**, 596 (1954).

[7] K. A. Anderson, Phys. Rev. **96**, 829(A) (1954).

[8] L. Mezzetti and J. W. Keuffel, Phys. Rev. **95**, 858 (1954).

[9] E. N. Mitchell, Bull. Am. Phys. Soc. **30**, No. 1, 24 (1955).

[10] John Marshall, Ann. Revs. Nuclear Sci. **4**, 141–56 (1954).

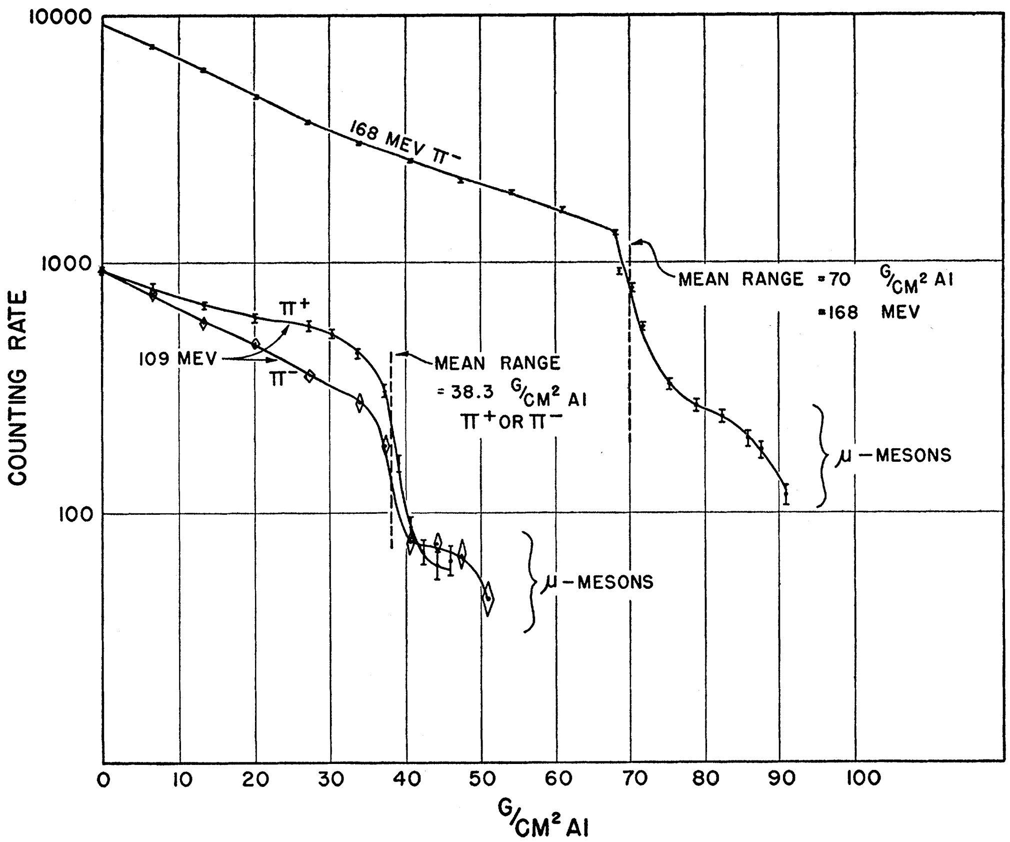

FIG. 1. Range curves for pions of two energies. These curves were taken by placing range blocks of aluminum between the twofold telescope and a larger area third scintillator in the beam after the analyzing magnet. The counting rate represents 3-folds per 10 000 (or 1000) 2-folds.

vector in the radiation from a positive moving charge might be 180° reversed, on the average, from that from a negative moving charge, and that the impulse given a photoelectron would, on the average, produce a different photoeffect for positive and negative particles of the same β. We owe the suggestion that such an effect might exist to Professor C. L. Critchfield.

II. EXPERIMENTAL METHOD

The source of particles consisted of the π-meson beams of the Chicago cyclotron. The π mesons had a sufficiently high upper velocity to cover a large part of the velocity-sensitive region for Lucite, and identical particles of both polarities were available. The momentum selection provided by the cyclotron fringing field and the slits in the radiation shield was improved by a 45° analyzing magnet. The beam was then defined and monitored by a pair of 1 in.×1 in.×$\frac{3}{8}$ in. plastic scintillation counters spaced 64 in. and 78 in. respectively from the analyzing magnet pole and in line with the maximum beam direction. These counters were connected through a twofold coincidence to a high-speed scaler, the resolving time being 3×10^{-7} sec. The Čerenkov detectors were placed directly after the second scintillator so that no beam particles missed the Čerenkov counters. The Čerenkov amplifier output was gated by the coincidence telescope and fed through an edge discriminator. A standard size pulse from the discriminator fed a second high-speed scaler, and the information was then extracted in the form of integral pulse-height curves from the Čerenkov counters. The number of pulses passing the discriminator was determined for various discrimination settings for a fixed number of telescope counts, usually 1000 or 10 000 for each beam energy. The beam energy was controlled by inserting copper or aluminum absorbers in the beam just ahead of the analyzing magnet, and adjusting the magnet current for maximum beam intensity for each absorber thickness. This method, which was adopted after numerous trials, produced apparently the smallest muon beam contamination at the counters.

The maximum beam energy was obtained from a range measurement. For this purpose the absorber slabs of aluminum or copper were placed just after the telescope, followed by a 3-in. diameter×$\frac{3}{8}$-in. thick plastic scintillation counter. Loss of beam through scattering in the absorbers was considerable, but a sufficiently sharp edge was obtained to fix the beam energy with satisfactory accuracy. Range curves were taken for the three types of beams utilized, namely for

109 Mev π^+, 109 Mev π^-, and 168 Mev π^-, and are shown in Fig. 1. From a knowledge of the maximum beam energy and amount of absorber ahead of the analyzing magnet, the various beam energies were determined. One such intermediate beam energy was checked by a range measurement after the analyzing magnet with very satisfactory agreement.

III. RESULTS

A. Velocity Dependence

The response of a Čerenkov counter composed of a Dumont type 6363 3-in. diameter end-window photomultiplier optically sealed to a 3-in. diameter×2-in. thick Lucite block is shown in Fig. 2. The block was painted black on the end, and the cylindrical surface was covered with aluminum foil sealed optically to the block with immersion oil. The tube was surrounded with a magnet shield of $\frac{1}{16}$-in. nickel alloy and a $\frac{1}{4}$-in. soft steel shield open at the end facing the beam. The pion beam passed through the block normal to the photosurface. The curves of Fig. 2 have been corrected for a small zero error in the discriminator and normalized as a group. The run was made in the 168-Mev beam with absorbers of copper to produce energies at the Čerenkov counter as indicated. The main qualitative features of the curves are as follows:

(1) The appearance is similar to that of a set of integral Poisson distributions with progressively decreasing average value of the parameter n as energy is decreased.

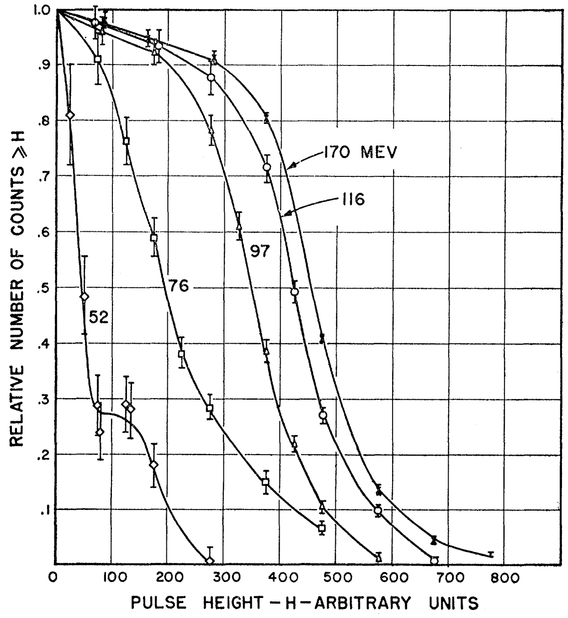

FIG. 2. Integral bias curves for end-window Čerenkov counter. Dumont 3-in. type 6363 photomultiplier. The curves represent number of Čerenkov pulses $>H$ as a function of H, for a fixed number (10 000 or 1000) of twofold telescope counts representing particles incident on the Čerenkov counter.

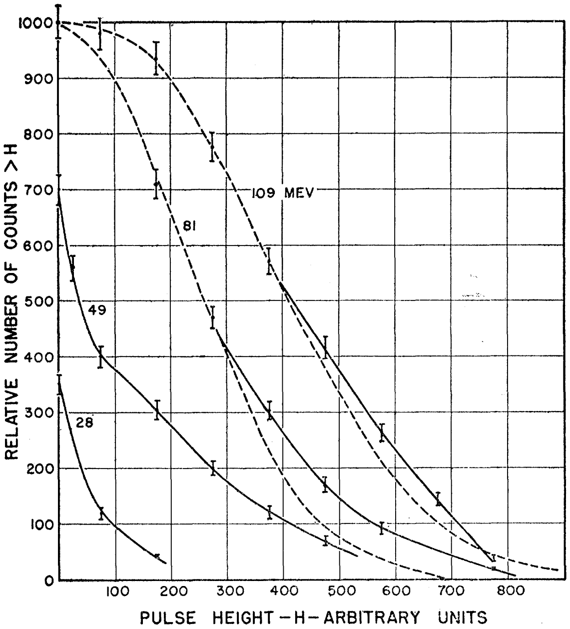

FIG. 3. Integral bias curves for side-window Čerenkov counter, RCA type 6372 multiplier. The dotted curves are Poisson distributions for a mean number of events per interval of 4 (109 Mev) and 2.4 (81 Mev). These Poisson curves have the same half-integral value as the experimental curves and indicate that the average number of photoelectrons per pulse from this photomultiplier lies between 1 and 4 for energies of Fig. 3.

(2) The counter has a remarkable energy sensitivity over a considerable range of energies.

(3) The response decreases to a low value near the Čerenkov cutoff for Lucite (48 Mev).

(4) The muon component is plainly evident on the lower energy curves as a plateau, corresponding to the residual muon group evident on the range curves of Fig. 1. A similar set of curves with the same detector was run on the 109-Mev π^- beam, and are closely similar in appearance.

Similar curves were also run using a side-window phototube, RCA type 6372. This tube was fitted with a 2 in.×2 in.×2½ in. thick block curved to fit the 2½ in. diameter cylindrical shell of the tube. The beam direction was normal to the axis of the tube, and the photocathode, and as in the case of the end-window tube, entered the central portion of the Lucite block. This tube was shielded with an Armco iron cylinder $\frac{7}{16}$ in. thick with a side tube surrounding the Lucite $\frac{3}{8}$ in. thick capped by a "mu-metal" plate 3/64 in. thick. The results for the 109-Mev π beam are shown in Fig. 3. A run was also made using the 168-Mev beam. The distributions are much broader with the side-window tube, probably due to less efficient light collection.

For comparison with theory one needs to know the mean number of photons, N, emitted per particle in the Lucite for each incident energy. If one assumes that the curves obey a Poisson distribution, then this number of photons is proportional to the Poisson mean,

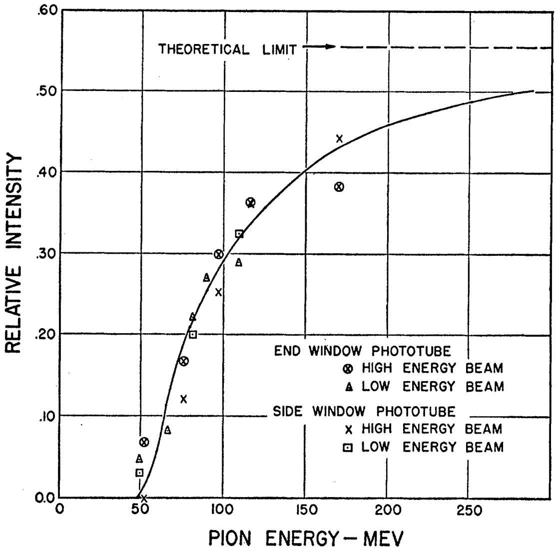

Fig. 4. Comparison of experimental and theoretical energy dependence of Čerenkov radiation from pions. The series of points for each of the four runs has been fitted by adjusting the relative intensity parameter for each run to the theoretical curve by least squares.

n, for each distribution. Approximate fits with integral Poisson distributions were attempted; e.g., in Fig. 3 the 109 and 81-Mev curves have been fitted with integral Poisson curves (dotted lines). The experimental and Poisson curves have the same half-integral values, although the fit is not so good for the larger pulse heights. It was found in all cases that a satisfactory result, with less labor, was obtained by using the half-integral value as a measure of N instead of the Poisson fitting.

The classical expression for the radiation intensity is

$$N=\frac{\Delta\omega\Delta x}{137c}\left(1-\frac{1}{\beta^2n^2}\right), \qquad (1)$$

where $\Delta\omega$ is the frequency interval, Δx the path length in cm, n the refractive index and N the number of quanta produced. However, because of ionization loss the particle velocity decreases in the block. The number of quanta produced in the block of thickness t is actually, therefore

$$N=\frac{\Delta\omega}{137c}\int_{E_0}^{E(t)}\left(1-\frac{1}{\beta^2n^2}\right)f'(E)dE \qquad (2)$$

where $f'(E)$ is the energy loss per cm in Lucite and β must be expressed in terms of the kinetic energy E for integration. E_0 is the incident energy. In Fig. 4 the results of the four runs are compared with Eq. (2).

The agreement is quite satisfactory with the exception of the highest-energy point for the end-window tube, which indicates the onset of a saturation at lower energy than predicted by theory. Near cut-off energy the points lie mostly above the curve. This may be due to the presence of the muon component, which as a velocity somewhat higher than the pion group for the same momentum as determined by the analyzing magnet. It is believed that these muons originate from the decay of the pions in flight and are difficult to suppress.

An experiment has been reported by Bianchi and Manducci,[11] using sea level cosmic rays, which indicated that the intensity of Čerenkov radiation increased at large energies more than predicted by classical theory. Since this experiment is outside the energy range of the present data, one cannot compare results directly. However, the question of showers when cosmic rays are used as the source of particles must be carefully considered and may affect the high-energy points.

In the foregoing discussion the details of the Čerenkov detector have not been specifically considered. One knows that because of the strong directional character of the Čerenkov radiation, the optics of a cylindrical radiator such as the Lucite blocks used here is complex. Another complicated situation exists at the photosurface, where the photoeffect takes place under internal reflection, and the angle of incidence of the radiation varies with the β value of the charged particle. As is well known, such photomultipliers also exhibit large sensitivity variations over the sensitive surface. One should also note that the classical formula (1) is

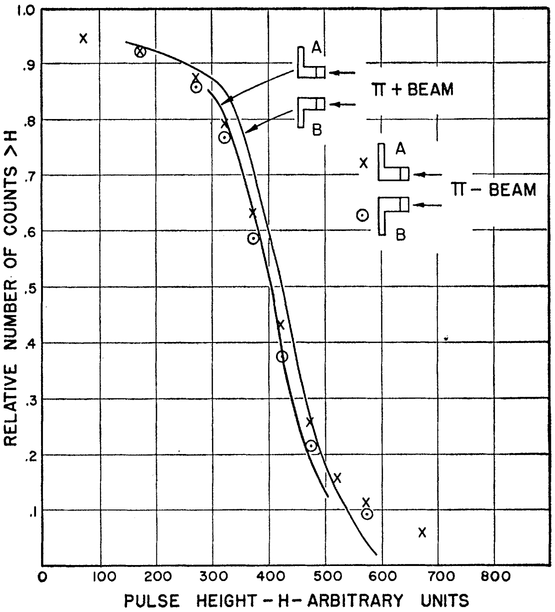

Fig. 5. Čerenkov radiation compared for π^+ and π^- mesons of equal energy, using the end-window photomultiplier (Dumont type 6363). Because polarity reversal requires reversal of all magnetic fields, the phototube was rotated 180° for each polarity (A and B positions). The π^- beam gives a slightly lower average output than the π^+ beam with this phototube.

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[11] A. M. Bianchi and C. Manducci, Nuovo cimento 9, 861 (1952).

derived assuming constant refractive index. In usual practice the limited spectral response of phototubes makes the experiments compatible with this assumption, but this may not be true if absorption regions appear in the radiating material in the spectral region under investigation. It is our intention to defer discussion of details such as mentioned in this paragraph pending further laboratory measurements on Čerenkov counters.

B. Polarity Effects

The polarity sensitivity of the end-window Čerenkov detector was investigated by exposing it to positive and negative pions of the same energy. This necessitated reversing the magnetic fields of both the cyclotron itself and the analyzing magnet, so that the location of the apparatus could remain unchanged. Although the photomultiplier was well shielded magnetically, it was anticipated that a change in gain would result from this field change. This was investigated by rotating the phototube 180° about its axis, and running integral curves with pions of fixed polarity and constant energy (set at 109 Mev). Such curves are shown in Fig. 5 and designated A and B. It is observed that with a positive beam a rotation of the photomultiplier about its axis 180° from A to B produces a shift in the half-integral point *upward* of 20 parts in 415 or 4.8 percent. The shift on rotation with the negative beam is *downward* 10 parts in 400 or 2.5 percent. There is therefore a *downward* shift of the average, when going from positive to negative, of 13 parts or 3.0 percent. This is therefore an upper limit for the positive-negative Čerenkov effect for this tube. The upper limit may well be less than this, as reversing the cyclotron and analyzing magnets may not be entirely equivalent to rotating the tube 180° with fixed field, i.e., the gain of the photomultiplier may be shifted somewhat differently in the two cases. It should be noted from Fig. 1 that the energy of the positive and negative pion beams was the same as determined by a range measurement.

The polarity effect was also investigated with the side-window tube, and the results are shown in Fig. 6. A shift in response due to rotating the phototube is observed in this case also. However, the average shift between the positive and negative pion beams is now *positive* and amounts to 27 parts in 427 or 6.3 percent. Since the two different types of photomultipliers give opposite apparent polarity response, and since it is obvious that magnetic fields are affecting the photomultiplier gain, it seems likely that the observed response changes are all due to this cause, and that polarity effects, if any, are very small.

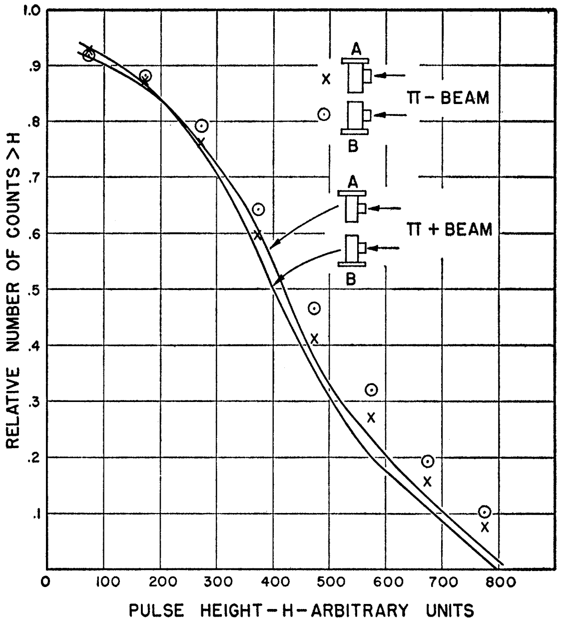

FIG. 6. Čerenkov radiation compared for π^+ and π^- mesons of actual energy using the side-window photomultiplier (RCA type 6372). The photomultiplier was rotated 180° for each polarity (compare with Fig. 5). In this case the π^- beam gives a larger response on the average.

IV. SUMMARY

In conclusion, it may be stated that the average pulse size from a photomultiplier coupled to a Lucite Čerenkov radiator varies with energy in a manner very close to that predicted theoretically. The experimental points from two different geometries indicate the correct cutoff energy. The muon beam contamination can account for certain observed differences between theory and experiment.

A search for a different Čerenkov response to positive and negative pions of the same energy showed this effect to be less than 3 percent, and smaller than magnetic effects on the photomultipliers due to reversing the cyclotron field.

The authors are indebted to Professor S. K. Allison for arranging for the use of the Chicago cyclotron, to Professor Herbert Anderson for his hospitality and advice in planning and scheduling the experiments, and to Dr. Maurice Glicksman for major assistance to the group in conducting the runs.