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Joseph W. Mather

(Thesis)

July 23, 1952

Berkeley, California

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PRODUCTION OF NEUTRAL MESONS BY 340 Mev PROTONS ON HYDROGEN

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July 23, 1952

ABSTRACT

The production of neutral mesons by 340 Mev protons on hydrogen has been measured directly by detecting a single gamma ray from a two gamma ray decay neutral meson, at 90° to the proton beam. A liquid hydrogen target and a focusing $\checkmark$ Cerenkov counter are described. The ratio of the cross section for neutral meson production from hydrogen relative to carbon is

$$\frac{\sigma_H}{\sigma_C} = 0.0059 \pm 0.0009 \text{ per nuclei}$$

where the error is standard deviation. Using the absolute cross section of neutral meson production from carbon as $1.5 \times 10^{-27} \text{ cm}^2$, one obtains the neutral meson production cross section for hydrogen to be $8.8 \times 10^{-30} \text{ cm}^2$.

The transition $^3P \rightarrow ^1S$ (allowed by the conservation of angular momentum and parity) for the protons can be interpreted as a triplet p-state interaction with the virtual emission of an s-state neutral meson before the usual s-state scattering of the two initial protons. The agreement with the existing data at proton energies of 440 Mev is good. The 340 and 440 Mev data give two points on the neutral meson excitation function curve, showing a steep rise. The experimental results give some evidence for the breakdown of the approximate selection rule which forbids the emission of s-state neutral mesons with final s-state nucleons. The relative cross section for carbon and nitrogen indicates that the yield of neutral mesons is due to the interaction of the incident protons with the neutrons in the nuclei.

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INTRODUCTION

It has been established by Hales, Hildebrand, Knable and Moyer¹ using a $\text{CH}_2\text{-C}$ subtraction method that the production cross section of neutral mesons by 340 Mev protons on hydrogen is less than two per cent of the carbon yield, specifically 0.07 ± 0.06 , normalized to the carbon data of 6.00. This seems to be in relative agreement with the theoretical results of the third order result considered by Brueckner². This type of analysis is a consequence of applying the meson field theory of nuclear forces (tensor forces in the n-p interaction) to the problem considered as a third order process. In view of the result given by Hales et al, an attempt is made to measure the direct production of neutral mesons from a liquid hydrogen target at 90° to the 340 Mev proton beam using a Cerenkov^{3,4} counter that employs a triple coincidence technique. Because of the small expected neutral meson yield from hydrogen and since only one gamma ray from a two gamma ray π^0 decay^{5,6} would be detected, it was thought, at the beginning of the experiment, that one could only place an upper limit on the neutral meson production cross section from hydrogen. Furthermore, no attempt was made to detect coincident gamma rays.

A recent experiment by J. and L. Marshall, Nedzel and Warshaw⁷ at Chicago, using the 440 Mev proton beam, indicates that

the production of neutral mesons from a liquid hydrogen target yields a cross section of $0.45 \pm .15 \times 10^{-27} \text{ cm}^2$ per nuclei. For the current reaction, (pp, π^0) assuming a pseudoscalar neutral meson emitted in a p-state, and if only s-states for the nucleons are considered, it is shown in Table I that the above reaction is forbidden because total angular momentum and parity cannot be conserved simultaneously. If the production of mesons in p-states represents a universal type of coupling for nucleon-nucleon collisions, then there exists a general selection rule prohibiting the (pp, π^0) process for final s-state nucleons.

Table I

Transitions allowed by Pauli principle, conservation of angular momentum and parity for production of pseudoscalar neutral mesons in nucleon-nucleon collisions.
(pp, π^0).

Initial State	Final State		Transition
p,p	π^0 Meson	p,p	
$1S_0$	s	$3P_0$	$1S_0 \rightarrow 3P_0$
	p	forbidden	none
$3P_0$ ↓ etc.	s	$1S_0$	$3P_0 \rightarrow 1S_0$
	p	$3P_1$	$3P_0 \rightarrow 3P_1$

However, the transition $3P \rightarrow 1S$ yielding an s-state neutral meson is possible. There are other (Table I) transitions yielding higher angular momentum states for the two final protons, but since the energy available to the two nucleons in the center of mass system is approximately 8 Mev, higher angular momentum states than the s-state will be suppressed.

It is known from the (pp, π^+) experiments by Cartwright, Richman, Wilcox and Whitehead⁸ and more recently by Schulz⁹, that the positive pi meson is emitted predominately in a p-state in the center of mass system. However the s-state yield of positive mesons is not zero⁹ and is thought to be approximately 1/8 to 1/10 of the p-state yield.

A general interaction is set up containing two terms,

$$\left[(\vec{\sigma} \cdot \vec{\nabla}) - (\vec{\beta}_\eta \cdot \vec{\sigma}) \frac{\delta}{\delta x} \right] \quad (1)$$

The first term $(\vec{\sigma} \cdot \vec{\nabla})$ leads to mesons in odd angular momentum states whereas the second term leads to mesons in even angular momentum states. σ is the nucleon spin operator, ∇ is a gradient operating on the meson wave coordinates only, and β_η is the relative nucleon velocity in the center of mass system. The second term, although it leads to transitions of the type of interest, namely ${}^3P \rightarrow {}^1S$, will be disregarded, perhaps hastily, on the basis that the matrix element squared involves a β_η^2 which is approximately 0.16. However, there are other reasons¹⁰ for neglecting the relativistic term, namely, there is yet no evidence from other meson experiments to support it. The first term of equation (1) will lead to mesons primarily in p-states although the following will indicate qualitatively how s-state mesons can be emitted in the transition ${}^3P \rightarrow {}^1S$ with respect to the center of mass. If for distances close to the nucleon the meson wave function $\psi(\vec{r})$ goes as r^ℓ , and if the interaction term is to be different from zero as $r \rightarrow 0$, then ℓ must be equal to one. This merely says that the meson wave function goes as r for small r , and that mesons will be emitted in p-states with respect to the nucleon. However, if a new meson wave function is obtained by transforming the

meson wave function relative to the nucleon to a new reference point, i.e., the center of mass of the two nucleon system, it is possible to obtain mesons emitted in s-states with respect to the center of mass of the two nucleons. For example, if $\psi \sim e^{ikr}$, where k is the momentum of the meson in the center of mass and r is the distance relative to the nucleon, then $\psi \sim e^{ikr}$ can be transformed to

$\psi \sim \frac{r_0 \cos \theta}{\lambda} + \frac{R}{\lambda}$ where r_0 can be taken as half the range of nuclear forces, λ is the meson wave length in the center of mass system, and R is the distance as measured from the center of mass of the two nucleons. The s-state contribution is then given as $(\frac{r_0}{\lambda})^2$ while the coefficient giving the amount of p-state is one. However, when evaluating the matrix element, the p-state term vanishes due to the selection rule, the cross term vanishes due to the orthogonality of the s and p waves, leaving only the s-state term.

Hence the quantity $(\frac{r_0}{\lambda})^2$ can be interpreted as the fraction of mesons that are emitted in p-states with respect to the nucleon but in s-states with respect to the center of mass of the two nucleon system. The above discussion holds only for the case where $\frac{r_0}{\lambda} \ll 1$. As the energy increases, r_0 may become large compared to λ and the estimate breaks down because the wave functions are no longer valid for large r .

The $^3P \rightarrow ^1S$ transition for the reaction

leading to an s-state neutral meson satisfies the conservation laws of total angular momentum and parity; however, there is evidence from high energy p,p collisions that the protons do not, in any measurable degree scatter from p-states. In order to circumvent this difficulty, the $^3P \rightarrow ^1S$ transition might take place in the

following way: To allow for s-state scattering of the two protons, the two protons can interact in a p-state, emitting a virtual neutral meson before the scattering of the two protons takes place. The meson is emitted from a p-state with respect to either nucleon, but comes out in an s-state with respect to the center of mass of the two nucleon system. In emitting the virtual meson, the relative angular momentum of the proton is changed by flipping its spin in order to scatter in an s-state in the usual manner. This would be a plausible explanation for the ${}^3P \rightarrow {}^1S$ transition with the emission of an s-state neutral meson and allowing for the p,p scattering in s-states.

On the basis of the ${}^3P \rightarrow {}^1S$ transition as indicated above, the current reaction at 340 Mev can be compared to that at 440 Mev (see section IV-C).

II EXPERIMENTAL PROCEDURE

A. Method of Detection

Neutral mesons decay into two gamma rays, one of which is materialized by pair production in a thin lead converter. The fast electrons are then detected by a $\checkmark$ Cerenkov counter. The scheme involves the detection of $\checkmark$ Cerenkov radiation from a fast electron passing through a medium of refractive index n in which the velocity of the electron is larger than the velocity of light in that medium. This radiation was first observed by $\checkmark$ Cerenkov¹⁸ and the theory was later developed by Frank and Tamm^{19,20}. Further experiments^{21,22} were shown to be in good agreement with the theory. More recently, Mather²³ has observed $\checkmark$ Cerenkov radiation from 340 Mev protons at the 184 in. cyclotron, as predicted by Frank and Tamm.

The $\checkmark$ Cerenkov radiation can be predicted from solutions of Maxwell's equations for a particle moving with uniform rectilinear motion through a medium of refractive index n . It takes a form analogous to the shock wave produced by projectiles moving through air faster than the speed of sound. Fig. 2 shows the Huygens wave construction for a bullet moving through air under the following conditions: (a) when the velocity of the bullet v is less than the velocity of sound v_s , and (b) when the velocity of the bullet is larger than the velocity of sound. For $v/v_s < 1$, the bullet is surrounded by a succession of spherical waves, the effect being a series of circles that are somewhat crowded together in the direction of motion. However, for $v/v_s > 1$, the spherical waves lag behind the bullet; hence the disturbances form a conical pressure shock wave pattern. This

wave phenomena can be readily demonstrated by observing the water waves emanating from the bow of a boat which is moving at a constant velocity.

Similarly, the directional properties of Čerenkov radiation can be obtained from a Huygens wavelet construction shown in Fig. 3. The wavelets combine with each other to form a conical wave front, symmetrical about the path of the particle. The normals to this wave front make a constant angle θ with the path of the particle,

$$\cos \theta = \frac{1}{n\beta} \quad (2)$$

where βc is the velocity of the particle, c the velocity of light in vacuum, and n the refractive index of the medium relative to vacuum. Thus the radiation appears as a cone in the forward direction, whose half angle decreases as $\frac{nv}{c}$ decreases. Since θ becomes imaginary for $v < \frac{c}{n}$, there is no radiation. The same is true, of course, when v/v_s is < 1 for the bullet case, for then there is no shock wave.

Usually the refractive index is a smooth function of the frequency for a given material. However it is a good approximation to assume that n is independent of the frequency in the range of frequencies of interest, that is, within the spectral response of a 1P21 photomultiplier. In actual practice, the cone of Čerenkov radiation (Fig. 3) does not produce a sharp wave front because most transparent materials introduce dispersion. If the refractive index n for a given material were independent of frequency and direction, then the velocity of the electromagnetic wave would be $\frac{c}{n} = \text{constant}$, giving rise to no spreading of the wave front.

The total energy radiated^{24,25} by a charged particle per unit

angular frequency ω in the distance L is

$$\frac{dW}{d\omega} = \frac{e^2 \omega}{c^2} L \sin^2 \theta \quad (3)$$

or, the number of quanta with angular frequency between ω and $\omega+d\omega$ emitted per unit distance by a particle of charge e moving with velocity v through a dielectric medium of refractive index n is

$$\frac{dN}{dL} = \frac{e^2}{h c^2} \sin^2 \theta d\omega \quad (4)$$

where h is Planck's constant divided by 2π . Thus for a very fast electron ($v \cong c$) passing through Lucite ($n \cong 1.5$), the number of quanta emitted per centimeter of path in the photomultiplier spectral region (3,000-6,000 $\text{\AA}$) will be approximately 425 quanta per centimeter.

B. Geometry

The general plan view of the 184 inch cyclotron is shown in Fig. 1a. As the 340 Mev scattered proton beam leaves the cyclotron, it enters a premagnet collimator which effectively shapes the beam before entering the final collimator that leads to the detection area. After the proton beam passes through the collimating slits, it is bent by a steering magnet toward a brass collimator 48 inches long passing through the concrete shielding surrounding the cyclotron. Most of the collimation is achieved at the premagnet collimating slits to prevent the spray of neutrons and general radiation from entering the detection area (cave). However, the background is high in the cave, but is nevertheless much reduced by the premagnet collimating slits.

The scattered proton beam has approximately a 20 microsecond duration, with a repetition rate of 50 cycles per second. This yields a duty cycle of 10^{-3} defined as the fraction of time the beam

is on per unit time. The flux of protons in the scattered beam for this experiment was maintained at 5×10^8 protons/sec, and was continuously monitored by a CO₂-Argon filled ionization chamber which was connected to an electrometer in the counting area. The electrometer actuated a Speedmax recorder which gave a visual indication of the proton beam level at all times.

The general arrangement of the liquid hydrogen flask, magnet and Cerenkov counter is shown in Fig. 1b. The hydrogen target was located 30 inches from the beam snout and the Cerenkov counter was situated at $32\frac{1}{2}$ inches from the center of the hydrogen target at 90° to the proton beam direction. This particular direction had one advantage, namely, it allowed us to discriminate against one of the competing reactions listed as 4 in Section III. The water-cooled magnet, which develops 20,000 gauss across a $1\frac{1}{4}$ inch gap, was located between the hydrogen target and the Cerenkov counter. This magnet served, as previously mentioned, to sweep the $3/4$ -inch diameter channel free of charged particles which would have given an erroneous interpretation of the hydrogen result.

C. Cerenkov Counter

1. Design and Construction

The design of the Cerenkov counter is similar to Marshall's³, except that a triple coincidence arrangement is employed to view the cone of Cerenkov radiation emitted from the Lucite radiator (Fig. 4). Gamma rays from neutral meson decay are allowed to impinge on a lead radiator. The electrons, produced by materialization of the gamma rays, then enter the Lucite radiator, producing Cerenkov radiation

as they traverse the material. The Lucite radiator is a partial spherical surface of radius 3.14 inches, and since the refractive index of Lucite is 1.5, the cone of $\checkmark$ Cerenkov radiation will be focused into a ring at twice the radius of curvature as measured from the vertex of the spherical surface. A cylindrical, aluminized mirror of half the ring diameter intercepts the $\checkmark$ Cerenkov rays and reflects them to a focal spot on the central axis, assuming that the initial particle entered the Lucite radiator along the central axis. However, to use three photomultipliers, it is necessary to split the $\checkmark$ Cerenkov radiation by an aluminized, mirrored prism which reflects the $\checkmark$ Cerenkov radiation onto the cathodes of three photomultipliers. The photomultipliers are positioned on a metal ring (Fig. 5) which affords adjustment of each detector over a velocity range of 0.85 to 1.1c. Three detectors were used in triple coincidence principally to lower the accidental coincidences due to noise pulses resulting from the high voltage on the photomultipliers necessary to detect the weak $\checkmark$ Cerenkov radiation.

Initially a doubles arrangement⁴ was constructed, using only two photomultipliers as detectors. This design was subjected to experiment to determine the effective aperture, directional properties, and, if possible, an efficiency for detecting gamma rays. It was determined, prior to experiment, that off-axis particles would not be counted as effectively as on-axis particles, and furthermore, particles entering the radiator making a small angle with the central axis would not be effectively counted. These effects can be approximated, but the analysis is complicated by the small multiple angle Coulomb scattering occurring in the radiator, angular dependence of electron

pairs in the radiator ($\theta \cong \frac{mc^2}{E}$) even though small, and since Cerenkov radiation contains a mixture of waves whose wave lengths extend over the entire visible spectrum, one can expect a small amount of dispersion in Lucite. Since the velocity in a material substance depends on the wave length, the index of refraction of a substance is a function of the wave length. Therefore, since the velocity varies with wave length, we say the substance exhibits dispersion. Dispersion therefore will spread the Cerenkov cone of radiation in angle because of Eq. (2). The foregoing effects, combined with the problem of focusing the Cerenkov radiation cone, make it necessary to use positioning devices for the photomultipliers. Other designs of Cerenkov counters (Marshall²⁶ gives a complete account of various designs) have been used successfully. Lucite material was chosen for the Cerenkov radiator because of

- (1) the ease of machining and polishing to the desired form,
- (2) the low atomic number, approximately 7, leading to small multiple angle Coulomb scattering, and (3) the low density and atomic number lead to a small rate of energy loss through ionization for a charged particle traversing the Lucite. Since the energy loss per unit path through ionization is approximately constant for a fast electron (2Mev/gr cm^{-2}), the small multiple angle scattering will reflect this energy loss because of its inverse energy dependence.

2. Performance of the Two Photomultiplier Scheme

a. At the 320 Mev Berkeley synchrotron, the x-ray beam was collimated to 1/8-inch diameter and allowed to fall on a thin lead converter. By careful alignment of the axis of the Cerenkov radiator with the direction of the x-ray beam, it was possible to obtain

the curves shown in Figs. 6 and 7, giving the aperture width at half maximum of 0.6-inch and the angular acceptance at half maximum of approximately 2.5° , respectively. Prior to this, data were obtained giving the response of the Cerenkov counter as a function of the photomultiplier position on the metal ring. The positioning devices were adjustable in all directions, and the maximum counting rate was obtained approximately at the predicted angle for fast electrons, with the Cerenkov rays coming to a focus at the sensitive cathode surface. The velocity selection was checked by moving one photomultiplier one cathode width off the determined position; the counting rate dropped a factor of 7. A further check to test the Cerenkov effect was made by reversing the counter 180° to allow the electrons to impinge on the back of the Lucite radiator. No counts were obtained that were statistically significant from pure accidentals as determined from a known length of delay cable placed in one leg of the coincidence circuit.

b. At the 184 inch cyclotron, it was possible to obtain a figure for the efficiency of detecting gamma ray energies in the energy range of 40-120 Mev by using the gamma ray decay of the neutral meson. The neutral mesons were produced by the 340 Mev circulating proton beam on a $\frac{1}{4}$ -inch carbon target at point "a" shown in Fig. 1a. The decay gamma rays were observed through the neutron hole in the concrete shielding in the zero degree direction approximately 50 feet from the internal carbon target. Since previous experiments on neutral mesons from carbon were performed by Crandall²⁷ using the pair spectrometer, it was felt that the efficiency of the Cerenkov counter, based on the gamma ray yield as recorded by the

spectrometer, would be a reliable figure. The ratio of observed coincidences to the total number of gamma rays incident on the Lucite radiator (effective aperture approximately 0.6-inch in diameter) was as high as 21 per cent. This efficiency is not to be construed to mean that a coincidence plateau was obtained, but rather indicates a result for a given voltage and discriminator setting.

c. Each particular particle direction in the radiator generates its own cone of radiation, and if the [✓]Cerenkov rays are geometrically followed through the optical system, it is then clear that each cone of radiation will be focused at a place determined by the original particle direction. In particular, neglecting spreading of the [✓]Cerenkov cone of radiation, the radiation from an on-axis particle will be focused at a point on the central axis, because the cone originated on the axis. However, for off-axis origin of the [✓]Cerenkov cone, a large fraction of the [✓]Cerenkov rays will never intersect the axis and consequently will come to a focus off the central axis. So, instead of a point focus obtained for off-axis particles, a general region of focal points will be obtained from all the [✓]Cerenkov photons that make up the initial cone of radiation. If the effect of spreading in angle of the Cerenkov cone is considered along with the foregoing discussion of off- and on-axis particles, then it is clear that the curves shown in Figs. 6 and 7 are indicative that [✓]Cerenkov radiation was being detected, and not general fluorescence. One would not expect fluorescence in Lucite, if present, to exhibit the directional property as shown by Fig. 7.

In conclusion, the curves shown in Figs. 6 and 7 indicate (1) that this particular design of counter has the advantage of being

directional, (2) that the Lucite radiator has no definite sensitive detection area, (3) that even though the half-maximum width be taken as the effective area, the resulting solid angle is extremely small, (4) that the efficiency of detection of off-axis particles is falling extremely rapidly, and (5) that the effective aperture of the Lucite radiator at half-maximum is reasonably close to the combined widths of the photocathode surfaces (approximately 2 centimeters) as expected.

3. Transition curves for the triple photomultiplier scheme

Whenever high energy gamma rays are detected, it is important to determine whether a converter effect is obtained. For the $\checkmark$ Cerenkov counter, this was carried out by placing thin sheets of lead before the Lucite radiator and observing the coincidence rate as a function of the thickness of the converter. This procedure was used also for the double scheme, yielding similar results. Considering only the lead converter, although copper curves (Fig. 8) were also obtained, characteristic curves were obtained for the attenuation part of the curve, but the transition from no lead to the peak of the transition curve was at most a factor of 2-3 at a converter depth of 1/16 to 1/8-inch lead. Since Lucite is not a good converter for gamma rays, although it gave an appreciable yield, the Z^2 effect of pair production in Lucite and lead is offset by the Z dependence of small multiple angle Coulomb scattering in both materials. The directional properties of the counter have already been discussed; hence it is not unreasonable to expect the small multiple-angle scattering in lead and Lucite to cancel the effects of increased pair production. Some evidence for this is given by the lead and copper

transition curves in Fig. 8, showing that the same maximum counting rate is obtained for each material. The total absorption coefficients for the attenuation part of the lead and copper curves are approximately 0.875 cm^{-1} and 0.298 cm^{-1} respectively, corresponding to a gamma ray energy of approximately 30 Mev as given by Heitler²⁸. Even though the attenuation curves were not extended to greater converter thicknesses than 5 cm, it may be fortuitous for us to assign the 30 Mev gamma ray energy on the basis of the experimental points. The total absorption coefficients for lead and copper for 70 Mev gamma rays from neutral meson decay are given by Heitler as 1.1 cm^{-1} and 0.38 cm^{-1} . Thus, from the observed absorption coefficients, it might be thought that a 70 Mev gamma ray absorbs like a 30 Mev gamma ray, perhaps because of the directional property of the $\checkmark$ Cerenkov counter. This data again refer to a given photomultiplier voltage and bias setting.

4. Details of Electronics

The output pulse from a photomultiplier depends directly on the number of light quanta that reach the photosensitive surface. Since the number of quanta available to the photocathode is only a fraction of those actually contained in the $\checkmark$ Cerenkov cone, and furthermore, if we consider that only one-third of the number of $\checkmark$ Cerenkov photons are directed toward one photocathode because of the aluminized mirrored prism, then each photomultiplier sees less than one-third of the total radiation emitted in the radiator. Further light losses are introduced by the two reflecting surfaces of the optical system and also by the imperfect focusing of the light rays reflected from the extreme ends of the 120° mirrored sector. Furthermore the photocathode efficiency, i.e., photoelectrons per photon, is usually in

the region of 1 to 5 per cent, depending on the light frequency range considered.

A block diagram of the electronics is shown in Fig. 9. A fast (approximately 5×10^{-9} seconds) negative pulse from each photomultiplier is fed to the limiter circuit (Fig. 10a) where it is slightly amplified and limited to a predetermined height. The output pulse from the limiter is clipped by four feet of shorting line (RG 21-342), giving pulse widths of approximately 10^{-8} seconds of uniform amplitude. The clipped pulse is then passed through a 100 megacycle distributed amplifier and fed to the grid of a fast (10^{-8} seconds) coincidence circuit employing a miniature beam tube (6BN6) shown in Fig. 10b. To form a triple coincidence it is necessary to first make a coincidence between signals 1 and 2 (Fig. 9). Then the output of the first coincidence circuit and the third photomultiplier signal are placed in coincidence, using an identical coincidence network. In order to make the second coincidence, it is necessary to properly delay the third signal because of inherent delay associated with the 6BN6, and also to invert the first coincidence output signal before mixing it in the second coincidence circuit. The inversion is accomplished with a small pulse transformer placed at the grid of the second coincidence circuit. Finally, the output pulse, which is a triple coincidence, is fed to a 10 megacycle linear amplifier which triggers a scaler gate and is scaled.

In an ideal coincidence circuit, the amplitude of the signals to be mixed should be unimportant, but in an actual coincidence network, the efficiency of coincidence counting is strongly dependent on the relative magnitude of the input signals. However, it is usual

practice to limit the input signal to a constant height before mixing. When using solid or liquid scintillating phosphors, there is little difficulty in obtaining limited pulses because the number of light quanta available at the sensitive cathode surface is large. It was stated earlier in this section that there are several factors influencing the availability of light quanta from Čerenkov radiation. It is expected that less than fifty per cent of all Čerenkov pulses are limited. This will then demand a coincidence circuit which can at least be adjusted over a wide pulse height range to detect approximately a 5-to-1 difference in pulse height. In any case, the Čerenkov light pulses must be amplified before a coincidence is made.

The limiter circuit shown in Fig. 10a was developed by Neher²⁹ using a 6AH6 pentode to limit photomultiplier signals from crystal phosphors. The limiter is mounted at the base of the photomultiplier in order to avoid long signal leads which would increase the capacitance to ground and thereby decrease the high frequency response of the circuit. The photomultiplier signal lead from the anode is already rather long within the photomultiplier tube, so that little is actually gained in mounting the limiter tube uncomfortably near the output of the photomultiplier. However, the dead time of the limiter is approximately 1 microsecond and seriously limits fast counting. With photomultiplier voltages in the neighborhood of 1700-1800 volts, it was expected that the thermal noise component would be serious. Nevertheless, it was possible to locate three photomultipliers with a low noise component at high voltages, so that the use of the limiters did not affect the interpretation of the coincidence counting rate.

The coincidence circuit shown in Fig. 10b is of extremely

simple design. Each coincidence circuit consists of one miniature beam tube (6BN6). Careful attention was paid to line terminations throughout the network so that maximum pulse height could be obtained at salient points. Each grid of the 6BN6 was biased independently so that the amplitude of the pulse required for coincidence could be varied as the condition warranted. This sensitive control is an extremely important advantage because it means that a coincidence between two unequal pulses can be obtained by adjusting the grid bias. If one is satisfied with approximately 10^{-8} resolving time, then this circuit offers the additional feature of forming a triple, quadruple, etc. coincidence without too much difficulty. However, there are several disadvantages which cannot be overlooked. Both grids of the 6BN6 are not internally shielded from the plate circuit; consequently a certain portion of the signal fed to the unshielded grid feeds through to the plate. The feed-through pulse is of the same sign as the grid input signal, but opposite in sign to the coincidence pulse formed. Thus with certain precautions the external part of the circuit can be made to respond only to pulses of one sign. Because the 6BN6 is a long tube (approximately 2 centimeters), the electrons spend a considerable time in transit between the grids and the plate. Since the velocity of the electron is proportional to the square root of the applied voltage, the transit time is not appreciably reduced by increasing the plate voltage. To overcome this difference in time, it is necessary to delay one grid signal with respect to the other if resolving times of 10^{-8} seconds are desired. If a triple coincidence network is used, then the inherent delay of the 6BN6 must be balanced by sufficient delay in the third

signal. For a higher number of coincidences, the delay cable needed becomes quite lengthy; consequently the pulse height will be attenuated by the cable.

A second type of coincidence circuit was used exclusively in the double Cerenkov scheme, utilizing crystal diodes in a bridge network, based on the principle outlined by Z. Bay³⁰ and further developed by Neher to give resolving times of approximately 10^{-9} seconds. Limited pulses were used as before, clipped to 2×10^{-9} seconds in width. When the bridge is balanced, no potential appears across the center arm (labeled a and b in Fig. 10c), and since the amplifier detects only a difference in amplitude, no coincidence is made. The bridge becomes unbalanced when one of the crystal diodes, namely D_2 , is effectively cut off by a positive signal; a difference in potential is then detected by the difference amplifier. This particular arrangement is critically dependent on the relative pulse amplitudes applied to the bridge. Since a large portion of the Cerenkov radiation pulses are not limited, the efficiency in detecting two unequal signals falls very rapidly. For this reason, the circuit shown in Fig. 10b was developed.

D. Liquid Hydrogen Target

A liquid hydrogen target formerly used by Cook³¹ was converted from an in-line target to a point source. The upper section of the target assembly, consisting of a liquid nitrogen jacket surrounding the hydrogen tube, was taken over to the new design. A cross-sectional view of the hydrogen target assembly is shown as a photograph in Fig. 12. The initial design of the liquid hydrogen container is the

work of Garrison³²; however the success in the construction of the container is due to the pooled efforts of many.

1. Design and Construction

The design of the liquid hydrogen container was dictated by the following considerations: (1) The thickness of the liquid hydrogen container and the outside jacket must be kept to a minimum if the competing reaction (i.e., production of negative mesons by high-energy protons in the walls of the container, leading to capture in hydrogen) is to be negligible. (2) The liquid hydrogen container must withstand at least 30 pounds per square inch internal pressure under test. In case the vacuum system fails, the liquid hydrogen would boil vigorously and build up in pressure. Therefore, 30 pounds per square inch test-pressure was thought to include a reasonable factor of safety under such a failure. (3) The container must withstand repeated thermal stresses set up by the cooling to liquid nitrogen temperature (77° K), and the warming to room temperature (293° K), to insure that the soldered joints will not crack or separate because of the differences in the coefficient of thermal expansion of the metals used. (4) The diameter of the liquid hydrogen container must be such that it will hold approximately 1 gram cm^{-2} ; this requirement was set independently by Garrison in order to do a p,p scattering experiment.

No provision was made for filling and emptying the hydrogen target during the experiment. However, the hydrogen target assembly (Fig. 12) provided a dummy target, identical to the hydrogen target, except that it was not evacuated. The dummy target and the liquid hydrogen target were fixed in place on a movable carriage, facilitating a change in target in a matter of seconds. However, because of the orientation of the target frame relative to the proton beam,

it was necessary to remove the dummy target each time the liquid hydrogen target was used.

The liquid hydrogen flask was fabricated from a 4 mill stainless steel foil, in the form of a cylinder 5.6 inches in diameter and 8 inches in length. The foil was soft-soldered to a stainless steel base and to a collar arrangement on the vertical hydrogen tube. The vertical stainless steel tube which connects to the hydrogen flask was reduced in steps from a diameter of 5.6 inches to 2 inches at the top (Fig. 11), mainly to decrease the hydrogen volume above the sensitive area of the target. This arrangement allowed a full day's run without refilling of the hydrogen flask. The outside aluminum jacket was 9 inches in diameter with 1/16-inch wall thickness, except where the proton beam penetrated. At this point there was a 3 inch diameter hole covered with a 5 mill aluminum foil to reduce the negative meson production. Since the proton beam emerges from a 2 inch diameter collimator (Fig. 1a), there is sufficient tolerance in the 3 inch diameter hole so that no protons impinge on the thick-walled aluminum jacket. Frequent photographs of the beam alignment were made throughout the experiment.

2. Heat Losses

The problem of heat loss was considered in some detail. The addition of heat to the system not only causes rapid evaporation of liquid hydrogen, but produces gas bubbles in the liquid, which effectively reduces the number of hydrogen nuclei present in the already small sensitive hydrogen volume as seen by the Cerenkov counter. There are several sources of heat transfer which cause the liquid hydrogen to boil: conduction down the metal wall of the hydrogen tube;

heat conduction through the air surrounding the hydrogen flask; and radiation loss.

The collision mean free path of an air molecule in a vacuum of 2×10^{-6} millimeters of mercury is approximately 200 meters. Hence the conduction loss through the vacuum surrounding the hydrogen flask is entirely negligible.

Heat conduction down the walls of the hydrogen tube was minimized by the following conditions: (1) the wall thickness of the tube was 1/32-inch; (2) the stainless steel material used for the tube has a coefficient of thermal conductivity of 0.12 calories centimeters seconds⁻¹ centimeters⁻² centigrade⁻¹, as compared to 0.49 for aluminum; and (3) the hydrogen tube was surrounded by a liquid nitrogen jacket to lower the temperature gradient down the tube. The rate of flow of heat in the steady state is

$$H = K A \left(\frac{T_2 - T_1}{L} \right) \quad (5)$$

where K is the coefficient of thermal conductivity, A is the cross sectional area of the wall, $T_2 - T_1$ is the temperature difference, and L is the length of the conducting section. The heat flow was therefore minimized by the foregoing considerations.

The rate of emission of radiant energy (actually absorption) per unit area is

$$W = e \sigma (T_2^4 - T_1^4) \quad (6)$$

where σ is a numerical constant depending on the units employed, e is a quantity called the "emissivity of the surface", and T is the absolute temperature in degrees Kelvin. The emissivity lies between zero and unity, depending on the nature of the surface. In general, it is larger for rough and smaller for smooth, polished surfaces.

Thus the radiation loss was minimized by polishing the hydrogen stainless steel flask and also by using a $\frac{1}{4}$ -mill aluminum foil as a radiation shield around the hydrogen flask.

After assembling the hydrogen target, a test (using liquid nitrogen in place of liquid hydrogen) was performed to determine whether any gas bubbles were present in the liquid nitrogen. When the liquid nitrogen reached a quiescent state, it was possible to look down the hydrogen tube. This was checked several times, and no gas bubbles were observed. Therefore it was assumed that liquid hydrogen would not bubble to any great extent, because the temperature difference between liquid nitrogen and hydrogen is only 50° . A further check of all heat losses was obtained during the hydrogen experiment over a period of twenty-four hours; it was found that the disappearance of liquid hydrogen corresponded to a heat flow of approximately $0.2 \text{ calories sec}^{-1}$. Since the hydrogen is continually vented to the atmosphere through a 2 inch diameter rubber hose, it is not difficult to account for most of the heat loss in this way. Thus it was concluded that no boiling of the liquid hydrogen in the sensitive volume of the proton beam was present.

III SOURCES OF BACKGROUND

In any experiment having a small yield, consideration must be given to other reactions which could conceivably lead to an erroneous result. The following possible reactions were considered in this experiment:

1. π^+ production in hydrogen and its associated $\mu^+ \rightarrow e^+$ decay.
2. Fast electrons from targets.
3. π^- production in the walls of the container, leading to capture in hydrogen.
4. π^0 production in the walls of the container.
5. π^- production in the walls of the container, leading to charge exchange in hydrogen.
6. π^-, π^+ ordinary scattering in hydrogen at 90° .

The foregoing reactions are discussed as follows:

The yields of reaction 1 and 2 were mitigated by use of a small magnet (see Fig. 1b) capable of producing a magnetic field across a $1\frac{1}{4}$ inch gap of 20,000 gauss. Similarly, fast electrons from nuclei bombarded by high energy electrons, as found by Neher, Alvarez and Moyer¹¹ using time-of-flight apparatus, were effectively swept away by the magnetic field.

Reaction 3 was thought to be the only local source of negative mesons that could lead to a misinterpretation of the hydrogen result. Negative mesons are not produced in hydrogen because of charge conservation. Therefore reaction 3 was calculated for ten mills of aluminum and eight mills of stainless steel with reference to data from Richman, Weissbluth and Wilcox¹² on negative meson production from carbon and lead at 90° . Taking the average value for $\frac{d^2\sigma}{d\Omega dE}$ at

17 Mev and 90° to be $5.2 \times 10^{-31} \text{ cm}^2 \text{ steradian}^{-1} \text{ Mev}^{-1} \text{ nucleus}^{-1}$ for carbon, and assuming that negative meson production depends on the number of neutrons in the nucleus, one obtains

$$\frac{d^2\sigma}{d\Omega dE} = 0.87 \times 10^{-31} \text{ cm}^2 \text{ steradian}^{-1} \text{ Mev}^{-1} \text{ neutron}^{-1}$$

at 17 Mev and 90° . By extrapolating the negative meson cross section per neutron, as previously given, to higher neutron nuclei, say lead, one finds an error of a factor of two too high, compared to that quoted by Weissbluth. However, we shall use

$$\frac{d^2\sigma}{d\Omega dE} = 0.87 \times 10^{-31} \text{ cm}^2 \text{ steradian}^{-1} \text{ Mev}^{-1} \text{ neutron}^{-1}$$

at negative meson energies of 17 Mev with confidence, knowing that it will lead to an overestimation of the negative meson capture in hydrogen. Consequently we are interested in negative mesons that originate in aluminum and stainless steel, and end their range in the sensitive portion of the liquid hydrogen target. Referring to Fig. 1b, the sensitive portion of the target is effectively a section 2.5 centimeters thick, transverse to the proton beam direction. Hence the minimum meson energy that will enter the sensitive hydrogen portion is 15.3 Mev, and the maximum meson energy will be in the range of approximately $\sqrt{2}$ times the minimum energy range, or 19.8 Mev, as obtained from the range-energy curves. So the interval of negative meson energies of interest are $\Delta E \approx 5 \text{ Mev}$ at an average negative meson energy of 17 Mev. The solid angle subtending the sensitive hydrogen volume by the walls of the container in the forward and backward direction of the proton beam can be estimated to be two steradians for the stainless steel wall, and one steradian for the thin aluminum window. We also make the assumption that the cross section for negative meson production at 0° is twice that at 90° , and

at 180° it is taken equal to the 90° cross section. This assumption is reasonable since the negative meson data for carbon¹³ at 0° is approximately that at 90° . In combining the above discussion, one obtains the average total cross section for the production of negative mesons at 17 Mev in the interval $\Delta E = 5$ Mev in the forward and backward direction from aluminum and stainless steel, as follows:

$$\sigma_{\text{al.}} = 1.83 \times 10^{-29} \text{ cm}^2$$

$$\sigma_{\text{s.s.}} = 7.5 \times 10^{-29} \text{ cm}^2$$

With these cross sections, the number of gamma rays from negative meson capture reactions¹⁴ will lead to an isotropic (π^- meson captured at rest) gamma emission in the sensitive hydrogen volume of

$$N(\gamma) = 0.0124 \times 10^{-29} N_0 F_p$$

where N_0 is Avogadro's number, and F_p is the proton flux in particles/sec. An experimental method for checking whether or not negative meson capture effects are important will be discussed in Section IV.

Reaction 4 is eliminated on the basis that the $\checkmark$ Cerenkov counter, because of its directional properties (see Section II C), looks only at the small sensitive hydrogen volume. Data given in Figs. 6 and 7 and Table 1 verify this.

Reaction 5 can only be roughly approximated. Taking the Fermi, Anderson, Lundy, Nagle and Yudh¹⁵ results of 20 ± 5 millibarns for the negative meson charge exchange reaction in hydrogen at 90° in the 80-120 Mev energy range, and further assuming that the spectrum of negative mesons from aluminum and stainless steel for 340 Mev incident protons reaches a maximum of 110 Mev, then the number of negative mesons that will charge exchange in the 80-110 Mev interval in

passing through hydrogen can be given roughly as

$$N(\pi^-) = 0.000065 \times 10^{-29} N_0 F_p$$

Clearly this will give a negligible contribution to the hydrogen yield of neutral mesons.

Reaction 6 was eliminated on the same basis as reaction 1. The interaction of negative and positive mesons in hydrogen has been investigated by Anderson^{16,17}, Fermi¹⁵, and co-workers^{15,16,17}, over the energy range of about 80-230 Mev. Although the scattering cross section for positive and negative mesons in hydrogen are in the millibarn region, the yield of particles at 90° to the proton beam is still quite negligible. However, the magnet serves to insure that no charged mesons will get down the channel and enter the detector.

IV RESULTS

Procedure

Since this experiment was expected to yield a low counting rate, the author was constantly on guard to assure that all electronics equipment continued to perform in good order. To dispel any uncertainty, a carbon target was periodically (every two hours) placed in the proton beam in place of the liquid hydrogen target. Repeating this procedure after a blank or liquid target exposure gave full assurance of the operation of the coincidence circuit and Cerenkov counter throughout the 32-hour run. In addition, the proper coincidence pulse levels were obtained on the basis of the neutral meson decay gamma rays from carbon. Only those coincidence pulses above a certain height as observed on an oscilloscope screen were recorded by the scaling unit.

Alignment

It was extremely important to align the central axis of the Cerenkov radiator and the axis of the 3/4-inch diameter lead collimator through the magnet with the level of the proton beam. The Cerenkov radiator direction was obtained by a simple telescope arrangement, while photographic exposure of the proton beam determined its level relative to the magnet channel and Cerenkov counter.

Solid Angle

The 3/4-inch diameter lead collimator was designed on the basis of Fig. 7 to exclude all radiation which originated outside of a cone of half angle of one degree. Thus the volume of liquid hydrogen available for neutral meson production was limited to a cylinder

approximately 2.5 centimeters in diameter, transverse to the beam direction. The sensitive area of the Lucite radiator was taken to be 0.6-inch diameter, from Fig. 6. Hence the Lucite radiator subtends a solid angle at the sensitive target volume of 2.6×10^{-4} steradians.

Background and Accidentals

At the beginning of the experiment, the empty hydrogen target was bombarded for one hour, with no measurable yield. The counting rate obtained from the blank or dummy target and that for no target was the same within statistics. This indicated that the Cerenkov counter was looking at the air in the blank target and not at the walls of the target. A calculation of the expected yield from air relative to carbon, shown in Table 2, gives additional evidence that the blank target yield is not a subtractable background. This background is considered as due to the neutral meson production from air, and should not be subtracted from the hydrogen yield.

The accidental rate with the carbon target in place was checked by inserting sufficient length of delay line in one leg of the coincidence circuit. It is necessary to insert a time delay of 6×10^{-8} seconds, which corresponds to the interval of time between two radio frequency pulses of the cyclotron. No accidentals were obtained and on this basis none were expected from the liquid hydrogen target.

A. Corrections to the Data

Because of the small sensitive volume of the target, compared to its dimensions (Fig. 1b), it was necessary to correct the experimental data for the attenuation of the proton beam through ionization and also for the decrease in intensity of the neutral meson decay gamma rays due

to pair production in the target material.

Since the sensitive volume of each target as defined by the collimating system was at the center of the target in each case, it was necessary to consider the energy loss of a 340 Mev proton in passing through the insensitive part of the target. The insensitive portion of each target, i.e., 2.5 centimeters of carbon, 7 centimeters of liquid nitrogen, and 7 centimeters of liquid hydrogen, resulted in an energy loss in the proton beam of 11, 16, and 3 Mev respectively, as obtained from the range energy curves. Since the neutral meson yield from carbon as a function of the proton energy is given by Grandall²⁷, the percentage decrease in meson yield from that at 340 Mev could be obtained. The values chosen were 26 per cent for carbon and 41 per cent for liquid nitrogen. The correction for hydrogen is uncertain. By referring to the excitation function obtained by Schulz⁹ for the $(p,p\pi^+)$ process, a 5 per cent reduction in meson yield would be expected.

When gamma rays pass through matter, their intensity decreases owing to absorption or scattering. Since the energy of the neutral meson decay gamma rays is approximately 70 Mev, the disappearance of the gamma rays will be due mainly to pair production. By knowing the mean free path for pair production for a given material, it is then possible to estimate the percentage decrease in the gamma ray intensity. For the thicknesses of carbon and liquid nitrogen as previously given, the gamma ray intensity will decrease 4.5 and 8 per cent respectively. The liquid hydrogen gives a very small contribution; less than 0.5 per cent.

The foregoing corrections were applied to the experimental data

and Table 2 lists the corrected experimental values for proton energies of 340 Mev.

B. Values Obtained

The values obtained for the neutral meson yield from carbon, liquid nitrogen and liquid hydrogen at 90° to the proton beam are listed in Table 2. The neutral meson cross section for hydrogen relative to carbon, based on per nuclei, is

$$\frac{\sigma_H}{\sigma_C} = .0059 \pm .0009$$

while the neutral meson cross section from hydrogen relative to nitrogen is

$$\frac{\sigma_H}{\sigma_N} = .0100 \pm .0015$$

The experimental corrected ratio of the counting rate from liquid nitrogen relative to carbon offers a further check of the consistency of the results as

$$\frac{N(\gamma)_N}{N(\gamma)_C} = .546 \pm .037$$

Taking account of the difference in density of carbon and liquid nitrogen, and further assuming the neutral meson production from liquid nitrogen to be 7/6ths of the carbon yield, the expected ratio of the counting rate from liquid nitrogen relative to carbon is

$$\frac{N(\gamma)_N}{N(\gamma)_C} = .537$$

The agreement between the experimental and calculated values listed in Table 2 give additional evidence that neutral meson production in light nuclei depends primarily on the number of neutrons in the nucleus.

C. Theoretical Discussion

On the basis of the discussion given in Section I, the cross section at higher proton energies may be estimated by using the present

Table 2

Neutral meson yields* for various targets
at 90° to the 340 Mev proton beam.

TARGET	TOTAL INTEGRATOR SWEEPS	TOTAL COUNTS	TIME (MIN.)	EXPERIMENTAL VALUE †		CALCULATED VALUE ‡	
				$\frac{\sigma}{\sigma_C}$	$\frac{N(\gamma)}{N(\gamma)_C}$	$\frac{\sigma}{\sigma_C}$	$\frac{N(\gamma)}{N(\gamma)_C}$
Carbon	60	382 ± 19	27.5	1.0	1.0	1.0	1.0
Liquid Nitrogen	145	392 ± 20	66	1.19 ± .08	0.546 ± .037	1.17	0.536
Blank (air)	625	4 ± 2	265	1.0 ± .5	0.0009 ± .0003	1.2	0.00086
Liquid Hydrogen	1659	47 ± 6.8	570	0.0059 ± .0009	0.0033 ± .0005	- -	- -

All errors are standard deviations.

† Corrected for energy degradation in target and for gamma ray conversion in the target material.

‡ Values obtained assuming production of neutral mesons to depend only on the number of neutrons.

* Yields based on per nuclei.

Absolute cross section for neutral meson production by 340 Mev protons on carbon by Grandall²⁷ ($1.5 \times 10^{-27} \text{ cm}^2$)

experimental results. Since the charged mesons in the (pp, π^+) process are emitted predominately in p-states, r_0 can be calculated from the matrix element $(\frac{r_0}{\lambda})^2$, giving the fraction of mesons that are emitted in p-states with respect to the nucleon, but in s-states with respect to the center of mass. By forming

$$\left(\frac{r_0}{\lambda}\right)^2 \sigma_{340}(pp, \pi^+) = \sigma_{340}(pp, \pi^0) \quad (7)$$

and, solving for r_0^2 and inserting it in the following equation

$$\left(\frac{r_0}{\lambda}\right)^2 \sigma_{440}(pp, \pi^+) = \sigma_{440}(pp, \pi^0) \quad (8)$$

one obtains

$$\sigma_{440}(pp, \pi^0) = \left(\frac{\lambda_{22}}{\lambda_{75}}\right)^2 \frac{\sigma_{440}(pp, \pi^+)}{\sigma_{340}(pp, \pi^+)} \sigma_{340}(pp, \pi^0) \quad (9)$$

where λ is the wave length of the meson in the center of mass system and r_0 can be taken as a measure of the range of nuclear forces in p,p collisions. To evaluate Eq. (9) it is necessary to estimate the ratio of the (pp, π^+) cross section at 440 Mev to that at 340 Mev.

The (pp, π^+) data at energies of 380 Mev obtained by Passman and Block³³ indicate a T^2 meson energy dependence where T is the maximum meson kinetic energy in the center of mass system. From the data of Schulz at 340 Mev, however, partial agreement is obtained with a $T^{3/2}$ dependence. A straight T^2 meson energy dependence yields a value for the ratio in Eq. (9) of 11.5. However, if the data of Passman and Block is extrapolated to proton energies of 440 Mev, then the ratio in Eq. (9) would be 7.

Using the extrapolated value, the cross section for the (pp, π^0) process at 440 Mev is estimated to be approximately $0.24 \times 10^{27} \text{ cm}^2$ using the value for the 340 Mev (pp, π^0) process from this experiment. Fair agreement is obtained with the Chicago result, although it is uncertain whether the extrapolation is valid.

In conclusion, it is shown (1) that the 340 Mev result for the (pp, π^0) process is in relative agreement with the 440 Mev result, and (2) that there is some evidence for the breakdown of the approximate selection rule which forbids the emission of s-state mesons with final s-state nucleons.

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✓
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ILLUSTRATIONS

- Fig. 1a Cyclotron layout.
- Fig. 1b Experimental arrangement in the cave, showing relative positions of hydrogen target, magnet and Cerenkov counter.
- Fig. 2 Huygens construction for a bullet passing through air.
- Fig. 3 Huygens construction showing the derivation of the equation $\cos \theta = \frac{v}{n\beta}$
- Fig. 4 Detail of Cerenkov counter.
- Fig. 5 Photograph of Cerenkov counter.
- Fig. 6 Variation of response across diameter of Lucite radiator.
- Fig. 7 Variation of response under rotation of counter.
- Fig. 8 Attenuation curves for the neutral meson decay gamma rays in lead and copper.
- Fig. 9 Block diagram of electronics.
- Fig. 10a Schematic of photomultiplier and limiter circuit.
- Fig. 10b Triple coincidence network.
- Fig. 10c Crystal diode coincidence circuit and difference amplifier.
- Fig. 11 Detail of liquid hydrogen target.
- Fig. 12 Photograph of liquid hydrogen target assembly.

FIG. 1

HUYGENS CONSTRUCTION FOR A BULLET PASSING THROUGH AIR UNDER CONDITIONS (a) WHEN $v/v_s < 1$ AND (b) $v/v_s > 1$

MU 3894

FIG. 2

HUYGEN'S CONSTRUCTION SHOWING THE
DERIVATION OF THE EQUATION $\cos \theta = \frac{1}{n\beta}$

MU3893

FIG. 3

(a) SIDE VIEW OF TRIPLES DETECTION SCHEME SHOWING ONLY 1 TUBE
 (b) END VIEW SHOWING PLACEMENT OF 3-IP21 PHOTOMULTIPLIERS

MU 3891

FIG. 4

ZN 382

FIG. 5

VARIATION OF RESPONSE ACROSS DIAMETER
OF LUCITE RADIATOR

MU3302

FIG. 6

VARIATION OF RESPONSE UNDER ROTATION OF
COUNTER ABOUT POINT C

MU 3303

FIG. 7

FIG. 8

MU 3890

BLOCK DIAGRAM OF ELECTRONICS

FIG. 9

SCHEMATIC OF PHOTOMULTIPLIER AND LIMITER CIRCUIT

FIG. 10a

MU 3896

A - POSITIVE SIGNAL IN } SEE FIG. 9
 O - NEGATIVE SIGNAL OUT }
 P.T. - PULSE TRANSFORMER
 $\tau \sim 10^{-8}$ SEC.

TRIPLE COINCIDENCE NETWORK
 FIG. 10b

MU 3897

CRYSTAL DIODE COINCIDENCE CIRCUIT AND DIFFERENCE AMPLIFIER

FIG. 10c

MU3898

FIG. 11
DETAIL OF LIQUID HYDROGEN TARGET

MU 3889

ZN 383

FIG. 12