Experimental Evidence for Particle Intrinsic Parity

Prof. C. Foudas, 31/5/2017

A number of experiments took place in the US almost half a century ago which aimed to measure the parity properties of the newly discovered $\pi^{\pm}$, π^{0} mesons as well as the parity of other particles. In this lecture we will discuss some of the most important of them. The parity that we will be discussing here is the **intrinsic parity** associated with each particle and this is in addition to the parity associated with the orbital wave function of the particle. In other words, **the parity of the wave function of a particle or a system of particles is the product of the orbital parity times the product of the intrinsic parities of the particles involved.**

In interactions where parity is conserved (electromagnetic and strong) we can use this to derive selection rules for the various reactions. We do this aided by the following two ideas:

I. Under parity the orbital wave-function will change by $(-1)^{L}$ where L is the angular momentum quantum number. This is because the parity operation, $\vec{r} \rightarrow \vec{r}\,' = -\vec{r}$,changes $\theta \rightarrow \theta - \pi \;\; ; \;\; \phi \rightarrow \phi + \pi$. Due to this change in the angles the orbital wave function, which always involves spherical harmonics (central potential), changes as $(-1)^{L}$. This is actually the reason that the photon has negative parity, and is referred to as an 1^{-} state. Photons are emitted via atomic dipole transitions where $\Delta L = \pm 1$. Hence the atomic parity changes by (-1) during these transitions and for the overall parity of the system (atom + photon) to be conserved (electromagnetic interaction) we must have that the photon has negative parity.
II. The overall wave function must be symmetric for systems of bosons and anti-symmetric for systems of fermions.

In summary, the overall parity of the wave function of a set of particles is given by:

$$P = (-1)^{-L} \times P_1 \times P_2 \times \ldots \times P_s$$

where L is the total angular momentum and $P_i, i=1,..,s$ are the intrinsic parities of the particles involved. This can be used to derive selection rules for reactions which proceed via the interactions which conserve parity, namely the strong and electromagnetic interaction.

The Positronium experiment of C.S. Wu and I. Shaknov at Columbia University (New York), 1949.

As we have already seen, the free Dirac equation is invariant under parity and this implies that fermions and anti-fermions (negative energy solutions of the Dirac equation) have opposite parity. J.A. Wheeler (see Fig. 1) proposed in 1946 to test this prediction of Dirac in positronium (electron positron atom) annihilation when the positronium is at a zero angular momentum state: $^1S_0$. Since the positronium is in a zero angular momentum state its parity is simply the product of the two intrinsic parities of the electron and the positron and if Dirac's theory is correct this product should be equal to -1. It is trivial to show that every time an electron and positron annihilate momentum conservation requires that two photons are emitted. It is left as an exercise for the reader to prove that positronium annihilation to one photon violates momentum conservation.

The predicted negative parity of the positronium should then be transferred to the two-photon system since the electromagnetic interaction conserves parity. The idea to test this hypothesis was the following: The orbital wave function of the two photons from the positronium decay should be given in terms of the only three vectors available to describe this two particle system i.e. the polarization vectors, $\hat{e}_{1,2}$, of the two photons and the photon momentum, $\vec{k}$, which satisfy $\vec{k}\cdot\hat{e}_{1,2} = 0$ (plane waves because the photon is massless). There are only two ways to combine the 3 vectors to make the wave function:

$$\Psi(x) \sim A(\hat{e}_1\cdot\hat{e}_2) \qquad \text{(symmetric under particle exchange; scalar)}$$

$$\Psi(x) \sim B(\hat{e}_1\times\hat{e}_2)\cdot\vec{k} \qquad \text{(antisymmetric under particle exchange; pseudoscalar)}$$

all other combinations result to either one for the two above or give zero result. **In a two body system interchange of the two particles has the same effect as the parity operation**. Hence, if the first is true then the positronium has positive parity and Dirac's theory is wrong and if the second is correct then the positronium has negative parity according to the predictions of Dirac's theory. The two choices of wave function imply that the photon intensity as a function of the angle between the polarization vectors will be:

$$I \sim |A|^2\cos^2(\Phi) \qquad \text{if the positronium is a scalar}$$

and

$$I \sim |B|^2\sin^2(\Phi) \qquad \text{if the positronium is a pseudoscalar.}$$

In practical terms if one could measure the polarization vectors of the two photons and found them mostly at perpendicular to each other then the second equation is true and the first is false. If on the other hand the polarization vectors are mostly aligned with each other the the opposite is true.

Wu and Shaknov (see Fig. 1) , then at Pupin Laboratories at Columbia University in New York, took up Wheeler's suggestion and designed an experiment to test this prediction. Their experiment used a ^{64}Cu source which is a positron emitter. As shown in Fig. 2, the source, enclosed in an Aluminium case, was placed in a lead block which had a hole drilled through it. Photons from positronium annihilation emitted not at the direction of the hole get absorbed in the lead block. Only the photons which are emitted left and right at the direction of the hole can exit the apparatus. Hence, the photon direction is well defined (collimated).

This way they selected only the events where, when an electron and a positron annihilate, two photons exit from the two sides of the lead hole. The photons are of course electromagnetic radiation and have their electric field perpendicular to the direction of motion, i.e the polarization vectors $\hat{e}_{1,2}$ and the photon momentum, $\vec{k}$, satisfy $\vec{k} \cdot \hat{e}_{1,2} = 0$. Wu and Shaknov placed at each exist of the lead block an aluminium scatterer. The two photons Compton-scatter by the aluminium in a process where the polarization vectors $\hat{e}_{1,2}$ do not change direction before and after the scattering. The reason for this is that the Compton cross section as low energy is approximately the Thomson cross section which is given by

$$\frac{d\sigma}{d\Omega} \sim (\hat{e} \cdot \hat{e}')^2$$

where $\hat{e}, \hat{e}'$ are the polarization vectors of the photon before and after scattering.

Another way of understanding this is that the incoming photon causes the electrons in the scatterer to oscillate at the direction of its electric field, i.e. perpendicular to its direction of motion. The oscillating electrons emit the scattered photon perpendicular to the line of oscillation i.e the scattered photon will have the same polarization as the incoming one. A diagram of the scattering process of the two photons is shown in Fig. 3. As seen there, the two photons travel at opposite directions and scatter off the aluminium scatterers. Each scattered photon has the same polarisation as the incoming photon which is perpendicular to its direction of motion. **Hence, the angle between the directions of the two scattered photons is the same as the angle between the polarization vectors of the two original photons from the positronium which we wish to measure.** So the experimental goal is to measure the intensity of the photons emitted as a function of the angle between the two photons.

The result of the experiment[1] is shown in Fig. 4 which shows that the two photons are emitted mostly perpendicular to each other. Therefore, the angle between the polarization vectors of the two photons is 90 degrees. **Hence, the positronium is a pseudoscalar and since it has angular momentum zero it means that the electron and positron have opposite intrinsic parities and Dirac's theory is correct.**

[1] *C.S. Wu and I. Shaknov, Physical Review 77, 136, 1950.*

Figure 1: *J.A. Wheeler and C.S. Wu*

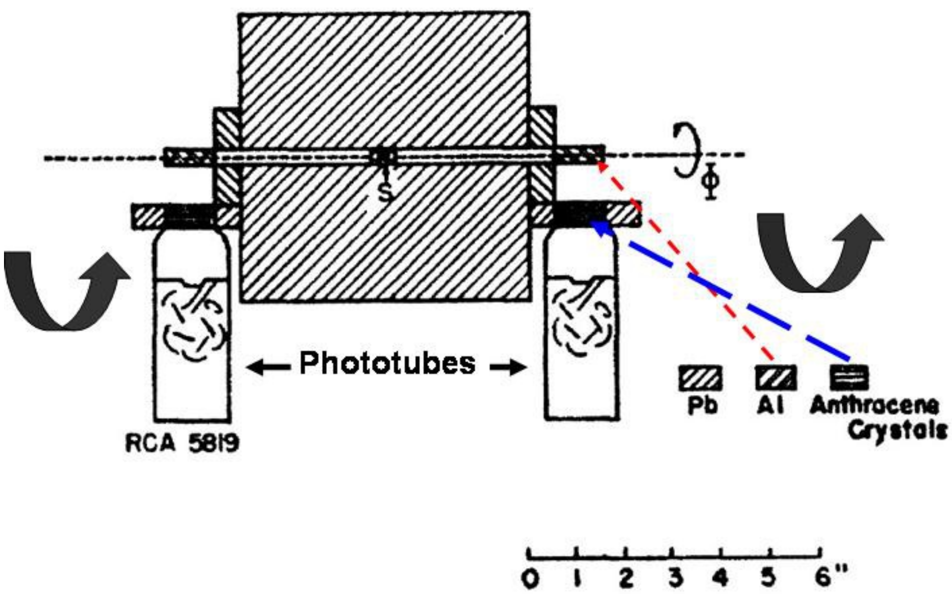


Figure 2: *The apparatus of C.S. Wu and I. Shaknov. The beta emitter, S, is shown in the lead collimator. The two aluminum scatters are seen left and right in front of the collimator holes. The phototubes can rotate in ♮and measure the intensity and direction o f the scattered photons. Crystals of a scintillator called Anthracene were used to detect the scattered photons. The light from the Scintillator was read out using two RCA 5819 phototubes. The size of the experiment in inches is shown at the bottom right, orders of magnitude smaller than todays HEP experiments.*

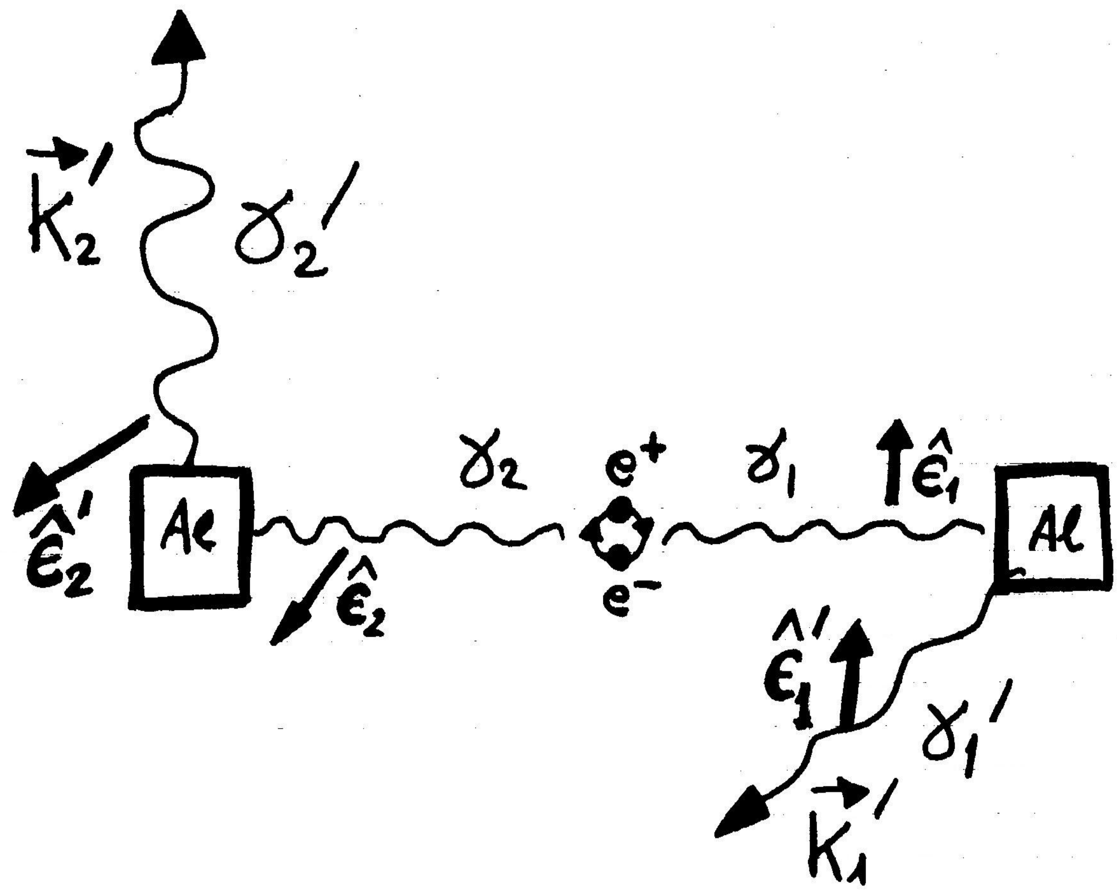


Figure 3: *Schematic diagram of the directions and polarizations of the two scattered photons in the Wu-Shaknov experiment.*

$$\frac{\text{Coincidence counting rate }(\perp)}{\text{Coincidence counting rate }(\parallel)} = 2.04 \pm 0.08,$$

Figure 4: *The measurements show that the rate ,when the two photons are perpendicular ,is twice that measured when they are aligned.*

Photon Interactions with Matter

Several experimental results which will be discussed next require knowledge on how photons interact with matter. Hence, we give here a brief summary:

As shown in Fig. 5, depending upon their energy, photons interact with matter via 3 main processes.

I. The photoelectric effect which should be well known to the reader from Quantum Mechanics courses.

II. The Compton effect where photons scatter off the atomic electrons, $\gamma e^- \to \gamma e^-$.

III. Via pair creation of an electron-positron pair which is sometimes called photon conversion. Obviously to do that the photon must have an energy which is at least twice the mass of the electron. Note also that this process also requires the presence of a heavy nucleus to proceed. Otherwise one cannot conserve both energy and momentum at the same time. Hence, photons will not pair create is absolute vacuum.

Clearly the Compton and Photoelectric effects are dominant in the range below 1 Mev photon energy, whilst the pair production dominates above 1 MeV where there is enough energy to produce electron-positron pairs.

As seen in the previous lecture the electromagnetic showers from photons are slightly different than those from electrons. Photon showers start slightly deeper than the electron generated showers (need to pair-convert first) and reach the shower maximum one radiation length deeper than electron showers. The energy loss by photons is given by :

$$E(x) = E_0 e^{-\frac{7x}{9X_0}}$$

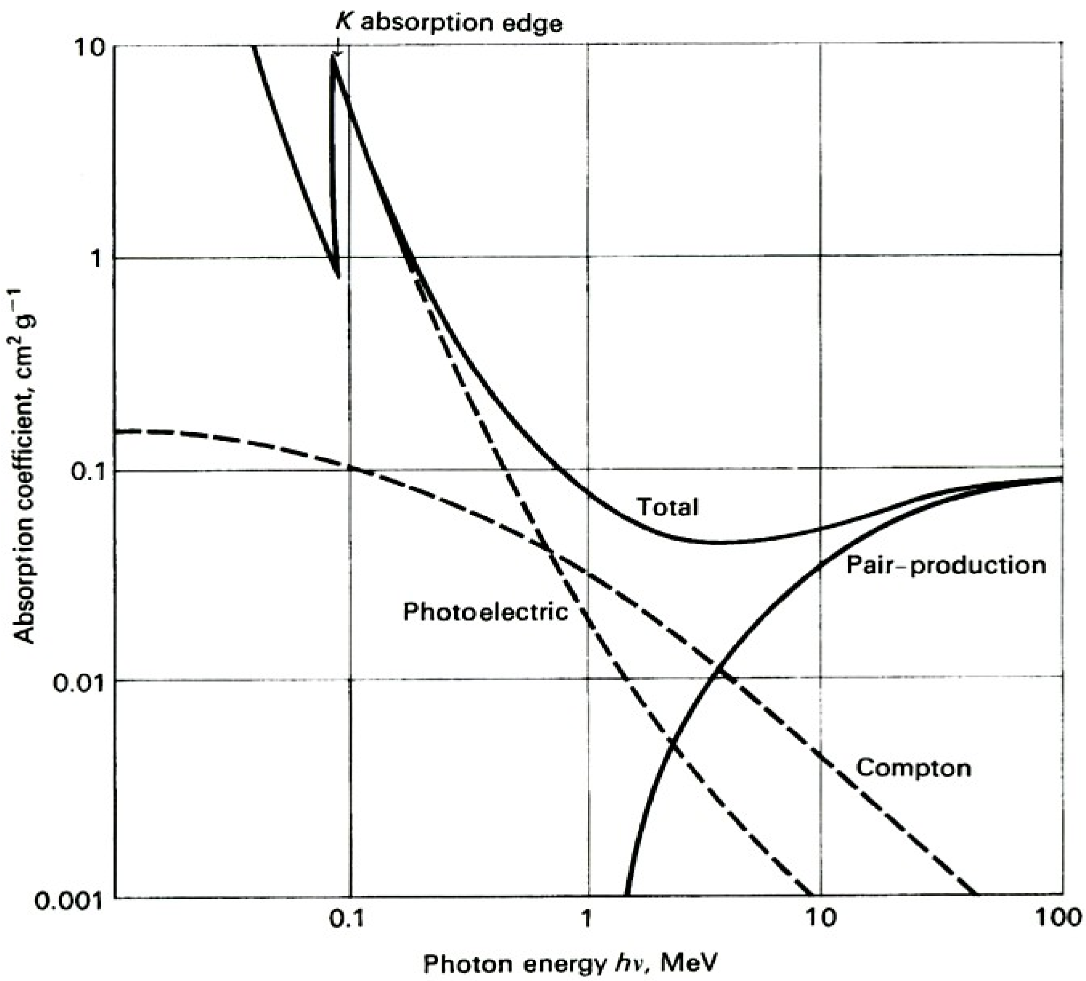


Figure 5: *The total photon absorption coefficient and its various components. Low energy photons are absorbed by matter via the Compton and Photoelectric effects. Photons of energy above twice the mass of the electron lose energy via the pair-production process. This is sometimes referred to as photon conversion process where the photon converts to an electron-positron pair at the presence of a nucleus. The reaction cannot proceed in absolute vacuum as it violates momentum conservation.*

Measurements of the Pion Masses and Parities

Evidence for the existence of the neutral pion:

As discussed before the charged pion was discovered in 1948 by Powel and collaborators at Bristol by exposing emulsion material in cosmic rays. Its existence was confirmed in the early fifties by the first accelerators which had enough energy to produce it. At the same time evidence started appearing for the existence of its neutral partner which was expected from the theory of Yukawa, using the strong isospin formalism proposed by Heisenberg in the 1930s. The first experiment to produce such evidence was the experiment of R. Bjorklund *et al.* at the Berkeley 184' cyclotron[2].

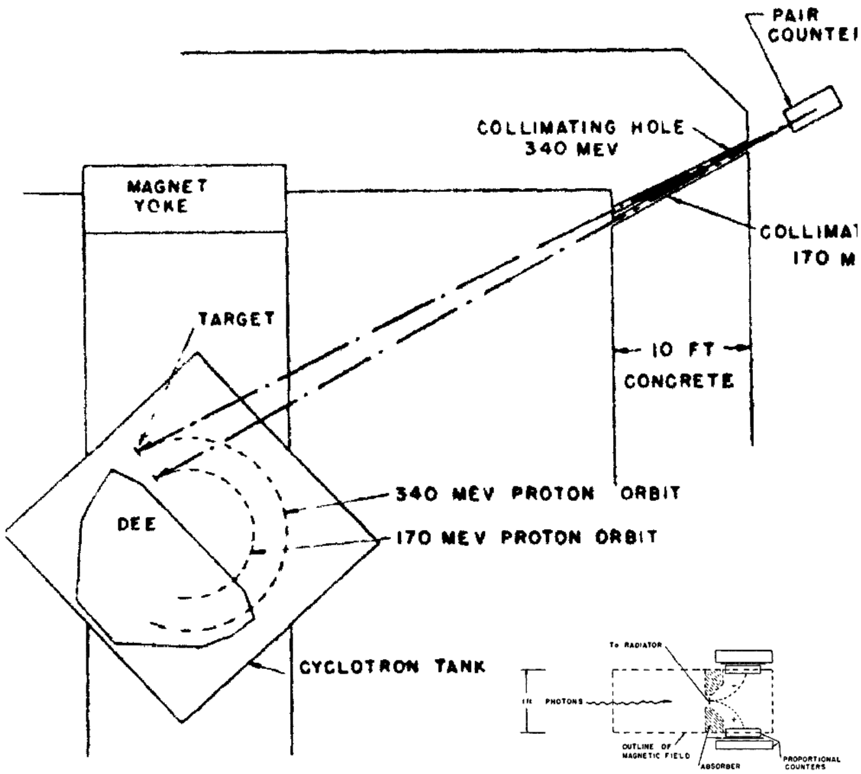


Figure 6: *The apparatus and results of the Bjorlund experiment. Seen at the left is the 184' Berkeley cyclotron which produced proton beams of different energies. They beams were directed to strike a target and produce a variety of particles. A pair spectrometer is seen at some distance from the target which was used to detect and measure the energy of the photons coming from the collision of the beam protons with the target. The details of the pair spectrometer as seen at bottom-left. A Tantalum converter is used first to force the photons to convert to electron positron pairs. The electron and positron momenta are then measured by measuring their bending in a magnetic field.*

[2] R. Bjorklund *et al.,* Physical Review 77, 213, Jan. 1950.

Bjorklund *et al.* directed the cyclotron proton beam to strike a target and searched for photons produced among the hadronic shower which resulted from the proton-proton collision. Their apparatus is shown in Fig. 6. Using a pair spectrometer to detect photons they observed the presence of 'hard' (high energy) photons in the shower and measured their energy distribution which is shown in Fig. 7. One can easily compute the available energy at the proton(beam)-proton(target at rest) centre of mass frame which is given by:

$$W = \sqrt{2M_P^2 + 2M_P E_{BEAM}}$$

where M_P, E_{BEAM} are the proton mass and the proton beam energy. As seen in Fig. 7 the photon energy spectrum changes markedly with increasing beam proton energy for proton energies above 290 MeV indicating that a new particle is being created. The authors excluded proton Bremstrahlung as the source of the high energy photons since as we have seen the protons do not radiate easily photons and when they do the result to a spectrum varying as 1/E with energy. The shape of the data for 180 and 230 GeV could be consistent with proton Bremstrahlung, although one would expect that the cross section should be orders of magnitude smaller. The shape of the data for proton energy 290, 340 MeV demonstrates clearly that this is not Bremstrahlung but something else. Nuclear Doppler effects were also excluded. Therefore, the results suggested that is a new channel (particle)opens-up as there is enough centre of mass energy to produce it.

Of course today that we know the neutral pion mass (135 MeV) we can calculate exactly what is happening. The threshold to produce two protons and a neutral pion in the final state is **2.011 GeV**. Table 1 shows the available energy at the centre of mass system computed using the formula above versus the proton beam kinetic energy. Hence, for 290 MeV beam kinetic energy we have exceeded the threshold to produce a π^0 and this is why the photon spectrum changes shape. They were seeing π^0 production. In addition by observing the photon spectrum around the threshold, where the π^0 will be produced almost at rest, one concludes that its mass is between 120 and 140 MeV.

Beam Kinetic Energy (MeV)	Proton Energy (GeV)	Centre of mass energy (GeV)
180	1.118	1.964
230	1.168	1.988
290	1.228	2.016
340	1.278	2.039

Table 1: *The Energy available at the proton-proton centre of mass frame(right) as a function of the proton beam energy(left).*

Of course the experiment of Bjorklund *et al.* gave only indirect evidence that some new particle is produced which decayed in to photons. The same is true for the experiment of Panofsky *et al.* which we will be discussing later in this lecture.

For direct experimental proof one needs to detect both photons from the π^0 decay in time coincidence and if possible to measure both energy and direction of the two photons to be able to reconstruct the mass. Two experiments measured such coincidences. The first one was done by Steinberger, Panofksy[3] and Steller (see Fig. 8) using a photon beam to produce π^0 and the second by Sachs and Steinberger[4] (see Fig. 9) and was using a π^- beam to produce the π^0. These experiments confirmed beyond doubt that a neutral meson was produced with mass similar to that of the $\pi^\pm$ and decayed into two photos which meant that its spin was an integer lesser than 3 and could not be 1. Hence, it was most probably a scalar or a pseudoscalar.

[3] J. Steinberger, W. Panofsky, J. Steller, Physical Review 78, 802, (1950).
[4] A. Sachs and J. Sreinberger, Phys. Rev 82, 973, (1951).

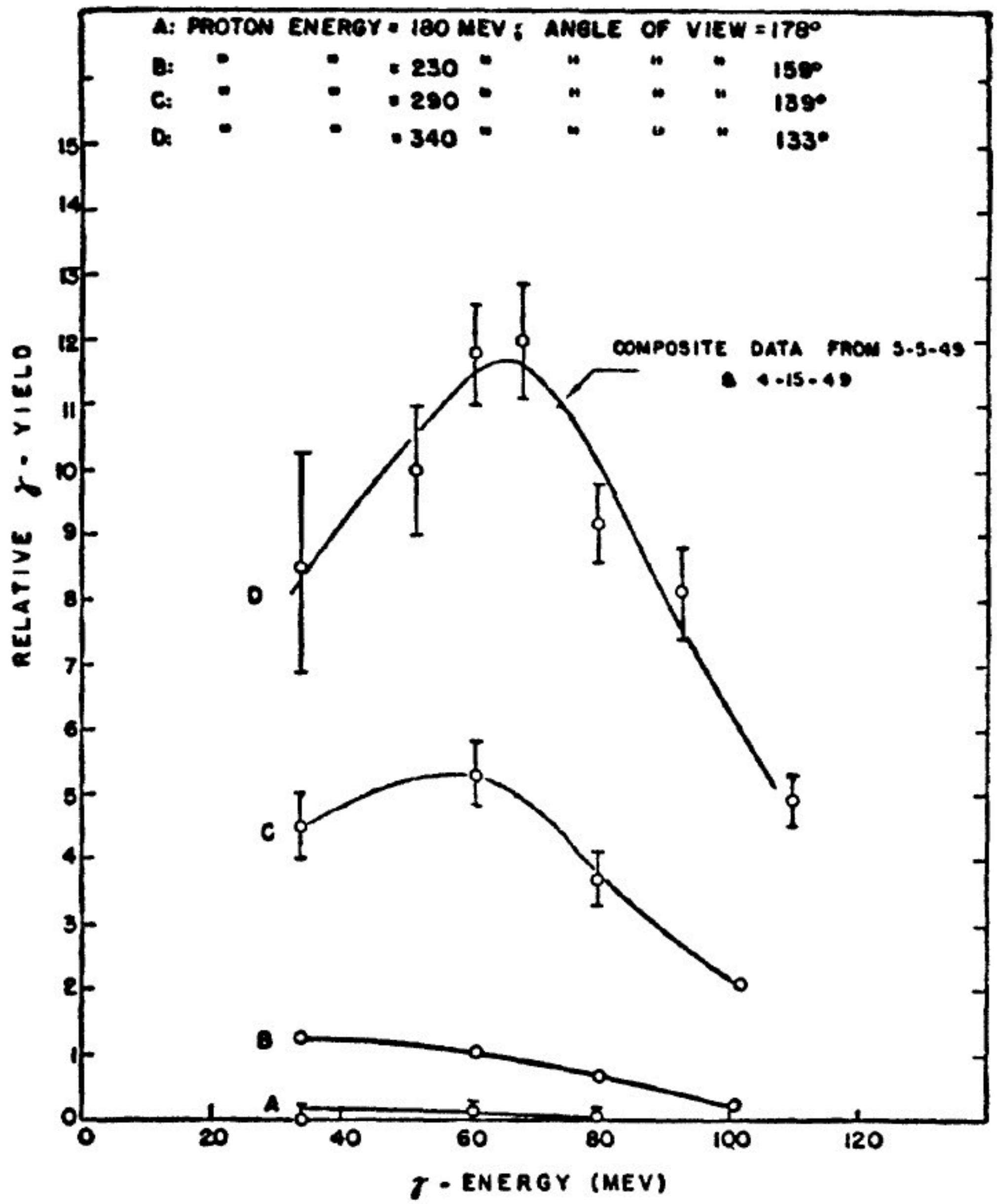


Figure 7: *The energy distribution of the final state photons for proton energies 180, 230, 290 and 340 MeV. The data sets C and D exhibit a very different shape than the sets A and B.*

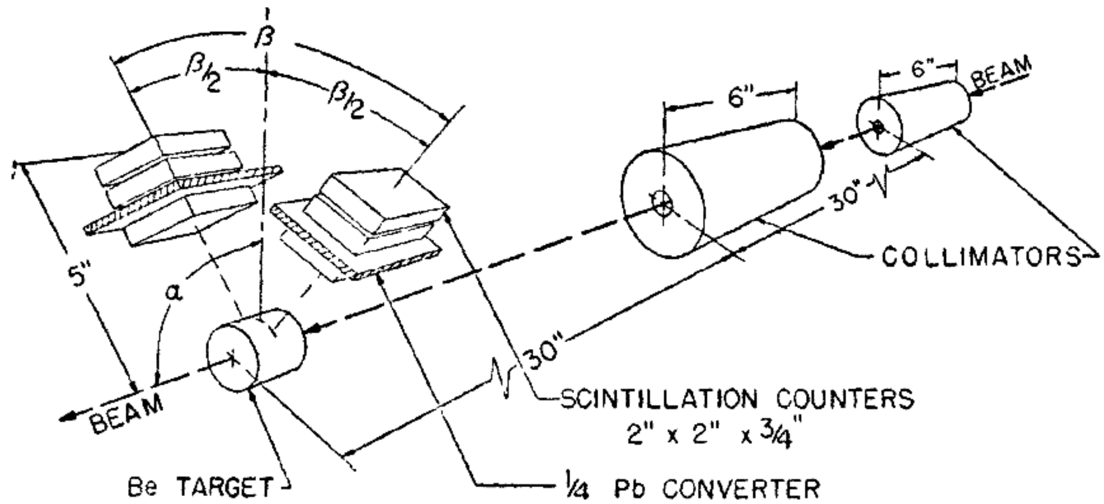


Figure 8: *The apparatus of Steinberger, Panofsky and Steller. Neutral pions were produced when the photon beam from the Berkeley synchrotron struck a Be target. The photon energy and direction was measured with the two detectors shown at the top. Each detector consisted of an initial scintillation counter followed by sheet of Pb converter and two more scintillation counters. A photon was identified if the first scintillation counter did not fire (neutral particle) and the other two did fire recording the products of a photon conversion.*

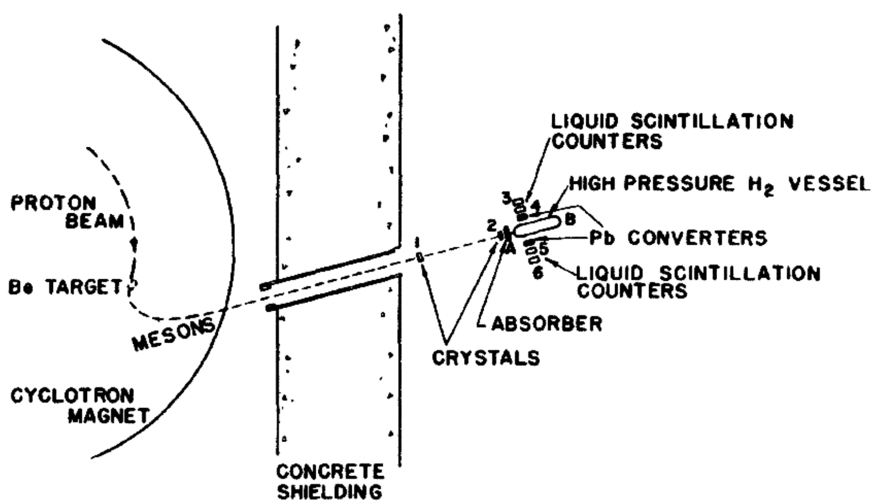


Figure 9: *The experimental apparatus of A. Sachs and J. Steinberger at the NEVIS cyclotron at Columbia University. Negative pions produced by striking the cyclotron proton beam on a Be target we collimated and directed to a Hydrogen target. The Hydrogen target is seen to the right. From both sides of the target two detectors are seen designed to measure photon coincidences which would verify that a neutral particle as produced and decayed in to two photons. The photon detectors used a sheet of Pb as photon converter followed by liquid scintillators which measured the energy of the electromagnetic shower.*

The experiments of W. Panofsky *et al.* at Berkeley Radiation Laboratory

After Bjorklund had seen the photons from the π^0, W. Panofsky and collaborators designed one of the most successful experiments[5] in particle physics which measured the masses the π^- and the π^0 and gave the first even if indirect measurement of the parity of the π^- . The apparatus of Panofsky and collaborators is shown in Fig. 10 and Fig. 11. The Berkeley 184' cyclotron 330 MeV proton beam struck a tungsten target and produced a hadronic shower. The resulting π^- from the shower were slowed down in a hydrogen tank at high pressure until they come to rest. Eventually the π^- at rest gets captured by the proton nucleus which is also at rest. The negative pions on capture initiated the following reactions:

I. $\pi^- \, p \to n \gamma$; where p , γ , n stand for proton, photon and neutron.
II. $\pi^- \, p \to n \pi^0$; the neutral pion decays subsequently in to two photons via the process $\pi^0 \to \gamma\gamma$.

The experiment searched for photons originating from the two reactions above. The outgoing photons were collimated using a concrete shield with a hole drilled through it as shown in Fig. 10 and were directed to a pair spectrometer, shown in Fig. 11 which measured the photon energy with the following way. As shown in Fig. 11 the photons first passed a thin Tantalum sheet where they converted to electron positron pairs. Next the electrons and positrons were bent using a magnetic field and their trajectories were measured using two arrays of Geiger counters. Behind the Geiger counter arrays two pairs of proportional counters were put in quadruple coincidence and provider the trigger for recording the data. The Geiger counters are two noisy for to provide the trigger and were used only to measure the position of the electrons and positrons once there was a trigger.

The measured photon spectrum is shown in Fig. 12 with the contribution from the two reactions very clearly separated. It is a simple exercise, left to the reader, to show that if the pion and the proton are at rest the first reaction will result to mono-energetic photons of energy:

$$E_\gamma = \frac{(M_{\pi^-} + M_P)^2 - M_n^2}{2(M_{\pi^-} + M_P)} \qquad \text{(A)}$$

Hence, the sharp mono-energetic peak at $E_\gamma = 130\,MeV$ represents the photons from the first reaction. However, since the proton and neutron masses were known to be $M_P = 938.3\,MeV$, $M_n = 939.6\,MeV$ one could solve (A) for the π^- mass to get:

$$M_{\pi^-} = -(M_P - E_\gamma) + \sqrt{M_n^2 + E_\gamma^2} = 140\,MeV$$

[5] W. Panofsky, R.L. Aamodt and J. Hadley, Phys. Rev. 81, 565, 1951.

and this was the first result of the experiment. In addition the reader can use addition of angular momenta to show that the fact that the first reaction occurs proves that the π^- is a boson with possible spin 0, 1, 2.

The contribution to the photon spectrum at lower energies, shown also in Fig. 12, are photons from π^0 decay originating from the second reaction. Since the π^0 is not produced at rest but it is boosted relatively to the laboratory frame the photons from the π^0 decay have their energies Doppler-shifted with a characteristic spectrum extending from E_γ^{MIN} to E_γ^{MAX} as shown before[1]. Furthermore, using relativistic kinematics one can show that the π^0 momentum in the lab frame is is given by $\Delta W = E_\gamma^{MAX} - E_\gamma^{MIN}$. Hence, the kinetic energy of the outgoing neutron is given by:

$$KE_n = \frac{(\Delta W)^2}{2M_n}$$

The non relativistic formula for the kinetic energy of the neutron is quite accurate in this case since as you can see using Fig. 12:

$$\Delta W = 85.0 - 53.6\, MeV = 31.4\, MeV \quad \text{(M)}$$

Panofsky *et al.* Used this to calculate the mass of the π^0. Here is their calculation:

Let $\Delta = M_n - M_P$ be the difference between the neutron and proton masses. Then

$$M_{\pi^0} = \sqrt{E_{\pi^0}^2 - P_{\pi^0}^2} \quad (1)$$

and

$$E_{\pi^0} = M_{\pi^-} - \Delta - KE_n \quad (2)$$

Since the π^- and the proton are originally at rest the momentum of the outgoing neutron is equal to the momentum of the outgoing π^0. Hence, it is then easy to show, and it is left as an exercise, that:

$$M_{\pi^0} = (M_{\pi^-} - \Delta)\sqrt{1 - \frac{2\,KE_n(M_{\pi^-} + M_P)}{(M_{\pi^-} - \Delta)^2}} = 134\, MeV$$

which is not very far from the particle data book value.

[1] See homework assignment 3.

Alternatively one could compute the π^0 total energy from:

$$E_{\pi^0} = M_{\pi^-} + M_P + \sqrt{M_n^2 + P_n^2} = M_{\pi^-} + M_P + \sqrt{M_n^2 + P_{\pi^0}^2}$$

using conservation of energy and momentum and then use (M) to arrive at the same result. Hence, the experiment showed that the neutral pion, the π^0, has a mass that was very close to its charged partners which are slightly heavier because they are charged. This is an example where the electromagnetic interaction breakes the isospin symmetry under which all three pions should have the same mass.

It is left to the reader to show the last conclusion of the authors. Namely the fact that because the second reaction occurs it means that the charged and neutral pion have the same intrinsic parity.

Next Panofsky *et al.* replaced the hydrogen target with a deuterium one. Negative pions in Deuterium gave rise to the following reactions:

I. $\pi^- D \rightarrow n\ n\ \gamma$; where D, γ, n stand for deuterium, photon and neutron.
II. $\pi^- D \rightarrow n\ n$.

Although they could not observe the second reaction with their apparatus, they could compare the photon yield of the first reaction with that from hydrogen and thus normalize the deuterium data using the hydrogen data. Here is what they found:

Particle emitted \ Absorber	H	D
π^0	0.45 ± 0.09 c/m	-0.007 ± 0.020 c/m
Single γ	0.470 ± 0.046 c/m	0.275 ± 0.034 c/m
Two fast neutrons		0.65 ± 0.11

Table 2: *Counts per minute for processes resulting to neutral pions, single photons and two neutrons for hydrogen and deuterium targets. The neutron rate is derived by summing the hydrogen rates and subtracting the deuterium single photon rate.*

Hence, they could tell that a large fraction, 70%, of their negative pions produced something else that they could not observe. From this they concluded that the second reaction must have occurred. However, their apparatus which was not sensitive to neutrons could not observe it. This is what we call indirect evidence for the existence of a reaction. Crucial to this result is that the reaction with two neutrons and a neutral pion in the final state does not occur for deuterium targets.

As we will see in the next discussion this reaction is crucial in determining the the parity of the negative pions. Panofsky *et al.* used this indirect evidence for reaction II to show that the parity of the negative pion is negative.

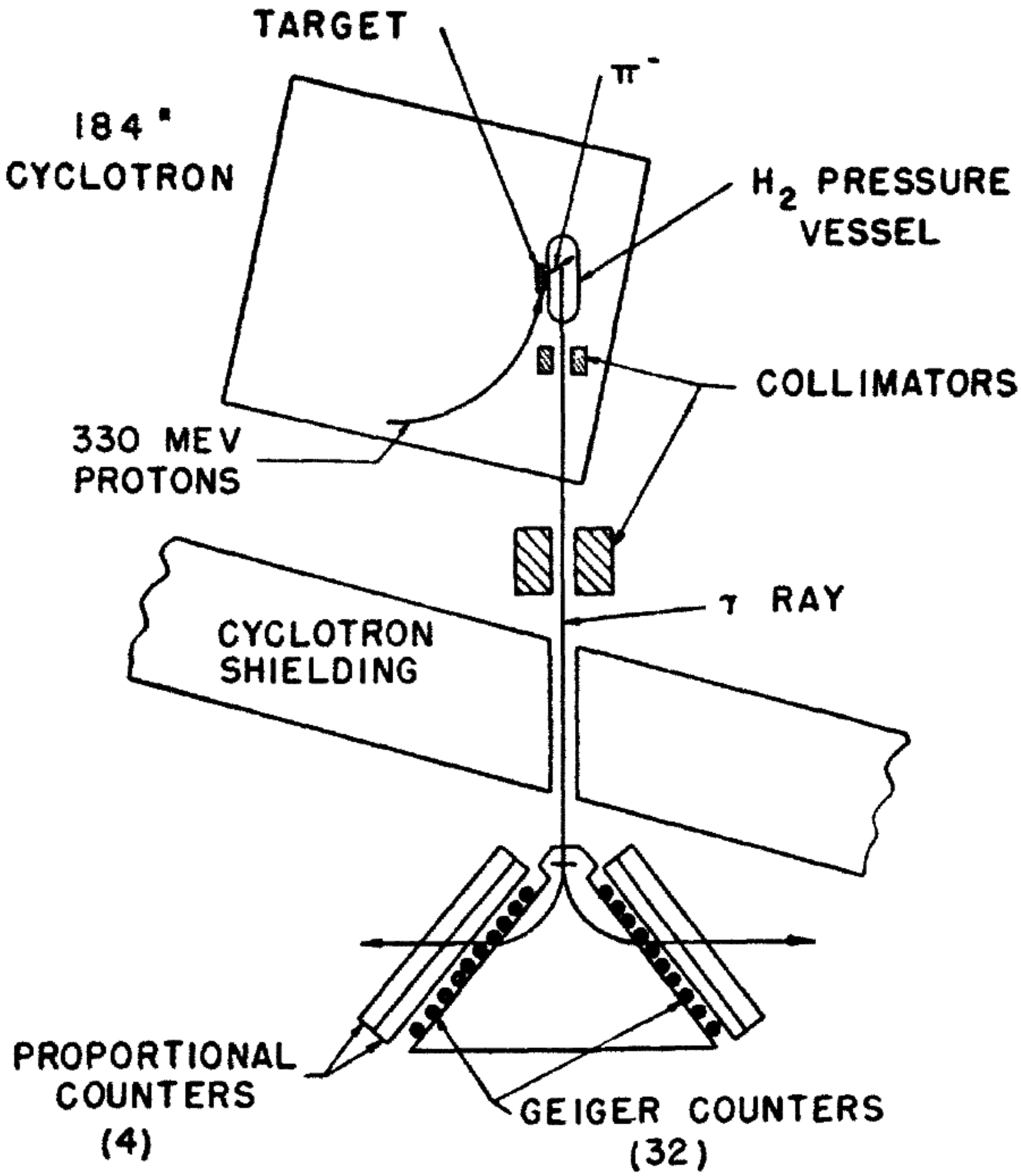


Figure 10: *The experimental apparatus. The 184' Berkeley cyclotron is shown at the top. The 330 MeV cyclotron proton beam strikes a tungsten target and produces mostly pions. The negative pions stop in the hydrogen tank and undergo reactions which produce photons. The photons are directed using collimators to a pair spectrometer which consists of a photon converter sheet followed by a spectrometer consisting of two sets of counters in a magnetic filed which used to momentum analyze the electron positron pair.*

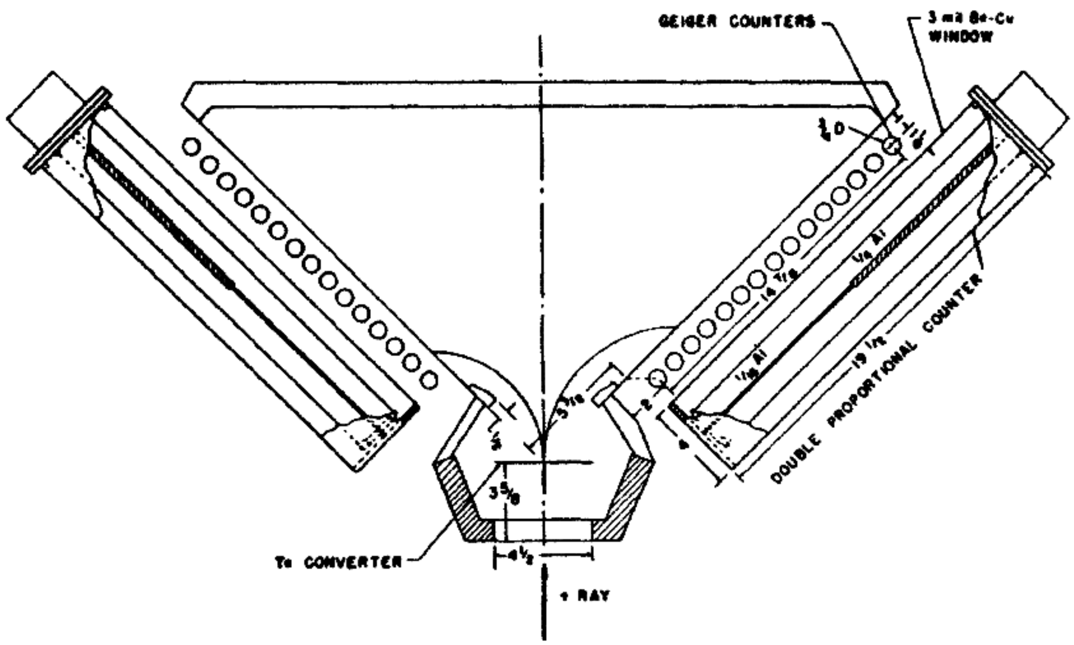
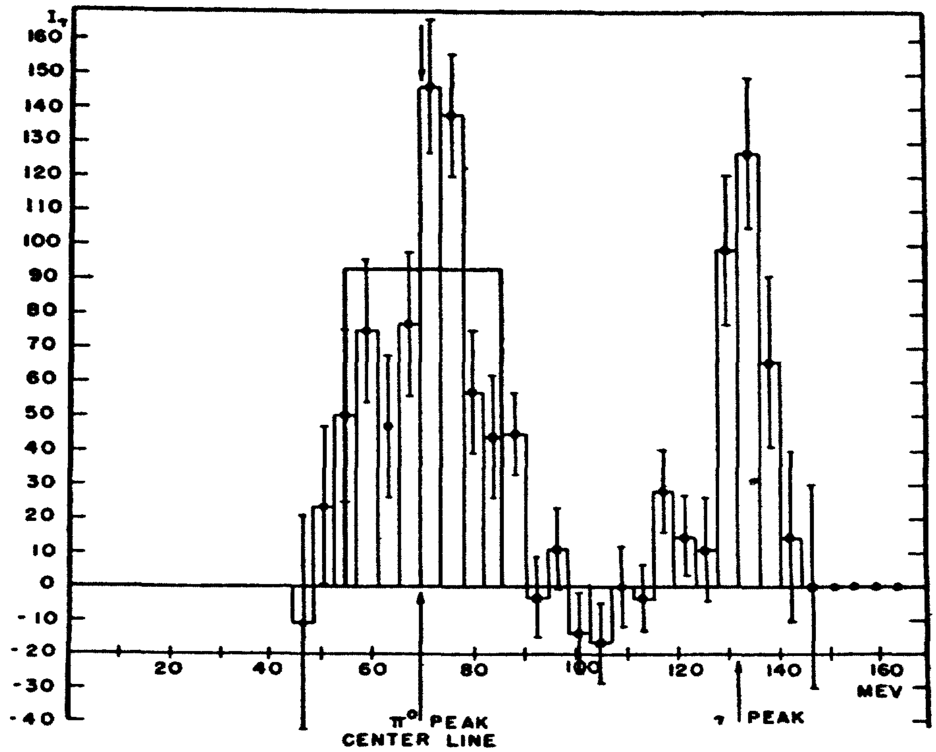


Figure 11: *The pair spectrometer consisted of two arrays of Geiger counters which measured the impact position of the electron positron pair and 4 proportional counters which were used for triggering. The photons come from the bottom of the picture and convert to an electron positron pair which then bends in opposite directions in the magnetic field. If the two electrons cause a quadruple coincidence of the proportional counters (all 4 sensing electrons going through) then the data of the Geiger counters were recorded.*



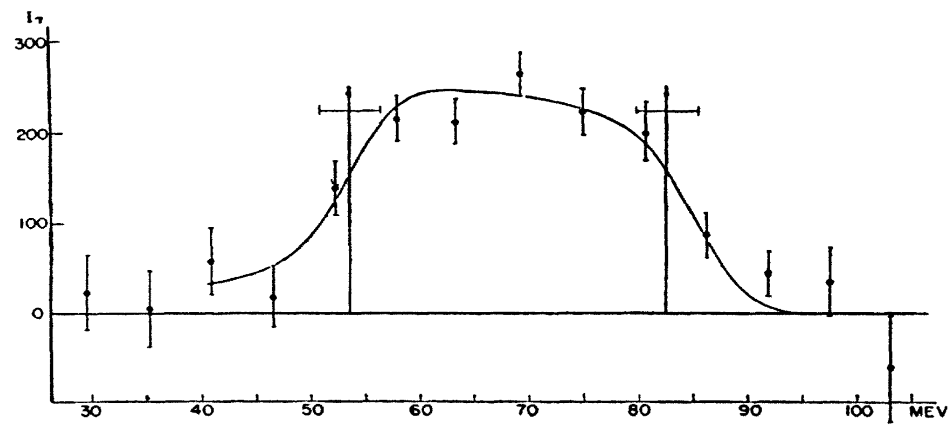


Figure 12: *The photon spectrum (top). The two components, one from the Doppler shifted* π^0 *photons at lower energy and a second from the mono-energetic photons of the neutron-photon reaction at higher energies are clearly visible. The photon spectrum from* π^0 *decay shown using an expanded scale (bottom) extends from 53.6 MeV up to 85 MeV.*

The Chinowsky-Steinberger experiment at Columbia University, Nevis Laboratories: The parity of the negative pion

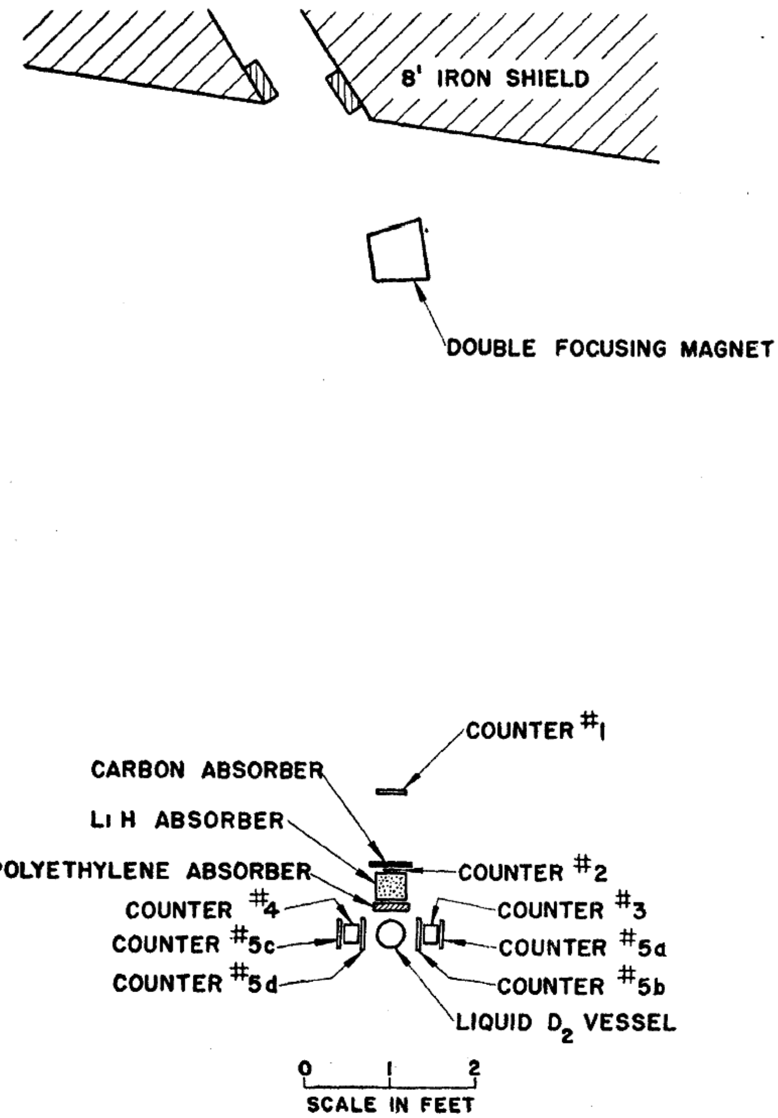


Figure 13: *The experimental apparatus of Chinowsky-Steinberger at Nevis Labs, Columbia University. Negative pions produced by striking the Nevis cyclotron beam on a target were slowed down by three types of absorbers. The slow pions stopped and got captured by the Deuterium. The resulting neutrons from the capture reaction were detected by the two neutron counters in coincidence producing a irrefutable evidence for the occurrence of the reaction* $\pi^- D \rightarrow n\ n$.

Chinofsky and Steinberger[6] decided to test the conclusions of Panofsky and collaborators by designing an experiment where they could detect the two final state neutrons and settle the question on the parity of the negative pions. Their apparatus is shown in Fig.13.

Negative pion capture by deuterium[7] (or hydrogen) can only happen when the pions are slow and the deuterium has enough pressure so that the life-time of the capture reaction is shorter than the pion lifetime. For this reason several pieces of absorbing material were placed along the direction of the pion beam to slow down the pions. Neutron data were recorded when counters 1 and 2 fired (a negative pion went through) in coincidence with the neutron counters 3 and 4 (consistent with neutron signature) and in anti-coincidence with the counters 5a, 5b, 5c, 5d (it was a neutral particle but not a photon). Hence, the experiment was tuned to detect the reaction $\pi^- D \rightarrow n\ n$.

The second reaction, $\pi^- D \rightarrow n\ n\ \gamma$, was used to optimize the amount of absorber in the direction of the pion beam with the purpose to maximize the number of pions which came to rest in the deuterium and got captured. The results of this technique are shown in Fig. 14.

As seen in Fig 14, where the number of photons are plotted versus the amount of the absorption material, the photon rate increases initially as the pions slow down and the number of the that gets captured increases. It eventually drops again as more and more pions stop in the absorber.

After optimizing the amount of absorber, the experiment consisted in measuring neutron rates and establishing that the reaction $\pi^- + D \rightarrow n + n$ occurred. The measured the neutron rates with and without deuterium in the tank so that they could subtract possible backgrounds. Their results are in Fig. 15 which established that the reaction above occurred.

[6] W. Chinowsky and J. Seinberger, Physical Review 95, 1561, (1954)
[7] K. Brueckner, R. Serber and K. Watson, Physical Review 81, 575, (1951).

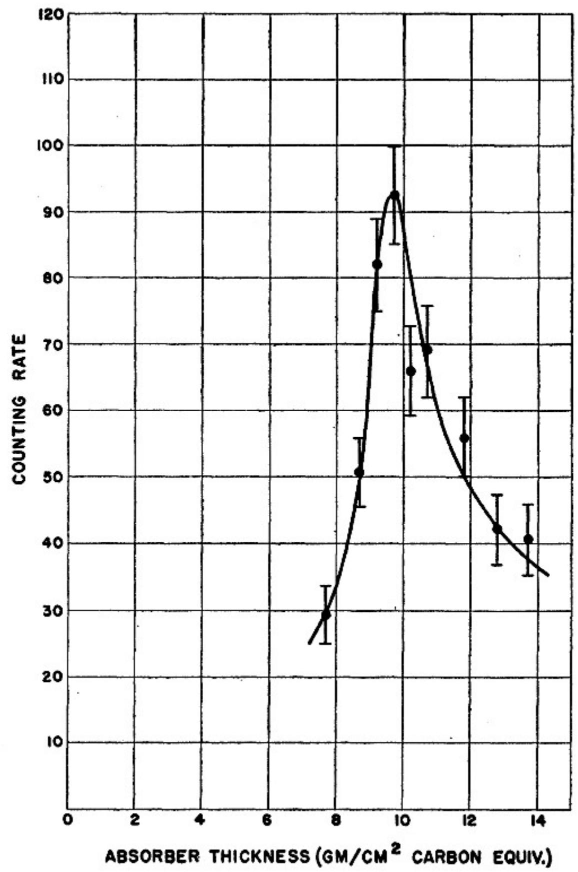


Figure 14: *The photon spectrum from the reaction* $\pi^- \ D \rightarrow n \ n \ \gamma$ *as a function of the amount of absorber inserted in the direction of the pion beam.*

	Counts with D_2 in cup	Counts with cup empty	Net due to D_2
1234	1.02 ± 0.19	0.08 ± 0.1	0.94 ± 0.20
1234−5	0.70 ± 0.16	0.08 ± 0.1	0.62 ± 0.19

Figure 15: *Neutron rates and backgrounds from negative pion capture in deuterium. The first raw shows the triggered rate without the anti-coincidence for neutral particles and the second shows the rate including the counter-5 anti-coincidence. Shown in the 3d column are the background subtracted rates.*

Having established that the reaction occurred they determined the parity of the negative pion as follows: The capture takes place in the S-state and the spins of the deuterium and pion are $S_d = 1$ and $S_{\pi^-} = 0$ respectively. The deuterium has positive intrinsic parity. The capture reaction gives two neutrons (fermions) in the final state.

$$\pi^- + d \rightarrow n + n$$

The problem can be solved by noticing that:

(1) The total initial angular momentum is $J = 1$ because the orbital angular momentum is zero (S-state). Hence, it is only the deuterium spin which contributes.

(2) The complete wave function of the two neutrons in the final state is can be written as:

$$\Psi = \Phi(orbital) \times S(spin)$$

and must be antisymmetric under exchange of the two identical fermions.

(3) The spin wave function of the two final state fermions is given by:

$$|1,1> = |\uparrow\uparrow>$$

$$|1,0> = \left(\frac{1}{\sqrt{2}}\right)(|\uparrow\downarrow> + |\downarrow\uparrow>) \qquad \textbf{(S=1; Triplet)}$$

$$|1,-1> = |\downarrow\downarrow>$$

and

$$|0,0> = \left(\frac{1}{\sqrt{2}}\right)(|\uparrow\downarrow> - |\downarrow\uparrow>) \qquad \textbf{(S=0; Singlet)}$$

From (2) and (3) we have that the parity of the neutron wave function will be:

$$(-1)^{L+S+1}$$

Note that: (a) in the two-body wave function the interchange of the two fermions amounts to parity inversion. (b) the singlet is antisymmetric and and triplet is symmetric. Since the total wave function must be anti-symmetric it means that:

$$(-1)^{L+S+1} = -1 \Rightarrow L+S = even$$

Hence, there are several possibilities:

L	S	J	L+S odd/even	OK/NOT OK
0	**1**	**1**	**odd**	**Not OK**
1	**0**	**1**	**odd**	**Not OK**
1	**1**	**0,1,2**	**even**	**OK**
2	**1**	**1,2,3**	**odd**	**Not OK**

And only the third one has both total angular momentum equal to one and **L+S** even.

Conclusion:

This means that the parity of the neutron system is: $(-1)^L = (-1)^1 = -1$ since the intrinsic neutron parity appears in square.

Because the pion capture is an electromagnetic reaction it conserves parity. Hence the parity of the pion deuterium system must also be **-1**. Considering that this system has angular momentum zero and that the parity of the deuterium is +1 we conclude that the pion must have negative parity. **Hence the negative pion is a pseudoscalar or 0^- .**

Bubble Chambers

Figure 16: *The Big European Bubble Chamber and its piston at CERN after being decommissioned.*

The Cloud Chambers used before and immediately after the WW-II in particle physics were replaced by instruments called Bubble chambers. The Bubble chamber (see Fig 16) was usually filled with a liquid gas such as hydrogen and had a piston which, just like the expansion Cloud chamber, moved synchronously with the accelerator beam pulses and brought the liquid in a superheated state (about to boil). Charged particle going through the chamber will create boiling-seeds which eventually become bubbles. Hence, charged particle traces could be seen as series of small bubbles. Cameras we synchronized with the Bubble Chamber expansion and would make pictures of the interactions. Such a picture of a positive pion decaying in to a positive muon and a muon neutrino is shown in Fig. 17.

The Bubble Chambers were filled with a liquid in contrast to the Cloud Chambers which were filled with a vapor. Hence, one could achieve larger event samples suing beams of similar intensity. Further more they could expand faster and be easily synchronized with the accelerator beams. Both these two features made the Bubble Chambers superior to the Cloud Chambers since they could record larger samples of interactions and one could study more rare phenomena than before such as neutrino interactions with matter.

Measurement of the Parity of the Neutral Pion

Steinberger[8] and his group constructed one of the early Bubble chambers which was filled with liquid hydrogen to measure the parity of the neutral pion. The idea for measuring the π^0 parity was the same as the idea of Wu and Shaknov experiment (positronium parity):

The π^0 decays predominately into two photons. However, 1 out of 30,000 times it decays into two electron-positron pairs in a process which is called internal conversion because the two photons convert immediately to electron-positron pairs. It turns out that that the planes of the two electron-positron pairs 'remember' the polarization of the virtual intermediate photos which produced them. As in the Wu and Shaknov experiment the plane polarizations of the two photons must be parallel for scalar pions and perpendicular in the pseudoscalar case.

The experiment used a negative pion beam which come to rest in the in the hydrogen of the Bubble Chamber and produced π^0 via the reaction $\pi^- p \to n\pi^0$. A π^0 event decaying in to two electron positron pairs is shown in Fig. 18. The angular distribution of the events is shown in Fig. 19. **As seen there the angle between the two photon polarizations predominately at 90 degrees as expected for a pseudoscalar π^0.**

[8] R. Plano et al., Physical Review Letters, 3, 525, (1959);
N. Samios et al., Physical Review, 126, 1844, (1962).

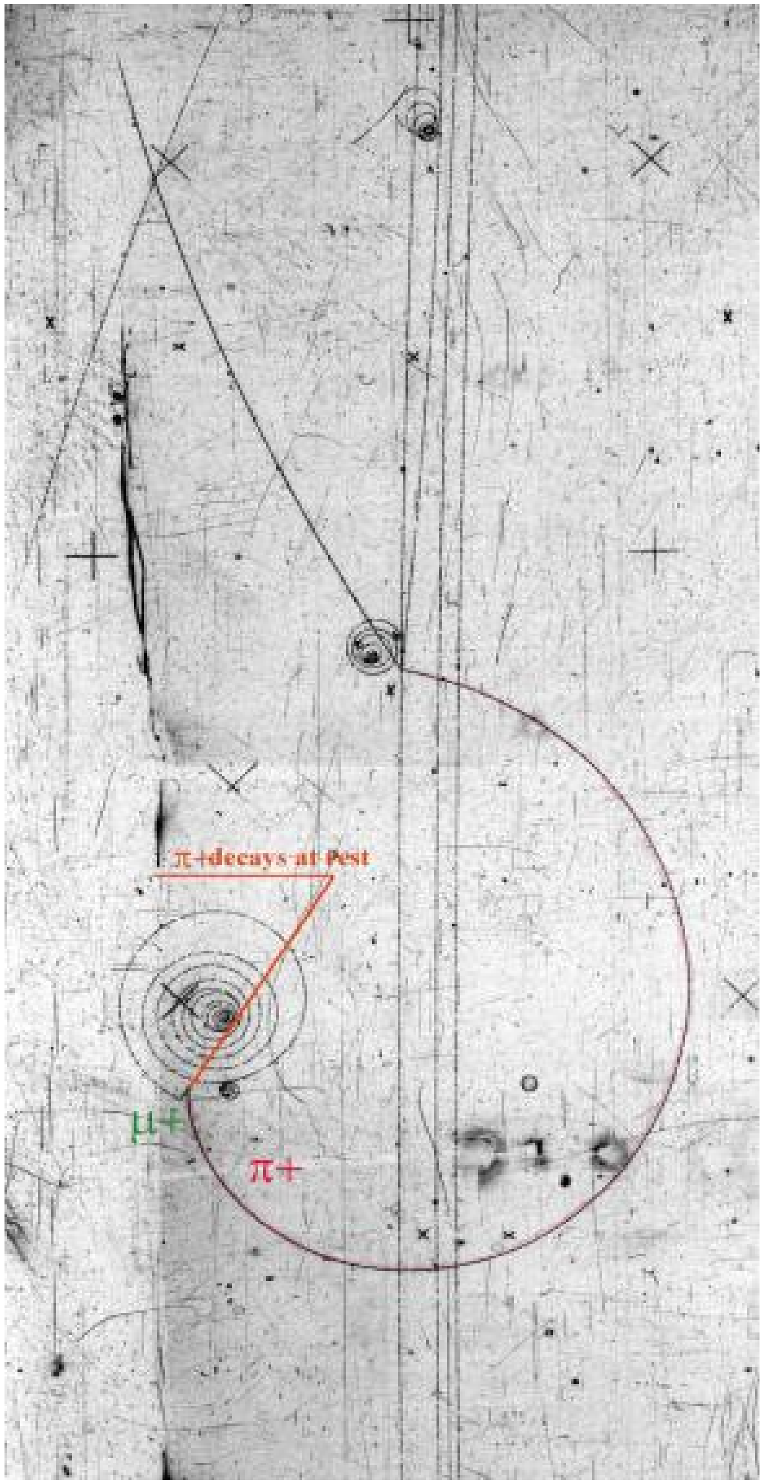


Figure 17: *A bubble chamber picture of a positive pion bending in the magnetic filed. The pion eventually loses enough energy and comes to rest where it decays to a muon (visible as a little stub) and an invisible neutrino. The electron from the muon decay is seen loosing energy radiatively and curling in the chamber magnetic field.*

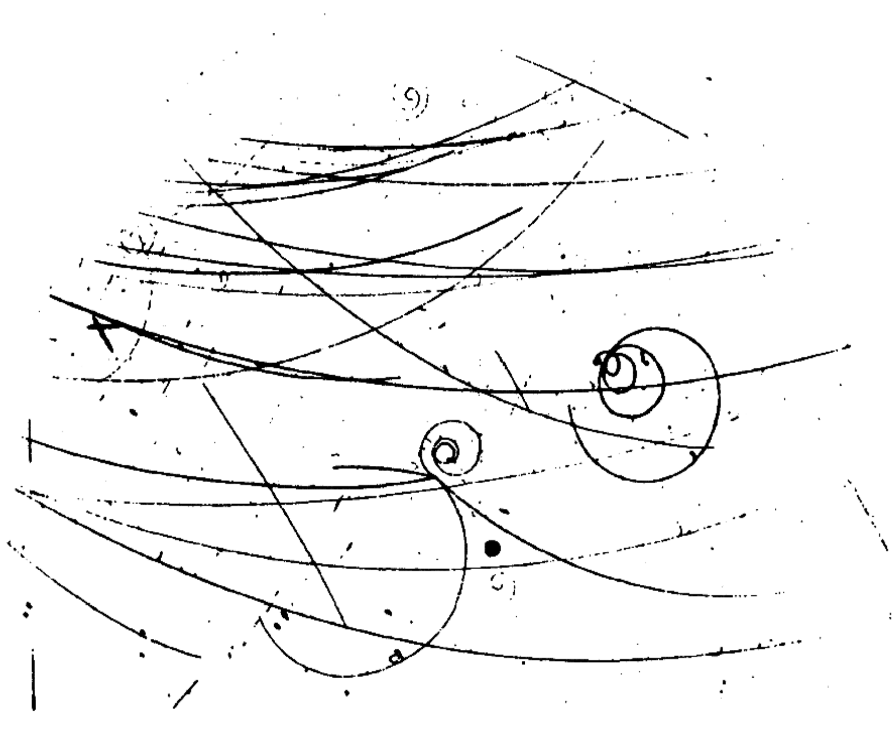


Figure 18: *A neutral pion internal conversion into two electron positron pairs in a hydrogen Bubble chamber at Nevis Labs, Columbia University.*

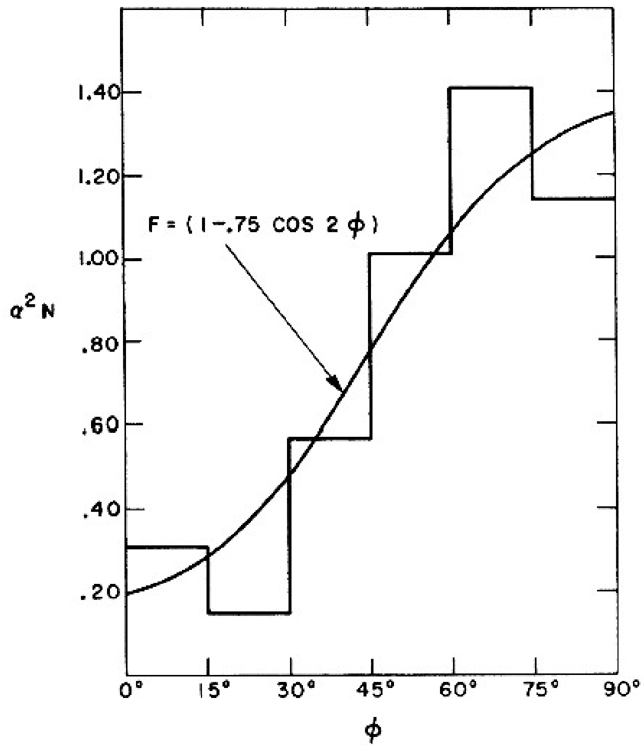


Figure 19: *The angular distribution between the planes of the two electron positron pairs. Superimposed on the data is the theoretical prediction for a pseudoscalar neutral pion which agrees well with the data.. The prediction for a scalar pion would be the exact symmetrical image of this peaking at zero degrees which would not be in agreement with the data.*

LHC physicists hope to try the same method to measure the parity of the Higgs particle once it is discovered. This would require a somewhat heavier than expected Higgs which could decay into two Z^0 bosons which will 'internally convert ' to two electron positron or two muon pairs.

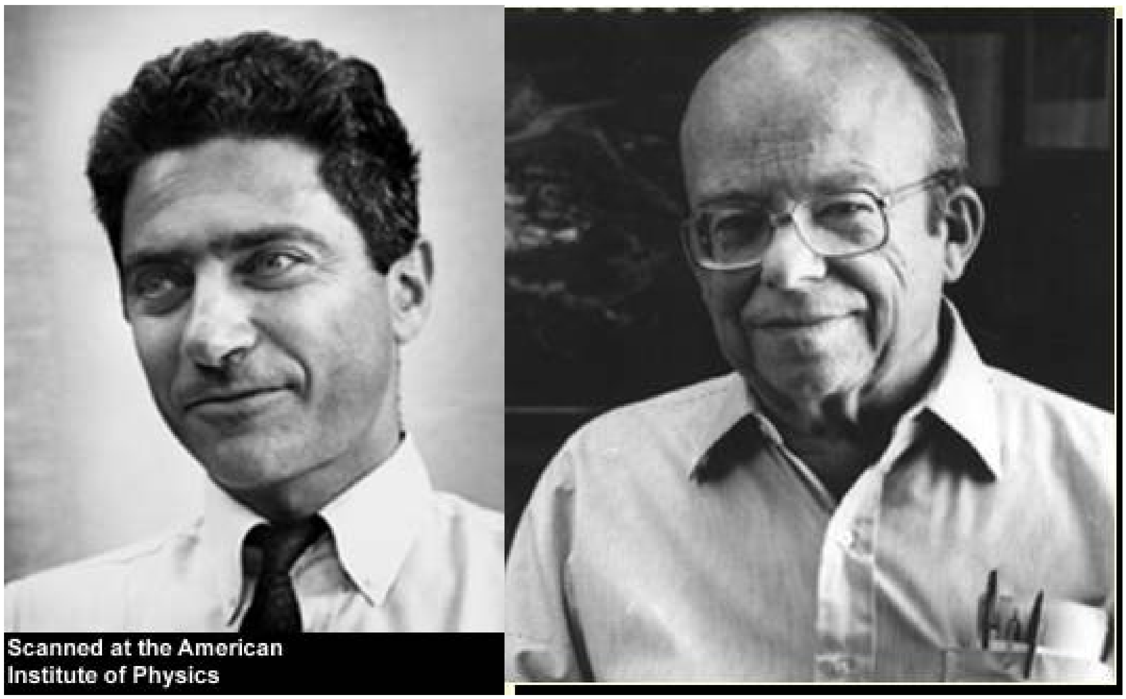


Figure 20: *Jack Steinberger (left) and Wolfgang Panofsky (right). Jack Steinberger shared the Nobel price in Physics for the discovery of the muon neutrino.*