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# LOS ALAMOS SCIENTIFIC LABORATORY

## OF THE UNIVERSITY OF CALIFORNIA ○ LOS ALAMOS NEW MEXICO

# PIONS, MUONS, AND NUCLEAR STRUCTURE

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OF THE UNIVERSITY OF CALIFORNIA LOS ALAMOS NEW MEXICO

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## PIONS, MUONS, AND NUCLEAR STRUCTURE

Summary of the conference held at the
Los Alamos Scientific Laboratory
August 19-31, 1963

by

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Leon Heller
Clarence E. Lee
James E. Young



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## FOREWORD

The Los Alamos Conference on Pions, Muons, and Nuclear Structure was held August 19-31, 1963 under the auspices of the Atomic Energy Commission. We wish to thank Dr. Norris Bradbury, Director of the Los Alamos Scientific Laboratory, for his encouragement and support, and Robert Porton of Public Relations and his staff for their fine organization of the material aspects of the conference. Other members of the Laboratory, too numerous to mention, contributed significantly to the success of the conference. The responsibility for the organization of the conference was shared by Darragh Nagle and Charles Critchfield.

Charles L. Critchfield
Leon Heller
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James E. Young

SPEAKERS:

Herbert Anderson, Chicago, Mesic X-rays.

Kenneth Crowe, LRL, Neutrino Experiments.

Samuel Devons, Columbia U., Nuclei Muon Interactions with Nuclei.

Torleif Ericson, CERN, Pion Optical Potential.

Ze'ev Fraenkel, Weizmann Inst., Pion Capture on Complex Nuclei.

Richard Haddock, UCLA, Production.

Arthur Kerman, M.I.T., Introduction.

Leon Lederman, Columbia U., Discussion on Neutrino Experiments.

Earle Lomon, M.I.T., Elementary Particles and the Boundary Condition Model.

Jack Menes, BNL, Muon Magnetic Moment.

Arthur Poskanzer, BNL, The Effect of Pion-Nucleon Resonances on Some Simple Nuclear Reactions.

James Rainwater, Columbia U., Optical Potential.

OUTLINE:

1. Introduction
   (Kerman)

   emphasis on nuclear structure - interest at Los Alamos - informal, unclassified - small group (more discussion, etc.)

2. Summary of lectures

   a. Mu capture or decay
      (Devons)

   b. Mesic X-rays
      (Anderson)

c. Pion-nucleon interactions
(Ericson, Fraenkel, Lomon, Poskanzer, and Rainwater)

d. Mu magnetic moments
(Menes)

e. Production
(Haddock)

f. Neutrino interactions
(Crowe, Lederman, and Marshall)

In addition to the scheduled talks and discussion from the floor there were brief presentations as follows:

Kenneth Ford, Brandeis, Charge distribution in nuclei.

Leon Lederman, Columbia, Hyperfine splitting in mu-mesic hydrogen.

Samuel Devons, Columbia, Possibilities with very high muon flux.

James Rainwater, Columbia, Pion scattering and the optical model.

Leona Marshall, University of Colorado, Muon production.

The complete list of those who attended is not known. However, a partial list of participants from other institutions follows:

R. Becker, ORNL; H. Bethe, Cornell; D. DeLise, Arizona; M. and G. Goldhaber, BNL; P. Gugelot, Leyden; G. Kolstad, AEC; H. McManus, Michigan State; S. Moscowski, UCLA; E. Nordberg, Rochester; J. Schiffer, ANL; N. Wall, MIT; and R. Wilson, Colorado.

Kerman: Introduction

The general content of this lecture comprised a survey of the potentialities of a high current accelerator with special emphasis upon its use in studying nuclear structure. For the sake of definiteness consider an 800 Mev proton accelerator with an everage current of $6 \times 10^{15}$ per second, a so-called meson factory.

The high intensity would enable one to do polarization and triple scattering experiments with good accuracy on nucleon-nucleon and pion-nucleon scattering and pion production. It was proposed also that the pion-electron collisions could be studied and the electromagnetic form factor determined. Moreover, with a high flux of pions one would naturally consider particle experiments with muons and even neutrinos which are derived from it. In addition, there would be increased opportunities to learn more about nuclear structure.

Even though the conference was narrowed to emphasis on nuclear structure, there are aspects which were not represented among the scheduled lectures. These topics were mentioned in the introductory lecture and were the subject of many discussions. Principal topics of this kind include the scattering of muons by nuclei and that of nucleons by nuclei, which, although not included by a strict interpretation of the title of the conference, is certainly a major area of investigation with a high current machine. Also alluded to were the possibilities of production of isotopes by charge exchange scattering of pions. Double charge exchange would be particularly interesting since it would produce isobaric states which have not been produced before.

Devons: Nuclei Muon Interactions with Nuclei

There are two separate categories of experiments in which a high-performance meson machine might be utilized to explore problems in nuclear structure: experiments with muons and pions. From a theoretical viewpoint the distinction is made sharpest by considering the weak and strong interactions separately.

The experimental and theoretical divisions are not, of course, exactly equivalent. In the case of 'complex' nuclei, strong interactions are always present, but even for the basic nucleon-muon interaction the presence of the (virtual) strong interactions makes itself felt. For example, if one postulates a fundamental universal Fermi interaction, i.e., symmetry in the NP-$e\nu$-$\mu\nu$ triangle, for the experimentally investigated process:

$$P+\mu^- \rightarrow N+\nu$$

the effective coupling constants would be expected to differ from those in $\beta$-decay and $\mu$-decay on account of the inescapable involvement of the nucleons in the strong interactions. Moreover in an actual and 'complex' nucleus, since the nucleons are interacting with each other, the effective coupling constants for the nucleons may differ appreciably from those for the free nucleons; i.e., the 'basic' weak interaction is modified by strong processes, and this modification is in turn dependent on nuclear structure.

One is faced, then, with two problems: the basic weak interaction as modified by the strong couplings (still insufficiently determined), and the relevant aspects of the structure of the particular nucleus. The difference in the behaviour, in this context, of free nucleons and nucleons bound in actual nuclei is, of course, a problem of some interest; in principle it can be explored by study of μ-nucleon interactions; in practice present-day experiments are insufficiently accurate or extensive.

With improved fluxes of stopped muons one could hope to get fuller and more precise information about the capture process in the lightest nuclei, H, $He^3$, $He^4$, and combining this with detailed measurements for more complex nuclei could contribute to an understanding of both the nature of the μ-nucleon interaction and of relatively unexplored aspects of nuclear structure.

An example of one particular way in which the capture process in heavier nuclei may be studied by established techniques was presented. This possibility arises from the fact that when a $\mu^-$ is captured in $O^{16}$, a few percent of the resulting states of $N^{16}$ are below the level for dissociation into nuclear constituents. These states comprise three excited states and the ground state, all of negative parity. The experiments measure both the resulting $N^{16}$ radioactivity and the intensity of the gamma rays from these excited states of $N^{16}$, thereby getting a measure of the transition probabilities during capture from the initial $0^+$ state to individual bound states of $N^{16}$.

It was also pointed out that special opportunities for experiments can arise from the fact that the spacing of the mesic-atomic levels is comparable to, or larger than, that in the heavier nuclei. The electromagnetic coupling between the muon and nucleus is sufficient to produce appreciable effects in $\mu$-capture and scattering.

In particular, the resonant scattering of muons was mentioned as a possibility if the intensity of muon beams were to become great enough. Owing to hyperfine interaction one might even determine the magnetic moment of very short lived excited states of nuclei in this way.

**Anderson: Mesic X-rays.**

When $\mu$-mesons are brought to rest in ordinary matter they are captured in outer Bohr orbits. After a series of radiative transitions they arrive at the lowest atomic level, the 1S state. The energy values of these levels are, of course, determined by the coulomb interaction between the $\mu$-meson and the nuclear charge. In the case of the lowest Bohr orbit the radius is of the order of nuclear dimensions even for relatively light elements. For this reason the binding energy in this state will be appreciably lower than it would be if the nuclear charge were concentrated at a point. The effect may be observed by measuring the 2P-1S transition which gives rise to the $K_\alpha$ x-ray line. Because the mass of the $\mu$-meson is some 200 times larger than that of the electron, this transition energy is correspondingly larger and can be observed quite readily in all but the lightest elements with a NaI scintillation spectrometer. In the case of a relatively light element like Mn ($Z = 25$) the 2P - 1S transition energy is 1.17 Mev, some 14% lower than it would be if the nuclear charge were concentrated at a point. The lines are sharp because, in contrast with the $\pi^-$-mesonic atoms, the specific nuclear interaction is weak in the case of $\mu$-mesons and the free decay lifetime is long.

These characteristics of the $\mu$-mesonic atom, the small radius and long lifetime of the low lying levels, prompted Wheeler (1) to suggest, more than 14 years ago, that the $\mu$-meson could serve to measure the extent of the nuclear charge distribution. This was demonstrated by Fitch and Rainwater (2), who measured the 2P-1S transition energies for a number of elements over a wide range of the atomic number Z. These classic experiments showed that the nuclear charge radius was in fact some 20% smaller than had been supposed. Expressed in terms of the radius R of a uniform distribution of protons, the variation with the atomic weight A was found to be described quite well by the relation $R = r_o A^{1/3}$ with $r_o = 1.19 \times 10^{-13}$ cm. Similarly small values of the charge radii had to be used to explain the electron scattering measurements of Hofstadter and his collaborators (3) at Stanford.

The usefulness of the μ-meson to probe other aspects of the electromagnetic structure of nuclei was also pointed out by Wheeler (4). Precise measurements of the μ-mesonic x-rays should reveal the effect of the shape, rotation and magnetic properties of the nucleus. Surprisingly little attention has been given to this field since the initial publications of ten years ago. Recently, there has been a revival spurred by the improvements in NaI spectroscopy and the availability of improved μ-meson beam intensities. New measurements have been carried out at Cern (5), Columbia (6) and Chicago (7), and the results were the subject of a great deal of discussion. The energy resolution of NaI spectrometers is still not sufficient to reveal the interesting level structure which a nuclear quadrupole interaction would produce. At best these effects have appeared as a broadening in the $K_\alpha$ x-ray lines of the heavy elements like Th and U. There is a clear need to develop new methods capable of higher resolution than is provided by NaI. The higher μ-meson intensities in prospect can bring a number of possible methods into the realm of practicability.

The accuracy with which nuclear radii can be determined by μ-mesic x-rays is comparable to that which can be obtained from electron scattering measurements for all but the lightest elements. Discrepancies have appeared which lie somewhat outside the limits of the errors quoted. It will be of interest to resolve these discrepancies by further more careful measurements to determine the extent to which effects like the nuclear polarization, which thus far have not been taken into account explicitly, might account for the differences.

An interesting result which has appeared is that the effective radius of the nuclear charge in $Ca^{44}$ is smaller than in $Ca^{40}$. If the radius varied smoothly with $A^{1/3}$ the $K_\alpha$ transition energy in $Ca^{44}$ would be greater than in $Ca^{40}$ by 2.8 kev. The experiment showed that it is smaller by $4.9 \pm 2.1$ kev, indicating a more compact nuclear charge distribution in $Ca^{44}$.

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Ericson: Pion Optical Potential.

The optical potential for the pion has taken on increased importance owing to the recent availability of high intensity beams. The strong interaction of the pion with nuclear matter augments its usefulness as a tool for the study of nuclear properties. Furthermore, the light pion mass and its distinguishability from the target nucleons makes the connection between the elementary pion-nucleon interaction and the optical potential very direct. This line of investigation is in a comparatively primitive stage, since the experimental material as yet is very limited.

In a first approach to the problem of determination of the potential, effective range theory is useful and may be employed. The procedure, as is well known, consists of parameterizing the S-matrix for $\pi$-nucleon scattering in terms of the initial and final momenta for the pion. This is done in a manner consistent with unitarity, time reversal and parity invariance for the two possible states of total isotopic spin. The two-body t-matrix is related to S in a trivial way and hence is also given. Next, the optical potential is constructed in the "form-factor" approximation, namely, $V_{opt} = t\rho$. The order of the operators is important in this product. We mean by $\rho$ the one-particle density for the given nucleus. Given that we know the elementary phase shifts for $\pi$-N, the parameters of t are fixed in this low-energy approximation. One may then proceed to solve the one-body Schroedinger equation for the scattering in the optical potential.

Up to this point, we have ignored the absorptive contribution to the potential. The pion absorption introduces a "bona fide" imaginary potential even at zero energy, in contrast to the nucleon optical potential. Assuming this absorption to occur on pairs of nucleons at close distance, the imaginary (absorptive) potential is obtained from the amplitudes of the inverse process of pion production in nucleon-nucleon collisions by detailed balance. The approximations involved are similar to those used for the real potential as constructed from the elementary scattering phase shifts. The deviations of the short range nucleon-nucleon correlations in the nucleus as compared to those of freely colliding nucleons are neglected in this approach. One realizes that $\pi$-production occurs with the pion in a relative S- or P-state as well as in different isospin states. This feature must be taken into account and introduces details but no new questions of principle.

An alternative way of obtaining <u>an</u> optical potential is through the study of the $\pi$-mesic atom, its level spacings and x-rays. It is not to be expected that this potential, calculated from level shifts and the transition rates, ought to agree with that discussed above. Very simply, the two potentials measure quite different things. That potential obtained from the mesic atom is a sort of polarization potential. The difference between the two types of optical potentials is, however, small for the majority of mesic atoms studied. This condition is not as strongly manifest in the continuum situation. It is, however, important that the experimental optical parameters of the potential of mesic atoms can be extracted in a very instructive way one by one by different experiments, in this case relying essentially only on a perturbation treatment of the mesic atom.

Fraenkel: Pion Capture on Complex Nuclei.

The capture of high energy pions on complex nuclei is examined. One raises the questions as to whether the capture occurs on several (two) or a single nucleon and if in the case of multinucleon capture some information concerning nuclear correlations might not be obtained. It is, for example, known that in a reasonable fraction (20 - 30%) of $K^-$-meson captures at rest, two fast baryons emerge instead of a single fast pion. Moreover, the impulse approximation has not been adequate to explain pion capture data on complex systems.

All of the previous considerations lead one to construct some alternative model for the capture process. Here, a decision has to be made concerning the possibility of interaction before decay. If we assume that at least one such interaction does occur, the logical direction of analysis is in that of the isobar model. Capture then becomes a two-stage process, i.e., $\pi+N \rightarrow N^*$, $N^*+N \rightarrow N+N$. This is just another way of summarizing the capture process on 2 nucleons, since we could have alternatively written, for example, $\pi+n+p \rightarrow N^*+N \rightarrow p+p$. There is considerable evidence for this point of view owing to the data for pion absorption on deuterons. The data looks like $\pi+N$ scattering, the absorption being characterized as occurring in the relative P-state, the cross section having a resonance in the vicinity of 170 Mev.

On the basis of the impulse approximation, which we have tacitly assumed to be valid in discussing the absorption in deuterium, the capture cross section on complex systems is expected to reflect the resonance shape of the elementary process $\pi+(n+p) \rightarrow N^{*}+N$. The cross section $N^{*}+N \rightarrow N+N$ is obtained from its inverse, by consideration of detailed balance. The resonant production of the isobar in a single collision may be computed from the Born pole for that process.

The isobaric capture produces the unstable $N^{*}$. It, the $N^{*}$, can undergo free decay, annihilation upon another nucleon and exchange scattering with a nucleon. Which of these competing processes is dominant depends to some degree upon the importance of 2-particle correlations in the nucleus. Such correlations have been postulated for the explanation of the $K^{-}$-absorption data. If this should be so, an important tool is available for the study of nuclear species. The exchange scattering of isobars with nucleons is of particular interest since the closeness of the Born pole to the physical region results in sharp asymmetric peaks in the total and differential cross sections.

The above discussion of the interactions of isobars in complex systems can be obviously extended to other short-lived particles or resonances. The future study of such processes opens the prospect of obtaining additional information concerning nuclear excited states.

Lomon: Elementary Particles and the Boundary Condition Model.

The boundary condition model (BCM) was first extensively applied to describe the scattering of nucleon pairs. In its pure form a logarithmic derivative is specified at some matching radius. This is done for each open channel in the scattering situation. One hopes that the logarithmic derivatives are sufficiently energy-independent to give an acceptable parameterization of the data; also, that some physical meaning can be given to the matching radius.

The early success of the BCM in its description of nucleon scattering subsequently led to its wider application. In addition, it became reasonable to search for its deeper implication. In its application to non-relativistic scattering of nucleons one found: (a) that the addition of TPEP, the two-pion exchange potential, obtained from meson theory, gave a good account of the data, e.g., the $^1D_2$ phase shift had the appropriate energy dependence in the vicinity of 300 Mev that could only otherwise be described by an extremely velocity-dependent potential; (b) that the matching radius was fixed at 0.7f, the Compton wave length associated with the exchange of two mesons; (c) that the rationalized pseudovector coupling constant $f^2 = 0.08$ was indicated by the data; (d) that the pair suppression and ladder parameters were less well fixed by the experimental data. This is more or less, then, the history of the modified BCM (BCM plus potential tail).

To make the next step, namely that of interpretation, the content of axiomatic S-matrix theory is examined, and, as typically done, certain models from non-relativistic situations are employed as a mathematical guide. The goal at this step is to apply the BCM to the description of elementary particle reactions. One element in every axiomatic theory is local, microscopic causality. In certain representations of theory, e.g., Mandelstam, there are detailed assumptions concerning analyticity and in which variables this behavior obtains. Of course, finally, we ought to have unitarity and those symmetries or invariances seeming to be general properties in certain formal expansions, properties such as G-parity invariance and crossing symmetry.

The causal statement from non-relativistic theory has been enunciated by Wigner. It places upon the logarithmic derivatives F the condition that their energy-dependence be restricted as $dF/dE \leq 0$. The equality holds in the limit of very strong non-local interactions. When the equality obtains we get the situation of maximal strength-of-the-interaction emphasized by Chew and others for the axiomatic theories. The BCM description is known to satisfy the unitarity and analyticity requirements as well as the Wigner criterion. This is in fact obvious, and thus when BCM is supplemented by certain symmetries, it should describe certain elementary processes. This turns out indeed to be the case.

Applications of BCM have been made, notably, to the $\pi$-$\pi$, $\pi$-N and

K-N interactions.

The $\pi$-$\pi$ interaction is sufficiently simple to allow the easy introduction of crossing symmetry. This has led to a discussion of the problem almost fully equivalent to the direct Chew-Mandelstam calculation, but simpler. The pure BCM (no potential tail) is used for the KN and $\bar{K}N$ systems. Good fits are obtained up to 400 Mev/c (and beyond), and the $Y_o^*$ accounted for.

For the $\pi N$ system Weisskopf showed some time ago that a linearly energy-dependent BCM was fully equivalent to the Chew-Low effective range theory for the $P_{33}$ state. Here we want to describe new results for the $S_{11}$, $S_{31}$, $D_{13}$, and $D_{33}$ states. A pure BCM is used that includes coupling between the $\pi N$ and dipion-N channels. For the $\pi N$ system S states we consider coupling to the P state T = 0 dipion-N system, as the data indicates. Thus only the T = 1/2 state is affected and the complicated structure (both elastic and inelastic) of this state up to 700 Mev pion laboratory energy is well matched. The T = 3/2 state is excellently matched over the same range by turning off the coupling to the dipion channel, so that the isotopic splitting is due to the inelastic channel. The $\rho$ exchange mechanism usually used to explain the isotopic splitting is a simplification of our mechanism that does not explain the data above 200 Mev. There are three logarithmic derivative parameters plus the boundary radius, which is at the theoretically expected value.

Similarly in the T = 3/2 D states we consider the coupling to the

$\rho$ N channel in an S state. The second resonance ($D_{13}$) is explained in detail: position, width, inelasticity, and the analyzed complex amplitude. The one pion exchange diagram indicates that the $D_{33}$ state should couple to the $\rho$ N channel with 1/4 the strength of $D_{13}$. When we reduce the coupling by 1/3 (keeping other parameters fixed) we predict the T = 3/2 850 Mev "shoulder," its position, width and inelasticity. The isotopic splitting is consistent with being ascribed entirely to the inelasticity. In the D states we have four logarithmic derivative parameters (a pair of them roughly related by the peripheral diagram) plus the boundary radius which is again at the theoretically expected value.

We intend to explore the small P states and the third resonance next.

Poskanzer: The Effect of Pion-Nucleon Resonances on Some Simple Nuclear Reactions.

Excitation functions have been measured for two simple nuclear reactions: $C^{12}(\pi^-,\pi^-n)C^{11}$ and $Al^{27}(p,p\pi^+)Mg^{27}$. The reaction products were determined by their radioactivity. Thus the reaction paths leading to low excitation energy products were selected. In the first reaction the excitation function parallels that for the elementary pion-nucleon interaction. This is in the spirit of the impulse approximation. The first resonance, the (3/2,3/2), dominates up to some 600 MeV where one begins to see higher $\pi$-N resonant states.

For the other reaction, $Al^{27}(p,p\pi^+)Mg^{27}$, the (3/2,3/2) resonance is again found to dominate the excitation function, only now in the region of 1 GeV, because of the different center-of-mass motion. The experiments agree with calculations which were performed by combining a Chew-Low peripheral model of the elementary particle interaction with a zero-temperature Fermi gas model of the nucleus. The absorption of the incident and exit particles has been ignored. Measurements of the average forward momentum of the $Mg^{27}$ recoils have also been performed and agree with the calculations.

Rainwater: Optical Potential.

The early attempts to obtain the optical potential describing the scattering of pions from complex nuclei are, among others, those of Watson-Brueckner and their collaborators, and Kisslinger. These were followed by Rainwater et al. in an attempt to explain the 80 Mev $\pi^-$ data of the Columbia group on Cu, $A\ell$, C and Li. This data and the corresponding analysis appear in the literature. The method chosen for integrating the differential equation giving the scattering raises some questions. These devolve upon the behavior of the effective mass of the pion in nuclear matter. There are conditions under which this quantity vanishes. While this is certainly different from the situation encountered in nucleon scattering, there is no prohibition upon this effect. The computational analysis is still unclear and unresolved.

Menes: Muon Magnetic Moment.

A large amount of recent investigation has been centered on the question of the applicability of quantum electrodynamics to the muon. Although the now observationally confirmed two-neutrino hypothesis differentiates between muon and electron in the weak interactions, to date no disparity has been observed in the electrodynamic behavior of muon and electron. Nevertheless, it is both necessary and instructive to continue the investigation of the electrodynamic properties of the muon. Consistent with this view, a new determination of the magnetic moment has been recently made at Columbia's Nevis Laboratory.

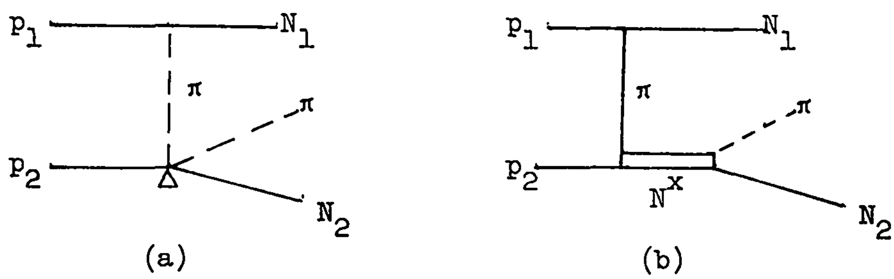
In the experiment reported, a direct method of determination was employed. This was of the magnetic resonance type in which the rate of precession of the longitudinally polarized muons in a vertical magnetic field was ascertained. As one is dealing with muons stopped in matter, many environmental effects influence the determination. These are different for positive and negative muons. For negative muons, these include effects due to motion of the muon in its 1S orbit, diamagnetic shielding by core electrons of the host atom, Knight shifts associated with conduction electrons in metals, finite nuclear size and, less significantly, nuclear polarization. For positive muons, the environmental effects are wholly chemical, being due to the electronic structure of the molecule formed by the muon and the target material.

The results of this experiment give, for the ratio of positive muon moment to proton moment, 3.18338 with an uncertainty of 4 in the last place. Together with the results of the g-2 experiment, one obtains a value of the muon mass of 206.765 $\pm$ .003 electron masses. The results for negative muons, after account is taken of the environmental effects, indicate equality of positive and negative muon moments to better than $3 \times 10^{-4}$.

Haddock: Production.

The design of pion production facilities requires a knowledge of the total production cross sections as a function of energy. Here we think of protons as the source of the production. The elementary p-nucleon cross sections which furnish this information are not known especially well either theoretically or experimentally over the energy range of probable interest, say, up to $E_p = 3$ Bev. The sense in which this is meant (we restrict ourselves to single pion production always) is the following. Pi-plus production in hydrogen is the best studied event. Its cross section is known for proton energies up to perhaps $E_p = 3$ Bev where a deuteron or n+p is produced in the final state. Theoretically, the problem is quite complicated since we quickly reach energies which are thresholds for other systems, e.g., $N^*$, ABC($2\pi$), $\rho$, $f^0$, $\eta$, $\omega$. These thresholds give inelasticity and off-energy shell effects which must be included in any calculation. In addition, the final state, $\pi^+$+D, $\pi^+$+n+p, has interactions which may not be negligible. The theory must approximate the physical situation and the experiment must be sufficiently accurate to sort out the various model approximations. This is presently not the case.

The situation is especially critical if we choose to produce pions from targets of complex nuclei, as we do. The cross sections here are controlled by those for the elementary process, ignoring nuclear structure effects. Apart from a knowledge of the elementary, off-energy shell elementary amplitude, we require, for example, the mean free paths of the unstable particles in the nuclear medium. This continues to be true even in the one-pion exchange approximation,where we might think of the processes represented diagramatically as




And, even when the unstable isobar is not produced, as in (b), the nucleon-antinucleon annihilation amplitude into two pions is required as in (a), for all of the relevant momentum transfers $\Delta$. The nucleons must "furnish" these transfers in the sense that components of momenta with magnitude $\Delta$ must be present in the nuclear form factor. It is concluded that beam design based upon estimation of the expected production cross sections can at best be carried out in only a very tentative way at present.

Lederman and Marshall: Discussion on Neutrino Experiments.

Lederman discussed an experiment using stopped pions from a meson factory, which give rise to 30 MeV neutrinos, to see if the selection rule against these neutrinos inverting β-decay, $\overline{\nu}_\mu + p \rightarrow n + e^+$, is exact. He concluded that it would be very difficult to perform the experiment even if the cross section were close to the "allowed" value. Similar considerations apply to other neutrino experiments. An interesting one is $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu}_\mu$ and the search would be for $\nu_e$-electron scattering. One again gets, optimistically (as stated in the talk) some ten events per ton per day: The problem of making a clean experiment out of this flux is very difficult; the inflexible duty cycle does not help. As for higher energy $\nu_\mu$ reactions, wherein one might, with great expense and trouble, get again some ten events per ton per day, the fruitfulness of this is not obvious, in view of the complex nucleus problem and the fact that CERN, BNL and Argonne will have been studying the reaction for five or so years at comparable rates. The main point is that, as currently conceived, these neutrino experiments would be marginal and exceedingly complex and costly. In the absence of more specific and compelling physics arguments than are at present on hand, extensive plans for neutrino experiments at meson factories would only impede what is otherwise a fruitful and unique program in meson and nuclear physics. This of course does not rule out some new technique for applying the very intense meson beams to "low" energy weak interaction problems.

L. Marshall took Berkeley results with a 743 MeV proton beam of $2 \times 10^{11}$ protons per second, giving rise to $2 \times 10^{6}$ pions per second of 310 MeV with a 2.5% momentum spread in $10^{-2}$ steradians and scaled this to $10^{16}$ protons per second, thereby obtaining $10^{11}$ pions per second. After a 14 meter flight path 44% of the pions have decayed, and then 10 meters of iron shielding absorb the remaining pions. The average solid angle subtended by one square foot of detector after the shield is $d\Omega = [30/(700+1000)]^2 = 3.1 \times 10^{-4}$ sterad./ft$^2$. For pions of 310 Mev kinetic energy, the ratio of center of mass solid angle to laboratory solid angle, for forward angles, is 39. Putting together these factors gives a neutrino flux at the detector of

$$\text{Flux} = 10^{11}\ \frac{\text{pions}}{\text{sec}} \times \frac{3.1 \times 10^{-4}\ \text{sterad/ft}^2 \times 39}{4\pi} \times .44 = 4.2 \times 10^{7}\ \frac{\text{neutrinos}}{\text{ft}^2\text{-sec}}$$

These neutrinos have 194 MeV and will, in the detector, produce the reaction $\tilde{\nu}_\mu + p \rightarrow n + \mu^+$ or $\nu_\mu + n \rightarrow p + \mu^-$.

The cross section for the second of these reactions (which has a threshold of 110 Mev) on free neutrons is approximately $2 \times 10^{-39}$ cm$^2$. For neutrons in a nucleus there are two complications: the initial motion of the neutron, and the Pauli Principle for the final proton. Since a proton going forward, from a reaction with a neutron initially at rest, has $\sim 45$ MeV, the Pauli Principle is not expected to have a large effect. Inserting a safety factor of 1/2 gives a cross section of $1 \times 10^{-39}$ cm$^2$.

Putting one ton of detector behind one square foot yields the following event rate.

$$\text{Event rate} = 4.2\text{x}10^{7}\ \frac{\text{neutrinos}}{\text{ft}^2\text{-sec}} \text{ x } 1\text{x}10^{-39}\ \frac{\text{cm}^2}{\text{neutron}} \text{ x } 9\text{x}10^{5}\ \frac{\text{gm}}{\text{ton}}$$

$$\text{x } 3\text{x}10^{23}\ \frac{\text{neutrons}}{\text{gm}} \text{ x } \frac{1\ \text{ft}^2}{900\ \text{cm}^2}$$

$$= 1.3 \text{ x } 10^{-5}/\text{ton/sec}$$

$$= 1/\text{ton/day}$$

To improve this rate, increase the momentum spread of the pions from 2.5% to 25%. The decreased pion intensity at higher energies is compensated by the increased neutrino cross section. Increase the magnet aperture from 8" to 20" and use ten tons of detector. These three changes will boost the event rate to $6 \text{ x } 10^2$/day.

Crowe: Neutrino Experiments.

A. Astbury and K. M. Crowe, Phys. Rev. Lett. 11, 234 (1963).