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Dora F. Sherman

March 10, 1950

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BIBLIOGRAPHY OF MESON RESEARCH

Dora F. Sherman

March 10, 1950

Introduction

This bibliography was prepared for the members of the film study group, consequently the papers abstracted were chosen for their pertinence to the research of this group. In this report are abstracted all papers in the journals which are reviewed in "Physics Abstracts" for the years 1946 through 1949, on the production and properties of mesons, on nuclear stars in photographic emulsions, and on photographic emulsion techniques for the study of mesons. Cosmic ray research and meson theory have been included if they gave information concerning properties of mesons which the film study group might measure. Theoretical papers were included if they suggested experiments which would choose decisively between conflicting meson theories.

The abbreviations of journal names are those used in Physics Abstracts.

The author hopes that these references and abstracts will prove to have value, and she will welcome criticism, correction of errors or suggestions for improving the usefulness of this report.
Mesons

1946


Photograph of a pair of diverging tracks in cloud chamber, interpreted as a proton, and a meson created by it.


Because multiple scattering in cloud chamber gas can cause large apparent curvature of tracks, measurement of $H$ is meaningless if $H$ and $\phi$ are low. All published meson tracks can be compatible with a unique mass of 200 e.m.


Calculated cross sections of pseudoscalar mesons for:
1. $(m, \phi)$ capture by nucleon
2. elastic scattering
3. creation of meson pair by meson-nucleon collision.

Calculated lifetime of pseudoscalar meson.


Value of $\tau/\mu c^2$ is constant, $2.6 \pm 0.3 \times 10^{-14}$ sec/ev. This excludes a spectrum of values of $\tau$.


To study the ratio $\gamma$ between meson decays and stopped mesons in a 3 cm Fe absorber, coincidence counters were used to detect decay electrons from mesons which had been sorted according to charge and energy by a
magnetized iron core \((B \sim 15,000 \text{ gauss})\). The values of \(\tau\) obtained were:

- for positive mesons \(\tau = .33 \pm 0.04\)
- negative mesons \(\tau = .077 \pm 0.02\)


Meson decay was studied by coincidence counting of the meson and decay electron. \(\tau = 2.33 \mu\text{sec.} \pm 6.5 \text{ percent.}\)


Mean range of decay electrons is about 2.5 cm of lead \(\pm 20 \text{ percent.}\)


They believe that the existence of several mesons with different lifetimes is impossible. A 20 percent excess of \(+\) to \(-\) mesons is found.


The measured diffusion through lead agrees with the theory of E. J. Williams.


Measured range in lead as a function of momentum. Mass of all mesons so measured = 202 e.m.


The layer of atmosphere in which non-ionizing cosmic rays produce mesons is above 16,800 ft. in the equatorial regions.


All methods for measuring masses are discussed. Ionization, range, and momentum loss in an absorber are discussed in detail; and the resolving powers of the three methods compared. A set of curves is given, from which the mass, and estimated error, are given as a function of momentum loss in an absorber.


Classical formulae for scattering by neutrons are obtained, taking account of radiation damping. The neutron is assumed to possess charge and dipole moment, the scattering due to each is treated separately. The formulae for scattering due to the dipole have the same form as the one obtained by Bhabha for transverse mesons. The scattering for high energy mesons is double, for low energies, half that of transverse vector mesons. The scalar and pseudoscalar charge and dipole interactions are considered in the quantum theory. The scalar dipole interaction does not give rise to scattering, all the scattering being due to the pseudoscalar interaction. In this case, the quantum theoretical formulae agree with the corresponding classical ones if the effect of radiation reaction is neglected.


Large errors in mass determination, but some evidence for a distribution of meson masses. One photograph shows pair production of low energy mesotrons.

Radiation damping equations are given corresponding to problems where the final state is different from the initial state, as well as when it is similar. A solution of these equations is obtained for production of pseudoscalar mesons by the scattering of photons by nucleons, and a comparison made with the pure scattering of photons. Results are also given for vector mesons. At high energies the cross section is proportional to $E^{-4}$ for processes in which the final state is distinct from the initial state, and proportional to $E^{-2}$ when the final state is similar.


The absorption of slow mesons was measured, using anticoincidence counters. The statistical error in the number of mesons stopped was less than 3 percent. The values obtained were compared with those calculated from the theory of energy loss by collision. The experimental values agreed with the theory only after account was taken of scattering, which is of particular importance in the heavy elements. For water, no reliable theoretical value could be calculated.


Study of large cosmic ray bursts indicate that they are produced by bremsstrahlung of mesons. Data compared with calculations of Christy and Kusaka indicate 0 or 1/2 for meson spin, and exclude spin 1.

The altitude dependence of burst production might be explained by mesons of spin 1, having a short enough mean life that they fail to reach sea level.
LE PRINCE-RINGUET, L. and LHERITIER, M,: Probable Existence of a Particle of Mass 990 $m_e$ in Cosmic Rays. J. Phys. Radium (Sér. 8) 7, 66. (In French.)

A value $m = 990 m_e + 12$ percent was obtained for one particle by observing elastic collisions. Similar collisions of other observed mesons show normal meson mass value.


Five particles were found in 10,000 cloud chamber photographs with apparent mass (measured by $H_\rho$ and ionization density) intermediate between protons and mesons.


Observed changes in curvature of meson tracks passing through matter. Meson mass reported $= 240 \pm 20$ e.m.


Observations of absorption in Pb plates in cloud chambers favor the assumption of meson decay yielding one electron and one neutrino.


Nuclear capture of $\mu$ mesons: probability of capture is large for slow, non-ionizing mesons. Capture produces stars in emulsions of the types

\[ \mu^- + N^{14} \rightarrow 2He^4 + 2H^1 + 4n \]
\[ \mu^- + O^{16} \rightarrow 3He^4 + H^1 + 3n \]
In 19 cases masses of $\pi^-$ mesons were either 140 or 200 $m_e$, no intermediate values found.


Eighteen page bibliography with abstracts of work in Europe between 1939-1946.


A study is made of a scalar meson pair theory involving charged and neutral mesons. Using this theory

(a) interaction of nuclear particles with meson fields

(b) interactions between neutrons and protons

(c) scattering of mesons by nucleons

(d) theory of $\beta$ decay.

It is shown that in this theory there is no possibility of absorption of a meson by a nuclear particle.

The assumption of the interaction

$$\text{neutrino} \rightarrow e^- + (\text{positive meson}) + (\text{neutral particle})$$

leads to $\beta$ decay with Fermi type interaction.

The process $(\text{charged meson}) \rightarrow e + (\text{neutral meson}) + (\text{neutral particle})$

can occur only if the mass of the neutral meson is smaller than that of the charged one.

The computation of the mean life of a neutral meson decaying to three or more photons requires the cutting off of a divergent integral. The author then discusses \( y^0 \rightarrow e^+ + e^- \) and \( y^0 \rightarrow n + n' \) as possible modes of decay, assuming that \( g_n^2/k_c \gg g_{ch}^2/k_c \) (\( g_n \) and \( g_{ch} \) denote the coupling of neutral and charged mesons with the electron neutrino field), and considering that electron neutrino forces are relativistic. He shows that these assumptions can explain the short life time of neutral mesons.


Secondary particle neutrons and protons have maximum energy \( \sim 200 \text{ Mev} \), due to large cross section of air for production of meson pairs. This maximum energy gives a measure for the mass of the meson of slightly more than 200 \( \text{m}_e \).


Measurements on cosmic rays with cloud chambers indicate two types of mesons. Mass of one between 100 \( \text{m}_e \) - 200 \( \text{m}_e \), and a mass exceeding 200 \( \text{m}_e \).

SCHAFER, W.: On the Question of the Types of Meson. Naturwiss. 33, 365. (In German.)

Data on cosmic rays are discussed assuming 2 mesons, one light, of long half life, and one heavy.


Cross sections for anomalous, non-Coulomb scattering were measured by comparison of scattering in two different Pb thicknesses. For meson
energies above $5 \times 10^8$ ev scattering through angles $5^\circ - 90^\circ$ is mostly anomalous. The present study of meson showers does not show saturation for shower production reported by Jánossy and Sinha. Study of slow, heavily ionizing mesons (energy < 20 Mev) gives some evidence that such mesons disappear by an as yet unknown process.


The cross section for non-Coulomb nuclear scattering is calculated to be $1.84 \times 10^{-26}$, for meson energy $2 \times 10^8$ ev. This is 25 times the experimental value of Shutt and Code, which may be low because of higher energy mesons which marked the effect of lower energy mesons.

Studies of scattering in 2 cm and 4 cm of lead showed an average angle of scattering about 50 percent of the value expected from Williams' $\sqrt{t}$ law. A Gaussian distribution of number of particles with angle of scattering is obtained.


Production of heavy mesons at 3860 m.


Studies of tracks in cloud chambers indicate that one must postulate two meson masses, about 100 and 200 mev.


Angular spread of electrons knocked on by mesons in Pb, Fe, Al.

Influence of scattering of electrons discussed.


Bethe and Fermi formulae for energy loss per cm of path in an
absorber are discussed, and using data for ionizing potentials obtained from α-particle absorption, the energy loss of mesons in air, water, and lead are calculated, and the results shown in nomograms.


Theory of density effect on stopping power. Range energy relations for mesons in Fe, C, H₂O, Pb and air given in nomogram form.

1947


Ten percent of cosmic ray particles of momentum > 180 Mev/c fail to penetrate 5.4 cm Pb. Reasons are given why these are not protons.


Photograph of a positive meson decaying to a positron, and interpretations.


Observations on magnetically separated positive and negative μ mesons in iron indicate that only the positive mesons show decay.

CALLISEN, F. I.: The Development and Application of New Techniques in Meson Research. Z. Natur forsch. 2a, 686. (In German.)

Technical developments in the study of mesons are summarized under the headings:
I. Methods of Measurement

Counters, cloud chamber, photographic emulsion, 
Čerenkov counters.

II. Evaluation of Results

Ionization by charged particles, absorption of mesons, 
errors in mass determination due to multiple scattering, 
interpretation of tracks in emulsions.


Cross sections of various processes obtained for transverse and 
pseudoscalar mesons. Calculation of energy spectrum of mesons as a 
function of energy of the producing protons.

Proper lifetime \( \tau \) (from data by Wilson) \( \tau \approx 2.7 \mu \text{sec.} \)


Production of high energy electrons by meson collision.


In iron, few negative mesons decay because the chance of nuclear 
capture is so large. In carbon, both \( + \) and \( \) mesons decay.


47.2 percent \( + \) and 52.8 percent \( \) mesons observed in energy range 
\( 0.6 \times 10^8 \) to \( 1.7 \times 10^8 \) ev. Precision 5.6 percent.


The cross section for emission of several mesons in a collision
between nucleons is calculated using the Williams-Weizsacker model and longitudinal vector mesons. The results, valid for incident nucleons of high energy and emitted mesons of low energy, indicate that the cross section decreases slowly with increase in the number of emitted mesons.


Meson mean life calculated to be 1.69 μsec.


Tracks of mesons and protons, and stars in emulsions. Meson masses measured, values, 200 and 250 ± 50 e.m.


If Conversi, Pancini, and Piccioni data (Phys. Rev. 71, 209) are correct, meson-nucleus interactions are smaller than formerly assumed, and energies much higher than threshold energies will be required for production of mesons by proton or photon bombardment.


Theory of energy loss, scattering by electrons and capture by nuclei of negative mesons.


Selection rules for the absorption of mesons by deuterons.


By studying the cosmic ray electron spectrum at sea level the
author failed to find evidence for the existence of mesons of half life $10^{-8}$ seconds, which in decaying would yield high energy electrons.


Formula for bombardment energy required for particle production as a function of the produced mass, and the nuclear species of the target.


The decay schemes (a) $M_0 \rightarrow \gamma_1 + \gamma_2$, (b) $M_1 \rightarrow \delta_1 + \gamma_2 + \gamma_3$, (c) $M_1 \rightarrow M_0 + \delta$, and (d) $M_1^{\pm} \rightarrow M_0^{\pm} + \gamma$, ($M_0$ - a pseudoscalar, $M_1$, a vector meson) are investigated. If the coupling constant, and meson masses of the Swinger mixture are used, the lifetimes are $\tau_a = 10^{-16}$ sec., $\tau_b = 2 \times 10^{-11}$ sec., $\tau_c = 10^{-18}$ sec., and $\tau_d = 4.8 \times 10^{-18}$ sec. All cases except (b) the calculation leads to logarithmically divergent integrals.


Satisfactory agreement of theory with experiment requires a meson mass $\sim 300$ e.m.u.


Justifying the explanation of Lattes, et al. (Nature 160, 453) of meson to electron decay.

Discussion of meson in hydrogen like orbit around a proton.


Cross sections for transformation of vector mesons to pseudoscalar mesons.

Phys. Rev. 71, 123.

A design for collimating Cerenkov radiation of a meson, and
directing this light onto a photomultiplier.


Masses of neutrons, protons and mesons can be obtained by a theory
that they are formed in a contracting universe by the association of
+ and - electrons.


The McMillan-Teller expression (P. R. 72, 1) is not valid near
threshold. The problem is studied by a perturbation calculation
near threshold.

HUGHES, D. J.: The Mass of the Mesotron as Determined by Cosmic Ray

Review of all previously published mass values and their errors.

Most of Hughes masses are reconcilable with a single mass ~200 e.m.

A small fraction have significantly different masses.


Data from penetrating showers of cosmic rays are interpreted as
showing that mesons are produced in groups by fast nucleons.

JÁNOSSY, L. and NICOLSON, P.: Meson Formation and the Geomagnetic Effects.


Most cosmic ray mesons must arise from protons and be produced
about nine at a time.
LATTES, C. M. G., MUIRHEAD, H., OCCHIALINI, G. P. S., and POWELL, C. F.:  

Two examples of meson decay in emulsions. Both $\mu$ mesons had same
energy, and masses 60 e.m. less than $\pi$ mesons. Examples found of mesons
produced in the emulsion. Grain counting and total energy release in
disintegration are compared as mass determination methods. Minimum mass
value determined, 240 e.m.

LATTES, C. M. G., OCCHIALINI, G. P. S., and POWELL, C. F.:  
Observations on the Tracks of Slow Mesons in Photographic Emulsions.

I. Existence of Mesons of Different Mass (Nature 160, 453.)

Boron-loaded Nuclear Research plates exposed at 5,500 m show 40
examples of production of $\mu$ mesons. Eleven $\mu$'s ended in emulsion, all
had same range. The $\pi/\mu$ mass ratio $\sim 2$, hence the momentum balancing
particle also emitted must have mass $\sim \mu$ mass.

II. Origin of Slow Mesons (Nature 160, 486.)

Photomicrographs show slow meson arising from stars, causing more
stars. These are called $\sigma$ mesons, and are assumed to have - charge.
They are believed to be similar, except in sign to $\pi$ mesons.

Half lives of $\pi^+$ and $\pi^-$ are in range $10^{-6} - 10^{-11}$ sec.

LHERITIER, M., PEYROU, C., and LAGARRIGUE, A.:  
225, 1304.

Momentum data are best explained in terms of 2 masses, $\sim 200 m_e$
and 300 $m_e$.

MÖLLER, C.:  
The Possible Existence of Mass Spectra of Fundamental Particles.
1, 184 (1948).
A mass spectrum, predicted by a 5 dimensional meson theory is discussed in relation to data on decay constants and masses of particles in hard cosmic rays.


Existence of heavy, strongly interacting mesons which decay to light, weakly interacting mesons is postulated. Possible masses and lifetimes are discussed.


Theoretically expected threshold energies, cross sections, and their energy dependence.

Threshold incident energy (based on Fermi degenerate gas) is 95 Mev, and is higher for positive than negative mesons. Cross section for single meson production varies with fractional excess energy as $E^{3.5}$, energy dependence for positives and negatives differ at low energies, because of non-zero initial kinetic energy of the positive meson.


Discussion of 300 stars found in emulsions exposed to cosmic rays.

Special emphasis on hammer tracks.


Photomicrographs of five stars found in emulsions exposed to cosmic rays, caused by negative mesons, whose masses were measured by change of grain density, and by variation of frequency of Coulomb scattering along tracks. 2 masses found: 100-230 and $350 \pm 100$ e.m.

Discusses need for experiments to determine the properties of mesons, i.e., lifetime, relation to nuclear forces, and β processes, classification of atomic energy levels. Discussion of available techniques for these studies.


A star found in emulsion exposed to cosmic rays is believed to be initiated by a slow meson. On the basis of possible disintegration schemes of the nucleus, the meson mass is estimated to be between 120 mₑ and 200 mₑ.


The intensity of cosmic ray mesons as a function of altitude has been interpreted as indicating a single type of meson of mean life \( \frac{\tau}{m_c^2} = 3 \times 10^{-14} \text{sec.}^{-1}/\text{ev.} \) An alternate explanation is that one type of meson, of mean life \( \frac{\tau}{m_c^2} = 1.5 \times 10^{-14} \) decays into a second, with \( \frac{\tau}{m_c^2} = 2 \times 10^{-14} \).


To obtain agreement between meson theory and experiment the following assumptions are suggested:

a. β decay is explained by the Fermi process without mesons
b. Meson spin is \( \frac{1}{2} h/2\pi \).
c. Meson disintegration yields 1 electron + 1 photon or 2 neutrinos.
d. Nuclear absorption of a meson is accompanied by neutrino
e. Meson production is more probable in pairs.


Scattering of fast neutrons by protons is calculated using the Møller-Rosenfeld meson theory of nuclear forces. The experimental results of Occhialini and Powell are compared with the predicted angular distribution of the scattered particles. A mass value of 215 me is deduced for the meson. The total scattering cross section predicted agrees with experimental results.


Proton proton scattering is studied using the Møller-Rosenfeld meson theory of nuclear forces. The theoretical predictions best fit experimental results if the meson mass is assumed to be 270 me.


Two cloud chamber photographs showing (a) an uncharged elementary particle of mass 770 me = 1600 me transforming into lighter charged particles, and (b) a charged particle of mass 980 me > m > proton mass, which decayed into 2 light particles, one charged, one neutral. Decay constant of particles \( \sim 5 \times 10^{-8} \text{ sec.} \)


Cloud chamber photograph of a slow negative meson of momentum \( 2.2 \times 10^7 \text{ ev/c.} \)

It is deduced that mesons are produced at a height where the pressure is 2 cm Hg and an average of 5 mesons are produced per proton collision. SIGURGEIRSSON, T. and YAMAKAWA, A.: Decay of Mesons Stopped in Light Materials. Phys. Rev. 71, 319.

Meson capture cross sections decrease with increasing atomic number of absorber. Values disagree with theoretical prediction.


The decay of a vector nuclear force meson to a scalar cosmic ray meson with lifetime $10^{-8}$ sec. is shown to lead to interactions of nucleons with $\mu$-mesons by means of virtual transformations to nuclear force mesons, of a magnitude in agreement with experimental evidence of negative $\mu$-meson capture.


From a study of the decay times of charged mesons using radiation damping it is concluded that only pseudoscalar mesons of lifetime $\sim 10^{-6}$ sec. can be observed in cosmic rays.


Expressions are given for the lifetime of a pseudoscalar meson decaying to 2 photons and a vector meson decaying into 3. Numerical values are $10^{-24}$ and $10^{-21}$ sec. respectively.


The bearing of multiple meson production, as described by Heitler theory on observations of bursts and penetrating showers of cosmic rays is discussed.

Cross section for creation of vector mesons recalculated by perturbation theory.


Calculation of total cross section for production of scalar mesons as a function of the energy of the incident quantum.


Study of decay in carbon, stainless steel, brass, water and beryllium. In steel and brass, only positive mesons decayed. In C, Be, H_2O both positive and negative mesons decay. Very few, if any, negative mesons undergo nuclear capture in C, Be, H_2O. Mass of decaying mesons ~ 200 m_e.


Probability for transition from vector to pseudoscalar meson, by e^ emission is calculated. If \( \tau \) has life \( \sim 10^{-8} \) sec., the coupling of one of the meson fields with nucleons must be weak.


To explain the difference in cross sections observed for production and capture of mesons, he assumes that there is an intermediate stage in the production process, so that production and absorption are not reciprocal.

Number of mesons produced is inversely proportional to $Z^2$, where $Z$ is the atomic number of the absorber.


The positive excess of cosmic ray particles at sea level decreases with increasing zenith angle. It is suggested that the positive excess is energy sensitive, decreasing with increasing initial energy of the mesons, and that the multiplicity of meson formation increases with primary energy.


Measurements made in both + and - mesons at various zenithal heights. Effects showing percentages of positive and negative mesons of low energy have been calculated. If a positive excess of 20 percent, uniformly distributed in the energy spectrum is supposed, comparison of experimental results and calculations indicates that the excess decreases with increasing creation energy. To explain the experimental results for a zenithal height of 60°, a 6 percent positive excess, if uniformly distributed must be assumed. The experimental results seem to show that the frequency of creation by protons must increase with creation energy, or that there is a considerable creation process by a non-ionizing radiation.

An ordinary microscope is used to study emulsions on both sides of 50 - 150 μ glass plates or acetate film support. Several curvature measurements can be made on the same particle by stacking several such plates with 2000 μ air gaps between. Measurements of magnetic deflection and matching of the superposition of plates is done with a projection microscope.


Electrons and protons may exist in unstable mesostates. There is one electron mesostate and 82 proton mesostates. The properties of the first nine proton states are tabulated and tentative assignments of recently discovered particles are made.


The absorption curve of cosmic rays was measured at a depth of 1000 m. (water equivalent). The data suggest that the radiation at this depth is formed at the decay of mesons in the atmosphere. Neutrini or neutral mesons may account for the findings.


A reflecting microscope enables emulsions to be examined through the backing plate, or allows study of tracks which traverse emulsions of two plates face to face.


The absorption thickness of the star producing radiation measured
in air, Al and Pb gave cross sections of the order of 1/2 to 1/3 the geometric cross section of the nucleus. The variation of star producing radiation in the atmosphere was compared with the intensity of production of mesons. In the low atmosphere, meson formation increases less rapidly with altitude than the star producing radiation, but at heights 20 km, the reverse occurs. It is concluded that the numbers of mesons formed increases strongly with decreasing meson energy.


A track in emulsion is interpreted to be a meson which scattered, exciting the scattering nucleus, although the probability of this being a decay is not excluded.


Summary of cosmic ray work, with bibliography.


Near the ground, in addition to the downward flux of \( \mu \) mesons, an upward stream of about 1/2 the downward intensity is observed, including \( + \) and \( - \) \( \pi \) mesons. Comparing the number of \( \mu \) mesons with the number of \( \pi \) mesons in the upward stream yields a value of \( 6 \times 10^{-9} \) sec. for the life of the \( \pi \) meson. Less than 15 percent of the negative \( \mu \) mesons stopped in the emulsion produce observable stars, nor are decay electrons observed. This may indicate that the capture of the meson leads to emission of a neutron and a neutretto.


Comparison of calculated meson spectrum at 14,250 ft. based on
spectrum at 18,100 ft., with experimental spectrum indicates that mesons of less than 400 Mev are produced in air between 14,250 and 18,100 ft.


Following the suggestion of the preceding paper, calculations show that two mesons can be involved in general nuclear interactions. If their mass ratio is 1.8 their masses are 320 and 176 m_e, if ratio is 1.65, masses are 312 and 190 m_e.


Derivation of the observed meson spectrum in cosmic rays, assuming they are decay products (10^-7 - 10^-5 sec. lifetime) of π mesons formed in nucleon-nucleon collision, average multiplicity of formation ≈ 5.


The hypothesis that a μ^- meson absorbs a neutretto, transforming itself to a π^- meson before being absorbed by a nucleus, leads to the correct order of magnitude for the half life of the capture process.


In the theory for meson creation in p-p collisions, the probability of emission greater than 1 is interpreted as multiple emission. A formalism is presented for computing the cross section for any multiplicity. The energy distribution of the mesons emitted is discussed. The relative order of magnitude of this type of process is compared with that of an ordinary high order process. The cross sections for low multiplicities are calculated numerically. They are much lower than Heitler cross sections, and are of the right order of magnitude.

The cross sections calculated previously for multiple processes are applied to the proton and meson components of cosmic rays. The value obtained for the penetration coefficient of the proton component and the variation of proton component with height agree better with experimental data than the results of the Heitler theory, which overlooks the possibility of multiple emission of mesons in proton-proton collision.


The positive excess in cosmic radiation is considered in terms of a primary proton component, which produces multiple meson emission, and of the contribution due to the asymmetry between positive and negative mesons depending on the influence of the Coulomb field of the parent nucleus on the diffused mesons.


Theoretical study of the spectra of electrons emitted in the decay of a meson in an atomic K-shell. Width of the spectral line is an increasing function of atomic number Z.


The ratio of the number of mesons stopped in emulsion to the number of stars in the same volumes increases by a factor 3 between 2,800 m and 23,000 m. It is suggested that spectrum of mesons locally produced by the primary component shows a strong maximum at low energies - in accord with the hypothesis of multiple production of mesons in collisions between nucleons.

From observations on large and small star disintegrations, and their frequency relative to each other and to slow meson production, it is concluded that multiple production of mesons by a very fast nucleon striking a heavy nucleus is unlikely. One might be able to correlate the observations by supposing total excitation of the nucleus to be a likely process, following which meson production competes with star disintegration.


Assuming the meson decay $\pi \rightarrow \mu + \nu$, where $\nu$ is a light particle of spin 1/2, the ratio of the mean lives of $\pi$-meson against decay, and $\mu$-mesons against capture by nuclei are calculated. For $Z = 11$, the ratio $\sim 10^{-2}$ and it increases with $Z$.


Considerations are outlined which are consistent with the existence of mesons of mass $\sim 200, \sim 300$, and $\sim 800 m_\pi$.


To any meson involved in nuclear forces there is a characteristic energy associated with the nucleon, and it is suggested that different mesons giving the same characteristic energy may be involved simultaneously in the interaction.

EPSTEIN, S. T., FINKELSTEIN, R. J., and OPPENHEIMER, J. R.: Note on Stimulated Decay of Negative Mesons. Phys. Rev. 73, 1140.

Theories in which decay is accelerated by electrostatic fields.
These always give radiative decay for free mesons. The competition of radiation less decay of negative mesons increases with $Z^5$. "Experimental evidence probably disproves theories of this kind."


Calculation of the relative probability of the different modes of disintegration of heavy nuclei (Ag Br) by mesons using evaporation Theory shows that the theory is in rough agreement with the observations of Gardner and Lattes.


Calculations for the time of capture of slow negative mesons by atoms were made to compare with the results of delayed coincidence experiments. Qualitative agreement with the results of Fermi and Teller was obtained, starting from different hypotheses.


Photograph of decay of a meson of mass 200 $m_0$ to an electron, with energy $15 \pm 3$ Mev.


Assuming Furth's principle of "elementary indeterminancy" the mass ratio of proton to $\Upsilon$ meson $m_p/m_\Upsilon = 2\Upsilon$, $m_\Upsilon = 293$. It is suggested the $\Upsilon$-$\mu$ decay is the analogue of the Compton effect, the $\Upsilon$ meson colliding with a nucleon. This gives $m_\Upsilon/m_\mu = 1 + 1/\Upsilon = 1.32$. This can be applied also to $\mu$ mesons, giving mesons of even smaller mass.
GARDNER, E. and LATTES, C. M. G.: Production of Mesons by the 184-Inch Berkeley Cyclotron. Science 107, 270.

Meson tracks were found in photographic emulsions exposed near C and other targets bombarded by 380 Mev a-rays. ~2/3 of the tracks end in stars. Meson intensity ~10^8 x that available in cosmic rays. Mass ~ 313 ± 16 m_e. Yield is much less at 300 Mev. Up to 195 Mev was available for particle production.


40 protons, 160 mesons in emulsions studied to determine masses. The spread of masses is large, but most mesons can be identified as μ, of ~ 200 m_e. The Σ mesons contain a large proportion of mesons of mass of Σ's.


A scattering formula is derived which depends only on the total length of the curved track and the distance between the ends of the track. The length of the track can be measured by means of a map measurer.


Normal mesons formed by decay of meson of mass 330 m_e, T ~ 6 x 10^{-8} sec.


Postulates the formation of neutral mesons, by nucleon or heavy meson bombardment; these mesons decay with very short half life into two photons.

An exact solution is given for the scattering of mesons by free nucleons, allowing for damping.


A counter telescope with magnetized deflecting plates operates a bank of neutron counters. The data obtained suggest that about 2 neutrons are produced per negative meson captured in lead.


The change in exponent of the absorption of cosmic rays at a depth of 400 m H$_2$O equivalent, is considered as a result of the range of $\pi$ to $\mu$ decay. From this it is estimated that the lifetime of the $\pi$ meson is $5 \times 10^{-8}$ sec.


When a light nucleus in a photographic emulsion captures a meson, the kinetic + binding energy liberated in the resulting star averages about 25 Mev. Using an evaporation model it is deduced that the disintegrating nucleus is excited to $\sim 60$ Mev, with a temperature of $\sim 6$ Mev, which suggests that most of the meson mass is set free in an unobserved way, such as kinetic energy of a single nucleon with velocity too great to produce a visible track.


No $\gamma$-ray was found accompanying meson decay.

Decay of neutral mesons to two photons (Lattes, Obs. 2237, '47) has been tested with coincidence detectors. The lifetime of a neutral meson so decaying must be \( > 10^{-10} \) sec.

HÖCKER, K.-H.: Protons as Cosmic Ray Primaries. Z. Phys. 124, 351, 392. (In German.)

I. Cross section and energy transfer of meson forming collisions, cross section = \( 2.2 \times 10^{-26} \) cm\(^2\), \( \sim 1/4 \) total energy goes into the meson field.

II. Sec. I is modified because of data by Schein. He now assumes the formation of neutrettos which can decay to neutrino pairs, or produce mesons by collision. The existence of \( \pi \) mesons and their bearing on this theory is discussed.

HOGREBE, K.: On the Existence of Two Values of the Meson Mass. Z. Naturforsch. 6a, 61. (In German.)

Meson masses reported by Fretter (Phys. Rev. 70, 625) and Hughes, (Phys. Rev. 71, 397), when appropriately weighted, fall into groups corresponding to 2 mass values, 171 \( m_e \) and 237 \( m_e \). The relationship of mesons of these masses to the \( \pi \) meson succession is considered.


The process \( \mu \rightarrow \beta + \nu_\mu + \) (neutral particle) is considered for cosmic ray mesons, and calculations are compared with experimental data on mesons.


A magnetic lens separates positive and negative mesons, whose mean
lives in carbon are then measured. Decay of 71 positive and 62 negative mesons yielded values of \( \tau = 2.16 \) and \( 2.25 \pm 0.20 \) microseconds respectively. Measurements in NaF and Al predict a 6 percent difference in the half lives.


Hypothesis that \( \mu \) mesons and neutral \( \mu \) mesons interact by means of a Yukawa field. The particles of this interaction he calls electrophotons. Some \( \sigma \) mesons may be of this kind. \( \Sigma \) and heavier mesons are metastable systems of mesons held together by this interaction. Maybe neutrons and protons are similar systems.

KOPPE, H.: The Meson Output from the Bombardment of Light Nuclei with \( \alpha \)-Particles. Z. Naturforsch. 3a, 251. (In German.)

The probability of emission of a meson following the capture of a 400 Mev \( \alpha \)-particle by a light nucleus is considered in terms of the temperature of the compound nucleus.


Measurements of meson decay in C indicate that, within the accuracy of experiment the mean life of the \( - \) meson is the same as that of the \( + \) meson.


New method of measuring curvature of tracks in emulsions due to Coulomb scattering, by measuring angles between chords instead of tangents, applied to 315 \( \sigma \)-meson tracks. Mass found \( 290 \pm 80 \text{ m}_e \). Method cannot resolve distinct mass groups, but if a group exists at \( m = 200 \text{ m}_e \), there must be a corresponding number with mass \( > 400 \text{ m}_e \).

$\pi/\mu$ mass ratio = 1.65 ± 0.11.

If the $\mu$ meson has mass 200 $m_e$, momentum balance indicates a mass 115 ± 30 $m_e$ for the neutral decay particle. The problems of grain counting: foreshortening of inclined tracks, variation in grain density with depth in emulsion due to different development, variation of silver halide in emulsion, resolution of close grains, and background fog of developed grains, are discussed. The constancy of range of $\mu$ mesons from $\pi$-$\mu$ decay, and lack of correlation between residual variation of range, and direction of the $\mu$ track, establish that the $\pi$ meson comes to rest before decay.

Lower limit of the lifetime is $\sim 4 \times 10^{-11}$ sec. Lower limit of lifetime of the neutral product of decay is $2.6 \times 10^{-21}$ sec.


The second disintegration of a double star in an emulsion at 4,300 m altitude is initiated by a meson from the first star, which appears to have been initiated by a particle of mass > 800 $m_e$, probably a meson of mass 1000 $m_e$.


The number of closely situated star pairs exceeds probable value. This is explained by assuming that the second star is formed by a neutron emitted from the first star. Perkins believes only a fraction of the second stars are produced by neutrons.

Theory of meson emission induced by nucleon-nucleon impact. Application to cross section (~10^{-26} cm²), multiplicity as function of energy, positive excess, primary spectrum, and angular distribution.


The mean life against nuclear capture of negative μ mesons is discussed. It is assumed that the interaction of heavy mesons with nucleons is related to nuclear forces, and that there is no direct coupling between light mesons and nucleons. It is assumed that nuclear capture of μ⁻ mesons is due to the process

\[
\text{proton} + \mu^- \rightarrow \left( \text{proton} + \pi^- + \rho \right) \rightarrow \text{neutron} + \rho
\]

in which \(\rho\) is the neutral particle associated with \(\pi^-\mu\) decay.

The half life of \(\pi^-\mu\) decay is calculated to be 4 x 10^{-8} sec. The interaction constant \(\frac{f^2}{m^2}\pi C\) for the strength of the \(\pi\) interaction with the \(\mu\) and \(\rho\) fields is 10^{-14} (calculated using \(m_{\pi}/m_{\mu} = 1.6\)). Because of this, the scattering of \(\mu\) mesons by nuclei is effectively due to Coulomb force only.


Calculation of proton-proton scattering, with various values of the potential energy of the proton. This energy is assumed to be the meson potential. The meson mass indicated by this potential is \(M_{\text{max}} = 330 \pm 30 m_e\).


The small capture probability for negative mesons by light nuclei is considered in terms of the fundamental length \(~10^{-13} \text{ cm}\).

The disintegration of a deuteron by \( \pi \) mesons is computed. The cross section for \( \pi^+ \) mesons is negligible because of Coulomb repulsion. For \( \pi^- \) at low energy, the cross section is about \( 10^{-27} \ cm^2 \) and this process competes with capture into the K-shell. This process could establish the existence of the neutral meson (if neutral mesons are sufficiently stable).


Theory of decay of \( \pi^+ \) meson into 2 \( \mu \) mesons.


It is suggested that \( \mu \) mesons are excited states of particles whose ground states are the electron and neutrino.


Discussion of the energy and momentum relations of meson formation in nucleon-nucleon collisions, in collisions of incident nucleons with complex nuclei and in \( \alpha \)-particle-nucleus collisions.


A comparison is made between intensities of slow mesons measured by different observers at different heights, and the intensities of fast mesons at greater heights. It is shown that the local production of mesons stops at 4000 m altitude.
NERESON, N.: Disintegration of Positive and Negative Mesotrons in Different Absorbers. Phys. Rev. 73, 565.

β-decay of + and - mesons in B, C, Al, Fe absorbers. Positives decay in all four absorbers, negatives only in B and C absorbers. For - mesons, capture before decay predominates.

NERESON, N. G.: Disintegration of Mesotrons in Be\textsuperscript{10}. Phys. Rev. 74, 509.

No significant difference was found between decay in Be\textsuperscript{10} and Be\textsuperscript{11}.


Results of the application of a method for measuring the ionizing effects of relativistic particles. The ionization spectra of cosmic rays were investigated at 3,200 m above sea level. In the range of soft components, three groups of particles showed ionizing capacities of 1.3, 1.8, and 2.7 times that of mesons. This plus path lengths led to mass estimates of (300-500) m\textsubscript{e}, (700-1000) m\textsubscript{e}, and (2000-3500) m\textsubscript{e}. Incidence ratio is \(\sim 0.15\) percent of the number of mesons.


Meson momenta were measured at 1000 m, in a cloud chamber. Momentum range data indicate two masses, of order 200 m\textsubscript{e} and 300 m\textsubscript{e}.


PICCIONI, O.: On the Capture of Negative Mesons. Phys. Rev. 73, 411.

Valley and Rossi hypothesis (Phys. Rev. 73, 177) is criticized. Events following nuclear capture of negative mesons have not been observed.

A search for photons of energy $\sim 50$ Mev, associated with mesons stopped in Fe, shows that no such photons arise from either the capture of negative mesons, or the free decay of positive ones.


Selection rules for transitions between states of different mass value.


Mass Determinations good to $\sim 10$ percent are made by studying tracks beginning in one and ending in the other of two plates, placed with emulsions facing, 3 mm apart, in a magnetic field. (The plates were studied with the reflecting microscope described in Nature 161, 473.)


The momentum distribution of decay electrons from negative mesons bound in $K$-orbits is calculated assuming a 2 particle disintegration

$\mu \rightarrow e^+ + \nu_{neutrino}$ or $\mu \rightarrow e^- + \nu_{neutretto}$. The resultant momentum distribution has a spread of $\sim Z/137 \ p_e(o)$, where $p_e(o)$ is the momentum of the decay electron from a free meson at rest. The effect of the meson's binding on its mean life decreases the mean life by a factor $\sim (Z/137)^2$.


Assuming the $\mu$ meson to be a heavy electron of spin 1/2 and the $\pi$ meson to be responsible for nuclear interactions, the following are calculated:
(a) the mean life of the $\pi$ meson
(b) the mean life for nuclear absorption of a $\mu$ meson from an extra-nuclear orbit.
(c) the energy spectrum of decay electron from $\mu$ meson assuming
the $\mu$ meson decays to a neutral meson, gamma ray and an electron.

Nature 161, 551.
Measurements of small angle scattering of $\pi$ and $\sigma$ mesons (Nature 160, 453 and 486) in photographic emulsions shows they have mass identical with those produced by Gardner and Lattes.

The majority of mesons produced in cosmic ray disintegration stars give rise to another star at the end of their range, but the majority of mesons entering the emulsion from outside come to rest without production of heavy particles. No $\pi^+$ mesons are observed ejected from stars. Results are consistent with production of $-\sigma$ mesons of large nuclear cross section and not more than 20 percent $\mu$ mesons in stars, and with failure to see $\pi^+$ mesons. Their results yield mass values of $\sim 320 m_e$ and $\sim 200 m_e$. No examples were found of a meson beginning in the emulsion, unaccompanied by at least one heavy charged particle.

The assumption that in negative meson capture most of the energy is carried off by a light neutral particle is developed. Assuming that this particle has zero mass, that the incident meson has negligible momentum and that the capturing nucleus contains equal numbers of protons and neutrons, the excitation of the nucleus arising from the recoil of
of the capturing nucleon leads to the probable emission of one neutron per capture.

RETALLACK, J. D.: Mesotron Decay. Phys. Rev. 73, 921.

Cloud chamber pictures of 27 negative mesons showed only one possible decay track, contradicting the Valley-Rossi hypothesis that accelerated decay occurs in heavy absorbers, instead of nuclear capture. Of 16 positive tracks which stopped in absorber, five showed decay positron tracks.


\( \pi \) mesons produced by 350 Mev a-particles on graphite were detected by photographic plates placed at deflections \( \pi \) and \( 3 \pi \) in 2 spiral channels. The ratio of the numbers of mesons in the two positions yields a half life of 7.7 \((\pm 2.1, -1.5) \times 10^{-9}\) sec., for \( \pi \)-\( \mu \) decay.


Five events, interpreted as the direct production of \( \mu \) mesons in cosmic ray showers, are reported. The identification of these as \( \mu \) rather than \( \pi \) mesons is based on mass measurements and the belief that they arise directly from stars, and not from \( \pi \)-\( \mu \) decay, is based on energy measurements, and consideration of the half life of the \( \pi \) meson.


Most of the penetrating particles in penetrating showers are positive and have momenta \( \sim 10^9 \) ev/c. From studies of interaction of these with Pb nucleons they identify these particles as protons, \( \pi^+ \) mesons or heavier mesons.

The differential range spectrum of cosmic ray mesons in lead shows a minimum at 450 Mev/c.


The experiment indicates that charge exchange, if present, is small, but not completely ruled out.


Experimental distinctions between slow meson and electrons in cosmic rays are discussed. The absorption curve of mesons up to 300 Mev/c momentum at sea level and at 2100 m altitude are given.


Delayed coincidences were sought between a meson stopped in lead and a delayed 50 Mev decay photon. In ~500 hours only 4 coincidences above background were observed, while ~100 should have been observed if the hypothesis under test were true. It was concluded that the meson did not decay into an electron plus photon, and that if the meson decayed to a neutral meson which decays to two photons, the mean life for this process is $> 10^{-10}$ sec.


Coincidence experiments established the presence of neutrons following the stopping of mesons in lead.

Description of stars in photographic plates exposed at 60,000 ft. Rate of star production (> 4 long range tracks) is 6000 stars /cc emulsion/ey.


The differential energy spectrum of cosmic ray mesons at sea level is measured by absorption, and detection of decay electrons. Measurements agreed with momentum data of Wilson, Nature 158, 414.


Using a delayed coincidence circuit and a C absorber, the residual range of decay electrons from μ mesons was measured. The results were not consistent with a unique initial energy for the electrons.


Meson decay electrons from a polystyrene stopping layer were detected, and ranges studied. The range of most electrons was consistent with energy \( \sim 25 \text{ MeV} \), but an appreciable number had energies up to 65 MeV. Decay electron spectrum appears to be complex.


Disintegration curves of + and - mesons stopped in \( \text{H}_2\text{O}, \text{NaF}, \text{Mg}, \text{Al}, \text{and S} \).


The observed mean lives in sulfur of positive and negative mesons are 2.04 \( \pm \) 0.23 and 0.54 \( \pm \) 0.12 microseconds. The ratio of positive to negative decay electrons corrected for 20 percent positive excess is 3.5 \( \pm \) 0.4.
These results support the hypothesis of competitive processes removing negative mesons rather than accelerated decay.


Negative and positive mesons are separated by a magnetized iron lens. Using a NaF absorber, the mean lives found were: negative mesons $1.33 \pm 0.4 \mu$sec., positive mesons $2.1 \pm 0.3 \mu$sec.


The magnetic moments are calculated for a vector meson field. The correct moment is obtained if the Kemmer interaction constant is used, by assuming a meson mass of about 150 $m_e$.


Using pseudoscalar theory, the cross section for scattering by nuclei, the probability of absorption by nuclei with emission of a photon, and the mean life before decay to an electron + neutrino.


Mean lives: $+_+$ $2.19 \pm 0.24 \mu$sec.

$-_-$ $0.74 \pm 0.17 \mu$sec.

The hypothesis is advanced that negative mesons are never captured by nuclei, but their life times are shortened when they are close to a nucleus.


Of 20 mesons stopped in Al plates, 12 showed decay electrons.
Scattering measurements gave an energy of $52 \pm 10$ Mev for one of these.

WESSEL, W. Z.: Infinite Representation of the Lorentz Transformation and the Mass Problem. Naturforsch. 3a, 559. (In German.)

A theory of particles leading to mass quantization is outlined. Meson masses are found sufficiently in agreement with experimental values to support the theory, which relies on yet unproved assumptions.


Studies of cosmic ray air showers indicate that if these showers originate from the decay of neutral mesons, these mesons must be produced either singly or in groups whose total angular divergence is not greater than $10^{-4}$ radians.


The probable number of electrons accompanying a meson beam emerging from a lead absorber, as given by Nassar and Hazen, Phys. Rev. 69, 298, is shown to be in agreement with the value given by Wilson in Nature 142, 73.


Moments of electrons from meson decay were measured from ranges in a cloud chamber containing Al absorbers. Three electron tracks found had energies 13, 18, and 50 Mev.

Two nuclear plates were exposed with a known separation between their surfaces, which were parallel, in a permanent magnetic field. Mass and charge measurements are reported for $\pi^+, \mu, \sigma, \rho$ mesons. No evidence of $\Upsilon$ mesons was found.


Absolute threshold energies are calculated for production by many types of incident beam and target. Reasons are considered for the disagreement of these results with the theory of McMillan and Teller (Phys. Rev. 72, 1).


A beam of about 0.1 microamps of 240 Mev protons was produced in the 130-inch cyclotron; $\pi^+$ and $\pi^-$ mesons were observed in photographic plates. A description of the cyclotron is given.


An explanation is proposed for the absence of either stars or decay electrons when negative $\mu$ mesons are stopped in lead. It is assumed that the negative meson is captured in a K-shell. Then the decay electron will require 38.6 Mev to escape from the Pb atom. The author assumes that no decay takes place if the electron has not sufficient energy to leave the K-shell. This hypothesis could be tested by using barium for the stopping material, since the electron would only require 18 Mev.
Experiments with absorbers of atomic numbers between sulfur and iron are proposed to determine whether the apparent shortening of lifetime in light absorbers is due to nuclear capture, or a true decrease of lifetime in the K-shell.


A counter experiment to determine the number of electrons accompanying fast mesons emerging from an absorbing layer, as a function of layer thickness.


The decay curve of a natural cosmic ray mixture of positive and negative mesons was determined using a series of ten coincidence counters covering a time interval 0.5 to 6.5 μsec. in 0.6 μsec. increments. The results lie on a smooth differential decay curve closely fitting the curve computed assuming competition between capture and decay of negative mesons, and can be fitted to a single exponential of mean life 1.7 ± 0.1 μsec. The effective mean life of negative mesons is less than 2.15 μsec. and appears to be approximately one μsec.


The relationship between the positive excess and the process of production of mesons in cosmic rays is explained. It is suggested that at high energies the positive excess may decrease with increasing meson energy.


Numerical values of the expected masses of mesons are $m = \frac{1}{\sqrt{\frac{xc}{e^2}}}$.
where $x$ is a root of $L_n^{(1)}(x) = 0$, where $L_n$ are Laguerre polynomials of the first kind. For $n = 1$, $m = 192 m_e$ is proposed as the theoretical mass of the most stable meson. In this theory there are an infinite number of possible meson masses.


Measurements of meson charge gives value equal to the electron charge within 2 percent. Range-momentum measurements on 86 mesons yielded masses 215 $m_e$ for 78 of the mesons, while 8 had mass 500-800 $m_e$.


The reduction of range and momentum data for mesons assumed to have unique mass, and assuming that the uncertainty of range and momentum is independent of their actual values, Data by Fretter (Obs. 902, 1947) yield a mass value $212 \pm 5 m_e$.


Kodak NT4, electron sensitive emulsions, 200 or 400 $\mu$ thick were used. About half of the stars were produced by particles of charge $e$, moving at relativistic speeds, the other half are due to neutral radiation. Most of the primary particles move in a cone of semiangle 40°. They appear to pass through nuclei imparting energy to the nucleons so that the nuclei evaporate. In each encounter there is a 50 percent chance the primary particle may undergo a change of charge equal to $e$. Photomicrographs of stars are given.

I. Decay of $\mu$ Mesons. Nature 163, 42.

Observations on processes in cosmic radiation were made with Kodak electron-sensitive emulsions, especially $\pi - \mu$ decay, and $\mu - \beta$ decay. The energies of the decay $\beta$'s were studied by Coulomb scattering. A preliminary report is made of observations of stars accompanied by showers of particles at minimum ionization.

II. Further Evidence for the Existence of Unstable Charged Particles of Mass $\sim 1000$ m$_e$, and Observations on Their Mode of Decay. Nature 163, 82.

An event is described which offers evidence for the existence of a meson of mass greater than the $\pi$ mass. A particle whose mass, determined by grain count, is $\sim 1000$ m$_e$ comes to rest in the emulsion, giving rise to three charged particles, one of which is apparently a $\pi$ meson. Evidence is given that this is spontaneous disintegration of the heavy particle into three charged mesons whose masses are in the region 200-300 m$_e$.


The ratio of cross sections for production of positive and negative mesons by photons is computed, and agrees with the experimental results of McMillan, Peterson, and White.


Capture of a meson into a nucleus is considered in terms of the transformation of a proton to a neutron, without emission of a neutral particle, or radiation, for meson of integral spin. Uncertainties involved may be great enough to bring calculations for scalar mesons (but not vector or pseudoscalar mesons) into agreement with experiment.
BUDINI, P.: Penetrating Particles in Extensive Air Showers. Nuovo Cim. 6, 163. (In Italian.)

Penetrating particles in cosmic rays are assumed to be mesons created by photons in a process with cross section proportional to $Z$. The theory does not give a complete account of all the particles observed, but the energy spectrum is in agreement with experiment.


Positive mesons produced by 380 Mev a-particles in the 184-inch have been detected by means of photographic plates. Heavy positive mesons are observed to decay into secondary mesons. Relative numbers of positive and negative mesons coming from a target are found by placing plates symmetrically on opposite sides of the target. Preliminary results indicate that for a 1/16 inch carbon target there are 1/4 as many heavy positive mesons as heavy negative ones for meson energies of 2-3 Mev in the laboratory system.


Cloud chamber experiments on absorption of negative $\mu$ mesons in aluminum, iron and lead foils indicate that no protons are emitted when a negative $\mu$ meson interacts with a heavy nucleus. The meson imparts only a small part of its rest energy to the nucleus and the remainder is given off as neutral, non-electromagnetic radiation, probably a neutral meson or a neutrino. Mesons which do not decay disappear by a charge exchange reaction. Meson associated photons can arise from transitions of a meson between Bohr orbits, or within the nucleus following reaction of the negative $\mu$ meson with the nucleus.
Ten photographs have been obtained of mesons stopping in Al foils in a cloud chamber. Four of these show the track of another particle originating from the stopping point, 3 light and 1 heavy particle.

Observations on the decay and capture of $\mu$ mesons in Kodak NT4 and Ilford G-5 emulsions are described. $63 \pm 4\%$ of the $\mu$ mesons stopping in the emulsion emit a fast electron. Emission of slow electrons is observed from $7.2\%$ of the slow mesons; these are ascribed to an Auger effect accompanying capture of $\mu$ mesons.

Stars formed by cosmic rays in emulsions exposed at a depth of 60 m water equivalent are believed to be caused by nuclear excitation from scattering of $\mu$ mesons. The estimated cross section $0.5 \times 10^{-23}$ cm$^2$ is $1/10$ that observed at sea level for this interaction. This may be due to the higher average energy of the meson beam at this depth.

The probability that a meson of integral spin decays to an electron, a neutrino and a photon is calculated classically, assuming the radiation is caused by the acceleration of charge in the disintegration. The result
is independent of the quantum mechanical properties of the meson field. The non-radiative decay is treated as a two body process in accordance with the original Yukawa theory; several types of coupling are used. The quantum mechanical probability for emission of one photon diverges at low frequency, this difficulty is avoided by using as a measure of this process the ratio of the mean energy emitted to the mean energy available for the process per unit time. This is of order \( \frac{e^2}{\hbar c} \). The energy spectrum is in agreement with the classical result.


It is shown that near threshold a beam of polarized mesons can be produced by the synchrotron gamma ray beam; that this beam will suffer no changes by magnetic fields, and that the only depolarizing effects will be those considered by Wentzel in his proposal to determine the spin of the \( \Pi \) meson by the angular distribution of \( \mu \) mesons resulting from \( \Pi \rightarrow \mu \) decay of a polarized beam (Phys. Rev. 75, 1810).


Cross Sections and angular distribution for production of mesons by photons on individual nucleons are graphed as functions of photon energy in the center of mass system for pseudoscalar and vector mesons, and strong and weak coupling. For heavy nuclei the threshold energy is lowered and at high energies the cross section approaches \( Z \sigma_c \) [\( \sigma_c \), the cross section for a single proton]. The production of mesons by photons on deuterons, and production by electrons are discussed.

Erratum - Phys. Rev. 76, 689.

In a cloud chamber photograph, the energy loss of the decay particle from a \( \mu \) meson was observed. The particle was emitted with energy \( 36 \pm 3 \) Mev and has 95 percent probability that its mass is \( < 7 \) \( m_\mu \).


Cross sections and angular distributions for production of single charged scalar mesons (scalar coupling) and pseudoscalar mesons (pseudo-vector coupling) by \( \gamma \)-nucleon collision. In the former case the cross section varies as the \( 3/2 \) power of the energy above threshold, angular distribution is of form \( \sin^2 \theta \). In the latter theory the cross section varies as the square root of the energy above threshold and the angular distribution is approximately isotropic. A note added in proof compares these results with results of McMillan and Peterson on synchrotron produced mesons reported in Science 109, 438.


The cross sections for production of \( \Upsilon \) mesons in nucleon-nucleon collision at energies just above threshold is computed using the nuclear potential from experiments on n-p scattering at 90 Mev. The cross section obtained is several orders of magnitude less than the results of Morette and Peng, based on a field theory approach.


The method suggested by Powell and Rosenblum for measuring masses of
light charged particles by arranging photographic plates to record deflection in a strong magnetic field is described. Details are given of an experimental device already in operation.


According to F"urth's principle of elementary indeterminacy, the ratio of the masses of the proton and $\mathrm{\Xi}$ meson is $2\uppi$. The ratio of masses of $\mathrm{\Xi}$ and $\mu$ mesons should be $1 + 1/\uppi$, which is in agreement with experiment. The possibility of a whole spectrum of meson masses is discussed.


Data on production of penetrating particles underground at a depth of 60 m water equivalent led the authors to conclude that groups of mesons are produced by high energy meson collisions with nuclei. The cross section for this process is $5 \times 10^{-29}$ cm$^2$/nucleon.


The rate of production of $\mathrm{\Xi}$ mesons created in ice by cosmic rays and their energy spectrum are determined by measuring their absorption in dense matter. It is determined that if there is direct production of $\mu$ mesons from stars in ice, that this effect is very small compared to the rate of production of $\mathrm{\Xi}$ mesons. However, the high mean energy of $\mu$ mesons in cosmic rays is interpreted as showing that these $\mu$ mesons are produced directly in the very high energy stars in the high atmosphere.

Mesons of about 3 Mev have been observed in a cloud chamber traversed by the neutron beam produced by the impact of 350 Mev protons on a 2 inch Cu sheet. In 100 photographs, seven meson tracks were found, and an example of the capture of a negative meson, probably by an argon nucleus, with the emission of 2 heavy particles is given.


The change in slope of the absorption curve of cosmic ray particles is discussed in terms of $\pi^-\mu$ decay at high energy, $\pi^- \tau$ lifetime, and $\pi^+$ and $\mu$ masses and the initial meson spectrum. The experimental results require that account be taken of radiation and pair production by $\mu$ mesons, but do not provide means of measuring the absorption of $\pi^-$ mesons.


Absorption experiments in Pb, Al, and C show bremsstrahlung from the decay electrons from $\mu$ mesons. The average energy of the decay electrons is greater than 25 Mev. The presence of bremsstrahlung makes absorption methods unsuitable for determining the upper limit of the decay electron spectrum.

HÖCKER, K.-H.: Investigation of the Meson Spectrum at Sea Level. Z. Phys. 125, 780. (In German.)

The positive excess of mesons and the production of penetrating ionizing particles by uncharged particles are discussed.


The change in slope of the absorption curve of cosmic ray particles

A photomicrograph is shown of a star in Kodak MTB3 emulsion. This star shows a dense shower of minimum ionization particles all in a cone of angular spread 2.5°. This is interpreted as showing both repeated multiple production of charged mesons and multiple production of G-rays which may be the decay products of neutral mesons. If these neutral mesons have rest mass ~150 Mev, and the G-rays are converted immediately to positron-electron pairs, the mean life of the neutral meson is $\tau_0 \approx 10^{-13}$ sec.


The probability of emission of $\pi$ mesons in the collision of two nuclei is calculated by statistical methods treating the nucleus as a black body with respect to meson emission. The results are shown to agree with the experimental results of Jones and White, Bull. Am. Phys. Soc. 24, 8.


The differential range spectrum of slow cosmic ray mesons is nearly flat to 100 g cm$^{-2}$ of air equivalent at sea level. The sea level electron intensity is considered and is consistent with the electron-2 neutrino decay of $\mu$ mesons provided there is a source of electrons in addition to mesons.


The spectrum of decay particles from mesons, as observed by curvature measurements in cloud chambers, extends from 9 to 55 Mev with an apparently continuous distribution of intermediate energy values, and a mean energy of 34 Mev. The shape of the spectrum and the upper energy limit are evidence
that the meson decays to an electron and 2 neutrinos. The meson spin is
half integral, and the mass, as deduced from the upper limit of the energy
spectrum is 217 ± 4 m_e.


LE PRINCE-RINGUET, L.: Mass Measurements of Mesons by the Method of Elastic

Masses are measured by observing elastic collisions between mesons
and electrons in a cloud chamber with a magnetic field. In addition to
the normal meson mass, a particle with mass 990 ± 120 m_e is reported.

LE PRINCE-RINGUET, L.: Photographic Evidence for the Existence of a Very
Heavy Meson. Rev. Mod. Phys. 21, 42.

A photograph is shown of a double star in which the first star is
initiated by a meson-like particle whose mass, computed from the energy
released in the star, is greater than 700 m_e. A σ meson originating
in this star, then initiates a second star.

LE PRINCE-RINGUET, L., BOUSSER, F., HOANG-TCHANG-FONG, JAUNEAU, L., and
Rev. 76, 1273.

A photograph is shown of a greater than 50 prong star which has 27
relativistic prongs, all in a cone of 30°. This is interpreted as a pro-
cess in which 5 to 8 mesons were created in an initial multiple process
which was followed by other processes (of smaller multiplicity) in the
same nucleus producing more mesons. Of these 27 relativistic particles,
17 are thought to be mesons.


LOVERA, G.: A Method for the Calculation of the Ratio of the Masses of the $\bar{\pi}$ and $\mu$ Meson. Nuovo Cim. 6, 229. (In Italian.)

Applying the linear relationship between grain spacing and the energy/mass ratio, to data by Lattes et al. (Proc. Phys. Soc. Lond. 61, 173) yields the value $m_{\pi}/m_{\mu} = 1.58 \pm 0.03$.

MARSHAK, R. E.: On Mesons $\bar{\pi}$ and $\mu$. Phys. Rev. 75, 700.

The present status of the two-meson hypothesis is reviewed. The nuclear capture of $\bar{\pi}$ and $\mu$ mesons can be explained assuming integral spin for $\bar{\pi}$ mesons and 1/2 integral for $\mu$. $\mu$ capture follows the scheme $\mu + p \rightarrow \bar{\pi} + \nu + p \rightarrow n + \nu$, where $\nu$ is a neutrino. The continuous spectrum of decay electrons is in accord with this theory. It is not clear whether a correct field theory of nuclear forces can be constructed with only one strongly coupled meson.


The cosmic ray star described by Kaplon, Peters, and Bradt, Phys. Rev. 76, 1735, is compared with experiments by Bjorkland, Crandall, Moyer, and York, to support the hypothesis of a pseudoscalar neutral meson of mass about 300 $m_\pi$, spin zero, and mean life $\sim 10^{-13}$ sec.


The lifetime for absorption of a $\bar{\pi}^-$ meson by a proton with
consequent emission of a high energy photon has been calculated for
scalar and pseudoscalar $\pi^-$ mesons, for absorption of free mesons and
absorption from bound states. The lifetimes from bound states are very
short compared with the lifetime for $\pi^-\mu$ decay. The competition between
neutral $\pi$ emission and $\gamma$ emission is considered. The inverse processes
are also discussed.

Radium 10, 156. (In French.)

The cross section for capture by deuterons of slow $\pi$ mesons, either
charged or neutral, pseudoscalar or vector, is of the order of $10^{-25}$ cm$^2$.
The distribution of protons emitted after capture of positive mesons is
very asymmetric.

McMILLAN, E. M., PETERSON, J. M., and WHITE, R. S.: Production of Mesons by
X-rays. Science 110, 579.

The conditions under which x-ray produced mesons have been observed,
the types of mesons, and types of meson track endings which have been
observed are described. The ratio of positive to negative mesons pro-
duced in carbon targets is given as $\pi^-/\pi^+ = 1.7 \pm 8$ percent. The
angular distribution of mesons is approximately spherically symmetric.
The energy spectrum of the mesons produced is given. The cross section
per quantum per carbon nucleus is $5 \times 10^{-28}$ cm$^2$.


The absorption of penetrating showers initiated in a layer of gaso-
line is greater than the absorption of showers initiated in air. It is
suggested that $\pi$ mesons are initially formed, but decay to $\mu$ mesons in
air showers, while the additional absorption of gasoline initiated showers
arises from nuclear interactions of $\pi$ mesons.
Nature 163, 959.

Theoretical spectra of the decay electrons from $\mu$-mesons are given. It is assumed the $\mu$-meson has spin 1/2 and decays (a) to an electron and two neutrinos, or (b) to an electron, a neutrino, and a neutral particle of finite rest mass. Charged particles are described using Dirac hole theory. Two alternate treatments are given for the neutral particles.


A survey of the status of meson theory at the end of 1948. The experimental data indicate that $\pi$ mesons are the quanta of the Yukawa field. $\pi$-$\mu$ decay seems to be accompanied by emission of a neutrino. $\mu$-$\beta$ decay seems to be accompanied by emission of two neutrinos, and shows close analogy to nuclear $\beta$ decay. The theory of mass states of elementary particles is discussed, and the $\mu$ meson is considered as a higher mass state of the electron.

MORETTI, C.: On the Production of $\pi$ Mesons by Nucleon-Nucleon Collisions.
Phys. Rev. 76, 1432.

The cross section as a function of energy is computed for production of mesons in nucleon-nucleon collision, assuming pseudoscalar mesons, pseudoscalar coupling and charge symmetric theory. The results are valid for all energies. Energy distribution of the mesons emitted and of the nucleons after collision are given.

From the observations of creation and decay of mesons in emulsions, it is assumed that \( \pi \) mesons are produced in the upper atmosphere by nuclear interactions and that their decay in flight produces fast \( \mu \) mesons, the major part of the penetrating component of cosmic rays.


A magnetic deflector has been constructed which makes meson produced in the 184-inch cyclotron by \( \alpha \)-particle bombardment available outside the cyclotron tank. The deflector consists of a magnetic shield designed to operate in high external fields. Its effect on the internal cyclotron beam is compensated by pole shims. The deflector yields a total meson flux of approximately 500 mesons per minute.


Observations made on stars produced by nuclear capture of slow negative mesons confirm the hypothesis that the meson rest energy is converted to nuclear excitation energy. Grain counting and mass measurements identify the star producing mesons as negative \( \pi \) mesons, of mass 185 m_{e}.


From the absence of tracks of recoil nuclei at the end of \( \mu \) meson tracks in emulsions, it is concluded that slow negative \( \mu \) mesons are captured by protons, producing a neutron and a light neutral particle.


The distribution of protons emitted in the disintegration of heavy nuclei can be explained by an evaporation at all excitation energies up to the nuclear binding energy. At higher excitation energies, either
fission or localized boiling causes ejection of α-particles. Observations on stars produced in layers of emulsion and pure gelatin indicate a cross section for disintegration proportional to the geometrical area of the nucleus.


By momentum measurements in a cloud chamber at 1000 m altitude it is determined that 33 percent of the particles observed under a 72 cm lead absorber were Π mesons, and under 24 cm lead, 17.5 percent were Π mesons.


Events in Ilford C2 plates, loaded with B, Li, or D, exposed at 12,000 to 15,000 ft, are discussed. The number of mesons seems to be sensitive to the amount of material near the point of exposure.


Cosmic ray stars in Ilford G5 emulsions show many minimum ionization tracks emerging from the explosion. The hypothesis that these are electrons is ruled out. It also seems unlikely that they are protons. Therefore the authors suggest that these stars show multiple production of mesons.


An account of the development of knowledge of the properties of Π and μ mesons up to the end of 1948.


Calculations of the mean life of a Π meson decaying to three
particles are made assuming the disintegration schemes: \( \tau^+ \rightarrow \pi^- + \pi^+ + \pi^0 \), 
\( \pi^- \rightarrow \pi^- + \mu^+ + \mu^- \), 
\( \tau^+ \rightarrow \pi^- + \mu^+ + \mu^- \), 
\( \tau^+ \rightarrow \pi^+ + \pi^0 \), 
\( \tau^+ \rightarrow \pi^+ + \gamma \), 
\( \tau^+ \rightarrow \pi^+ + 2\gamma \).


Measurements of \( H \rho \) and range of mesons in cloud chambers were made for 43 cosmic ray mesons. 37 of these have a unique mass 215 ± 4 m.e. Of the six remaining mass values, four are between 475 and 717 m.e. and two are 114 and 120 m.e. The former cannot reasonably be considered normal \( \mu \) mesons.


Two photographs of penetrating showers are presented as evidence for existence of \( \tau \) mesons. Of the heavily ionizing particles in cosmic ray showers, one group is identified with mesons of mass about 200 m.e. (although this might be \( \sim 300 \text{ m.e.} \)), and of the lightly ionizing particles, one group is identified as a type of meson of mass different from the 200 m.e. meson.


The author states that his data suggest that \( \mu \) mesons may be created directly in nuclear collisions.


A relativistically invariant theory is presented for a meson possessing a vector and a scalar state of different mass, tightly coupled by the electromagnetic field. With a high coupling constant there is a high probability of producing excited state mesons and decay photons by electromagnetic processes, e.g. Rutherford scattering of mesons in heavy material.
Thus a possible explanation of the many photons observed in nucleon nucleon scattering is that they result from excited state mesons which are produced directly. An experiment is proposed to test this theory by detecting decay photons on passage of a beam of mesons through a heavy target. The Christy and Kusaka argument against spin 1 for the $\mu$ meson is not affected by this theory.


The theory of nuclear interactions is discussed considering the experimental data on spins, masses, and charges of mesons.


A short historical introduction is followed by discussion of decay, nuclear absorption, and other behavior of $\mu$ mesons. It is concluded that $\mu$ decay gives rise to a single electron, and is not accompanied by high energy photons. The spectrum of the decay electrons is not well known enough to determine the disintegration scheme uniquely, but it contradicts the assumption of decay yielding an electron and one neutrino. The mean lives of negative $\mu$ mesons in different elements are presented. Experimental data indicate that nuclear absorption of $\mu$ mesons is accompanied by emission of neutrons, but not of high energy photons, while the emission of protons is as yet undetermined. These results suggest that only a small fraction of the rest energy of the captured $\mu$ meson is used to excite the nucleus.

In the symposium here reported, the behavior of negative μ mesons in absorbers of varying atomic number is discussed, considering capture into Bohr orbits, nuclear absorption, neutrons associated with stopped μ mesons, accelerated μ-β decay, and possible μ-β decay schemes.


An experiment to study nucleon meson interaction by observing the type of singly charged particle resulting from capture of a π⁻ meson by helium. The relative probabilities for a triton, deuteron, or proton resulting are given for certain types of reactions.

SINHA, M. S.: Photograph of a Shower Produced by a π Meson and a π⁻μ Decay. Phys. Rev. 75, 1757.


The cross section for the process e + P → e' + P' → e' + N + π⁺, and e + N → e' + P + π⁻, is found to be \( \sim 10^{-33} \text{ cm}^2 \) for production of a vector meson at electron energy 300 Mev. These single nucleon cross sections are to be multiplied by factors \( \sim Z \) for positive vector mesons and \( \sim (A-Z) \) for - mesons to give cross sections for meson production in a nucleus, so that values of \( \sim 10^{-31} \text{ cm}^2 \) may be attained with heavy nuclei.


The cross section for production of pseudoscalar mesons by collisions
of electrons with nuclei is calculated, assuming the electron interacts with the nucleons through the electromagnetic field. For 300 Mev electrons the cross section is $2 \times 10^{-30} \text{cm}^2$ per nucleon.

Snyder, C. W.: Current Ideas about Mesons. Nucleonics 5, 42.

Evidence for the existence of mesons of masses $\sim 200$, 300, and 1000 me is reviewed. Modes of formation and decay are discussed with emphasis on studies made in emulsions. Evidence for $\Lambda$ mesons (mass $\sim 10$ me) is inconclusive.


The absorption of electrons emitted in cosmic ray $\mu$ meson decay was measured. The results indicate that the spectrum is either continuous from 0 to about 55 Mev with an average energy $\sim 32$ Mev, or consists of three or more discrete energies. No variation of the lifetime with the thickness of absorber is observed. The experiment supports the hypothesis that the $\mu$ meson disintegrates into three particles.


Lifetimes are computed for decay of a neutral meson to 2 and 3 $\gamma$-rays, into a positron-electron pair, into another neutral meson and photon; decay of a charged meson into another charged meson and a photon, and into an electron or $\mu$ meson and a neutrino. The results are compared with experimental results of Moyer and York, Phys. Rev. 76, 187, and other experimental data.


Sakata meson theory, assuming spin 0 or 1 for $\bar{\Pi}$ mesons is applied to
explain the frequency of star formation. The small range of nuclear forces predicted by this theory is not contradicted by high energy neutron-proton scattering experiments, but to explain the deuteron quadrupole moment, a meson field with longer range must be added to the $\pi$ meson field. The theory accounts for $\pi-\mu$ decay and nuclear capture of $\mu$ mesons. Nuclear $\beta$ decay and $\mu-\beta$ decay must be considered direct processes, as in Fermi theory, instead of involving virtual emission and absorption of $\pi$ mesons.


A supplement to Phys. Rev. 76, 60, this paper considers the $Z$ dependence of $\mu$ meson capture probability, the excitation energy of nuclei after $\mu$ meson capture, and possible interaction schemes between mesons and nucleons.

TIOMNO, J. and WHEELER, J. A.: Charge Exchange Reaction of the $\mu$ Meson with the Nucleus. Rev. Mod. Phys. 21, 153.

$\mu$-meson capture by a nucleus is discussed, assuming the model $\mu^- + p \rightarrow$ neutron + neutral meson. Meson capture by this model, neutron decay, and $\mu$ meson decay yield (within the limits of error) identical coupling constants. The excitation energy of the nucleus is found to be much less than the meson rest mass, and for capture in heavy elements may lead to neutron emission. In light elements it may be insufficient for release of any particle.


Spectra of decay $\beta$ particles from $\mu$ mesons are computed for a three particle decay scheme, assuming the particles are either an electron, a neutral meson and a neutrino, or an electron and two neutrinos, assuming $\mu$ masses 200 m$_e$ or 220 m$_e$, neutral meson masses ranging from 20 m$_e$ to 80 m$_e$, and all types of coupling. The theoretical spectra are compared with the known experimental data.

A $\mu$-$\beta$ decay spectrum calculated assuming spin 0 for the $\mu$ meson is compared with the spectrum of Leighton, Anderson, and Seriff, Phys. Rev. 75, 1432, and nuclear excitation on capture of a spin zero $\mu$ meson is compared with the excitation due to capture of a spin 1/2 $\mu$ meson. In each case, agreement is close enough, that the possibility of spin zero for the $\mu$ meson must not be disregarded.


The cross section is given for the scattering of a fast nucleon with emission of a meson, using scalar meson theory and perturbation theory. The result, that the cross section is proportional to $1/E^2$ agrees, to first approximation, with the approximate calculations of Nordheim and Nordheim.


Forked tracks obtained in a cloud chamber are interpreted as mesons giving rise by interaction with nuclei to short, heavy tracks, probably protons.


The decay of a charged $\tau$ meson into a photon and a charged $\pi$ meson by virtual creation and annihilation of nucleons is studied. Unless both mesons have spin zero the lifetime of the $\tau$ meson is too short to permit it to be observed photographically.


A silver chloride crystal is used to detect $\mu$ mesons and their decay
electrons. The mean life of $\mu$ mesons is measured to be $1.9 \pm 0.3$ $\mu$sec.

Of 263 mesons observed to stop, 40 decayed, and of the 78 presumably negative $\mu$ mesons which did not decay, five were accompanied by large pulses which might have been nuclear stars. It is shown that in general if stars are produced by nuclear capture of negative $\mu$ mesons, the energy of the charged particles is less than 3 Mev.


Experiments on anisotropy of scattering are proposed as a means of establishing the spin of the $\Upsilon$ meson.


Mass measurements of slow particles in cloud chambers, involving momentum determination. For particles of mass less than 200 m$_e$, one should use hydrogen filled chambers.


Three tracks in Ilford C-2 emulsion exposed to cosmic rays are described, and attributed to mesons of mass 725 m$_e$ by grain counting. One of these originated in a star, and formed another star at the end of its range.


Energy levels of mesons in orbits around nuclei, interlevel transitions resulting in photon or electron emission, pair creation, and meson induced fission are discussed.


A silver chloride crystal was operated as an ionization chamber to
measure the ionization produced by two groups of cosmic ray mesons, one at minimum ionization and one in a higher energy region. The distributions of pulse heights due to mesons in each group were compared with theoretical computations made taking into account Symons fluctuation theory and the density effect of Halpern and Hall.


A meson mass spectrograph is described, in which the trajectories of mesons are determined by four pairs of crossed horizontal layers of Geiger counters. Deflections of trajectories are due to both electrostatic and magnetic fields. For mesons of mass 200 m\( \text{e} \) and momentum \( 10^6 \text{ ev/c} \), the angle of deviation is \( \sim 6^\circ \). Experimental errors are less than 1 percent. The anticipated number of mesons is twelve per day.

Photographic Emulsions Used in Nuclear Physics

1946


Preparation of dense emulsions containing 95 percent AgBr in small grains.


The variation in spacing of developed grains along the track of an ionizing particle of known mass and energy is calculated. The results are verified experimentally.


New emulsion has eight times the silver halide to gelatin ratio of ordinary half-tone emulsion, and has improved energy resolution. Chemical methods of improving discrimination between tracks of different types of particles are described. Emulsion can be loaded with other atoms.


B\(^{10}(n,\alpha)Li\(^{7}\) α-particle source used to calibrate Ilford half-tone concentrated plates. Accuracy \(\approx 1\) percent.

1947


The loading of emulsions is discussed, using uranium loading as a special example. The velocity of uptake of the loading atom decreases rapidly with time of immersion. The quantity absorbed is linear with concentration in the range 3.3 percent to 0.01 percent, but is more efficient for concentrations less than 0.01 percent. Absorption is greater in neutral than in acid solutions. High concentrations of neutral salts depress the uptake. Lead ions, even in 80 times excess, do not displace uranyl ions in the emulsion.

Continuing the report in J. Sci. Instrum. 24, 136 (preceding abstract); the uptake of uranium by emulsion is greater than that possible by absorption alone. The excess is attributed to adsorption. The isotherm has the form (wt. absorbed) = const. x (conc.)^{0.8}. The adsorption of lead was measured using solutions of ThB, and estimating the uptake by track counting.


The nuclear emulsion introduced in Phys. Rev. 70, 86, is described. The individual grains have diameter ~0.2 microns; the tracks often appear as continuous lines. Grain spacing is not the main cause of apparent straggling except below a range of 4 mm in air. The standard deviation in determining energy from a single measurement of range is 3.25 to 3.5 for protons of 0.6 to 2.4 Mev and 1.3 to 1.9 for α-rays of 4.0 to 8.5 Mev. Fission fragment tracks are easily seen, slow electron tracks are sometimes seen. The action of sensitizing and desensitizing chemicals is discussed. A theory is given for the probability of development of grains, in terms of specific energy loss, and a sensitivity parameter of the emulsion. This theory approximately explains the observed variations of grain spacing with residual range, of protons, α-particles, and fission fragments.


Curves are given of the stopping power of Ilford B1 emulsion for protons of energy 2-13 Mev, and α-particles. These are believed to be
applicable also to C-2, C-3 and E-2 emulsions. The resolving power, as demonstrated by a histogram of the ranges of 2000 tracks, is such that the precision with which the energy of a proton track can be measured is limited only by straggling. The discriminating power is such that protons can be distinguished from α-particles.


A full account of the work reported in Nature 159, 301 (preceding abstract).


The stopping power of these plates varies rapidly for proton energies up to 5 Mev. Above 5 Mev it remained constant.


Scattering of fast neutrons by protons was observed using "half tone" photographic emulsion for detecting the recoil protons. Empirical methods are reported for correcting for tracks escaping from the emulsion, taking into account small angle Coulomb scattering of protons from Ag and Br nuclei. These methods are important in the use of plates to study disintegrations produced by bombardment with very energetic particles from accelerators.
1948


Kodak NT4 nuclear emulsion is described, capable of recording tracks of charged particles at minimum ionizing power. The sensitivity is 3 times that of NT2a electron recording emulsion. Photomicrographs are shown of 100 µ electron tracks, and straight line tracks of high energy particles at minimum ionization. It is considered that NT4 emulsion can record tracks of charged particles of any energy.


Uniform development through the entire thickness of 200 micron emulsion is obtained by a two bath development. In the first bath, containing no alkali, the developer penetrates the emulsion. In the second bath, which contains all the constituents of developer (plus alkali), the actual development takes place. The temperatures of the solutions are kept constant.


Photomicrographs of sections of α and deuteron tracks. In tracks of low energy particles, there are enough developed grains that the tracks are nearly continuous. As the energy increases the number of developed grains decreases, the number for deuterons decreases more rapidly for deuterons than α-particles. There are enough developed grains so that tracks are easily followed, if α energy is \( \leq 200 \text{ Mev} \), or deuteron energy \( \leq 20 \text{ Mev} \).

For 300 μ emulsion, first soak in water. Place in 5°C developer, raise temperature for development period. Give a cold stop bath. Begin fixing in a cold solution afterwards warmed.


When it is desired to study the range-energy of recoil nuclei of low velocity, partial fading of the latent image by exposure to water vapor increases the grain spacing, making observations at the origin of an event more accurate.


Latent image fading of Po α tracks in nuclear emulsion studied by counting the number of developed grains per track at increasing time intervals between exposure and development. Different concentrations of the same developer and development times from 15-45 minutes do not influence the fading. Fading diminishes with increasing sensitivity, and can be reduced by low temperature and by loading with B. Stored emulsions show increased fading effect.


Description of a laboratory made nuclear emulsion. Range-energy for α-particles up to 10.5 Mev is established experimentally. Proton ranges calculated from a data and Bethe-Livingston formula.
HANNI, H., TELEGI, V. L., and ZUNTI, W.: Nuclear Photoeffect in Carbon with

Stars from the reaction $^{12}C(n, y)3He^4$ were observed in Kodak Alpha Emulsion. The energy released in the stars was calculated to be
10.1 and 7.5 Mev. The energy of γ-particles in the 10.1 Mev stars extended continuously to 5.3 Mev, with a maximum at 4.7 Mev. Analogous
behavior is observed in the $^{11}B(p, 3a)$ stars. The $^{12}C + y = 3He^4$ probably takes place in 2 steps $^{12}C + \gamma \rightarrow Be^{8*} + He^4; Be^{8*} \rightarrow 2He^4$.


Bibliography.

Phys. Rev. 73, 1131.

Length measurements of tracks in emulsions with a protective surface
layer 1 µ thick, are appreciably smaller than true lengths. These layers also alter the initial energy or entering angle of the track.


Methods of recording charged particles in photographic emulsion are described, and illustrated chiefly from work at Bristol. A comprehensive bibliography dating from 1910 to 1948 is appended.

ROSS, M. A. S. and ZAJAC, B.: Range Energy and Other Relations for Electrons

The range energy relationship was determined by bombarding the plates at glancing incidence with electrons from a β-ray spectrometer. The mean grain density along the track and the stopping power were measured. The stopping power, which depends on the energy of the electrons, is of the order of 3000 times that of air.

Ilford C2 50 micron emulsions were exposed in controlled experiments at temperatures ranging from -60°C to +20°C. The grain density at -60°C is about 1/3 less than that at +20°C.


Using Kodak emulsions, an energy loss of 0.005 Mev per cm (corresponding to 100 KeV electrons) can be recorded.


On the basis of the highest energy particles that can be recorded as recognizable tracks, an energy loss of 0.013 Mev per cm air path is taken as the threshold sensitivity of the best nuclear emulsions. This corresponds to a-particles of energy > 100 Mev, deuterons of 100 Mev, protons of 50 Mev, electrons of 20 KeV. Range-energy curves of α's, protons, deuterons and mesons in high silver halide concentration emulsions are given. These are based on constant stopping power values of the emulsion. Relative stopping powers of 1800 for α's and 2000 for protons, deuterons and mesons were used. Data are presented on the composition, sensitivity, physical characteristics and recommended uses of commercially available emulsions. Curves are given for calculated and observed stopping power vs. energy for α's and protons. Grain density, and grain density variation, are discussed, pointing out that grain density for low energy particles approaches a maximum value determined by the grain population of the unexposed emulsion. Grain spacing as a function of ionizing power, and latent image formation as a function of ion-pair production in the grain, are discussed. Using an energy loss of 0.013 Mev per cm as a threshold and 7.6 ev for the energy required to produce an ion-pair in AgBr, it is shown that 150 ion-pairs must be produced in a single grain to form a latent image.

Normal fading of latent images of a tracks can be accelerated by exposure to saturated air at 35°C. Images can be destroyed by storage at 25°C for 4 hours over 3 percent H₂O₂. Storage in fresh distilled water has no effect. Method is inapplicable to coarse grain, light sensitive emulsions. Loading with borax or Li salts inhibits the action of H₂O₂, hence exposure to eradicator must precede loading. Dessication over CaCl₂ restores sensitivity.


The rate of latent image fading in nuclear emulsions is influenced by many factors, including humidity, loading, temperature, H₂O₂ and vacuum. The rate of fading with humidity decreases exponentially with the amount of the H₂O retained in the gelatin. Salts increasing the pH of the emulsion act as sensitizers, those decreasing the pH accelerate fading. Latent image fading is negligible in vacuum or inert gas, while the rate of fading in O is twice as great as in air, and ten times as great as in N. Fading is believed to be an oxidation process. An interpretation based on the Mitchell theory of latent image formation is given.


Fading of latent images was studied by grain counting. Fading is almost entirely due to oxidation, all known factors affecting it doing so by changing the rate of oxidation. Fading varies exponentially with temperature, and its dependence on humidity follows closely the swelling
of gelatin. The difference in fading of Ilford Bl, B2, Cl, C2, D1 and El plates is accounted for by pH differences.


The relation between grain density in photographic tracks and particle energy has been derived theoretically, assuming that the probability that a grain be developed is given by \( p = c(1 - e^{-b(\frac{dE}{dR})^{1/2}}) \). Using a single pair of parameters \( b \) and \( c \), all experimental curves published for \( \alpha \)-particles, tritons, protons, \( \pi \) and \( \mu \) mesons can be well represented.


The fading of \( \alpha \)-particle tracks in Ilford Bl and C2 plates was studied as a function of time, temperature and humidity. The number of tracks remaining as a function of storage time follows the Gaussian probability law, with the average life of a track and the standard deviation varying with temperature and humidity, but their ratio constant.


It is shown that a relation of the type \( \frac{R_0}{R} = A\beta^k \) holds for velocities in the range of \( 0.035 < \beta = \frac{v}{c} < 0.28 \), where \( R_0 \) is the range of the particle in dry air, 15°C, 760 mm Hg. \( R \) is the range in emulsion. \( A \) and \( k \) are constants which depend on the emulsion. For Ilford C-2 emulsion \( A = 2760, k = 0.157 \).


Measurements of the effect of reduced temperature on the sensitivity of emulsions show that it can be used to preserve plates without impairing their sensitivity when the temperature is raised.

Curves are given for mass measurements from multiple scattering observed in Ilford nuclear emulsions.


The density of proton tracks as a function of energy in the range 2-7 kev was measured by bombarding the plates with protons from a mass spectrograph. Characteristic curves of various types of emulsions have been obtained by this method.


Attempts have been made to establish the range energy relationship of electrons in emulsion. Sensitivity of emulsions.


A simple projection system and film holder for taking photomicrographs of tracks is described. With this film holder a series of exposures covering long lengths of track is obtained on a single film as adjacent segments of track are successively focused and recorded.


A study is made of the influence of the pH of emulsions on the efficiency of development. The absorption of buffer solutions as a function of weight, volume and pH of the emulsion shows a minimum between pH of 2-3, and an almost linear increase between pH 5-12. Equilibrium
of the pH of Ilford C-2 emulsion with that of buffer solutions is reached after 4 hours impregnation for pH values between 4-10.5. An increase of pH intensifies the action of organic developers.


Shrinkage factors were determined by measuring thicknesses of processed and unprocessed emulsions as functions of loading, gelatin concentration, thickness, method of development, fixing and washing. The shrinkage factor is smaller than, but varies roughly as the ratio of the volume of emulsion to the volume of gelatin. For normal composition, Ilford C-2, E-1, G-5 and Kodak NT-la, 2a, and NT-4 have shrinkage value 2.7 ± 0.2. For lithium loaded emulsions this may increase to 3.2. Increasing the strength of developer, time of fixing, or washing increases the shrinkage factor. By experiments using lithium loaded emulsions, it has been determined that the shrinkage of the emulsion is uniform with depth, and for tracks with large dip angle (greater than 25-30°) the shrinkage factor for the track is less than that for the emulsion. The angle at which this behavior begins is a function of the grain spacing along the track.


Processing techniques which will develop all tracks, including electron tracks in 100-175 micron and 200-260 micron Eastman NTB emulsions are described. Development should begin at a low temperature, and completed.
Nuclear Stars in Photographic Emulsions

1946


The emission of different kinds of particles when nuclei are struck by protons of ~10 Mev, and the frequency distribution of stars of different multiplicity in photographic plates exposed to cosmic rays are discussed. Ilford half-tone plates were exposed to cosmic rays at altitudes of 7000, 12,000, and 14,500 ft. under absorbers of air, water, paraffin and Pb. Tracks having a mean grain spacing less than 0.4 μ are assigned to protons and α-particles, others mainly to mesons. Multiplicity of tracks and absorption investigations tend to verify the theory that the primary cosmic particles are protons.


Variation of the energies of individual prongs of stars with excitation energy. Variation of number and energy of prongs with height.


Stars with fewer than five prongs, with ranges < Th C1 α are attributed to radioactive contamination in the emulsion or air. Procedure for measuring depth of tracks is described.
1947


24 prong star, caused by particle of mass 0.31-15 nucleon masses.


Fifteen cosmic ray stars in photographic emulsions are studied.


Number of stars produced in photographic emulsions is proportional to the number of single tracks. Study of the effect of absorbers on star production.


Proton tracks in photographic plates, placed under mica sheets exposed to cosmic rays.

1948


Several methods are discussed for determining the charge and energy of heavy nuclei found in primary cosmic radiation. Tracks formed by heavy primaries in Ilford C-2 emulsion show the presence of nuclei from \(~\text{C}\) to \(~\text{Fe}\). A nuclear explosion caused by the collision of a \(>\) 3 Bev carbon or oxygen nucleus with a silver nucleus in the emulsion is discussed.


Using photographic emulsions, a comparison is made between the number
of nuclear stars observed at 17,000 m and 3,500 m above sea level. The mean free path of the star producing radiation is determined to be 140 gm/cm².


Star with 18 prongs, probably a Br nucleus disintegrating.


In a 9 prong star, α-particles were preferentially projected in one direction, protons and the recoil nucleus in the other. This supports the assumption that the initial nucleus splits into two parts, the lighter of which evaporates completely, emitting mostly α-particles, while the heavier reverts to a stable condition by emitting protons and neutrons.


Relative numbers of meson, proton, deuteron tracks. Number of protons relative to stars. Classification of stars according to nuclear origin. Energy-momentum balance, estimates of mass of particles initiating stars.


Angular distribution of particles emitted from 24 stars, having 15-22 prongs, from AgBr or I. Protons emitted symmetrically, α-particles emitted in direction opposite heavier particles. Results discussed by
"evaporation theory." Excitation energy 500-1000 Mev. These stars are thought due to inelastic scattering of fast cosmic ray particles, not captured neutrons or mesons.

YAGODA, H.: A Nuclear Evaporation Recorded in an Emulsion Near Sea Level. Phys. Rev. 73, 263.

Star in emulsion shows 1 a track, 5 protons. If it is assumed that 5 neutrons also emerged, the event can be interpreted to be the explosion of $\text{H}^{14}$ by a meson of mass $\sim 300 m_e$.

1949


Evidence is presented for a reaction of the type neutron + nucleus $\rightarrow$ deuteron + nucleus (of low excitation) found in photographic plates exposed to the Berkeley cyclotron.


Stars consisting of 4 a-particles were observed in photographic plates radiated with $\gamma$ rays of energy up to 23 Mev from a synchrotron. Measurement of the energy released and momentum balance indicate the reaction $^{16}\text{O} \rightarrow 4\text{He}^4 - 14.6$ Mev. The mean cross section at 20-23 Mev is $2 \times 10^{-29}$ cm$^2$.


Disintegration of $^{12}\text{C}$ into 3 a-particles by inelastic scattering of fast neutrons has been studied using photographic plates. Cross sections for the process have been determined for neutron energies 10.8 to 14.5 Mev.

Cross sections for star formation were measured using "gelatin sandwich" nuclear plates. Stars formed in the emulsion proper arise from Ag or Br, those formed in the gelatin are due to C, O, or N. The latter are identified by their centers not being visible. The ratio of gelatin to emulsion stars is 5.8 ± 0.7 percent. Computation of this ratio from the geometric cross sections gives 4.53 percent.


The ranges of star prongs were studied. In particular, the length and angular distribution of recoil tracks, due to residual nuclei left when highly excited nuclei had cooled by particle emission, were studied, and it is concluded that the majority of cosmic ray stars are due to fast neutrons (which are not actually captured), to fast mesons, which give up all their rest energy, or possibly to heavy mesons which are captured.


A star observed in an Eastman NTB-3 plate appears to have been caused by an α-particle which was deflected 2.5° in the collision. The star has eight more prongs, including a Π-meson which comes to rest in the emulsion.


The number of stars decays exponentially with the amount of the atmosphere above the point of observation, while the size of stars is independent of height. These facts are consistent with the theory that one primary particle makes several effective collisions. The mechanism of star
production is discussed, and it seems likely that nucleons passing through the atmosphere alternate in state between protons and neutrons as a result of collisions, and that each primary particle makes several stars. A mathematical analysis of the energy loss of primary particles is made.