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Search for Highly Absorbable Negative Cosmic-Ray Particles at Sea Level*

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A search has been made at sea level for negative cosmic-ray particles (other than electrons) which are absorbed in 147 g/cm^2 of lead and which have momenta greater than that of mu mesons of this range. The momentum and sign of the charge of those particles stopping in the absorber were determined by means of a counter controlled cloud chamber operated in a magnetic field. During 1400 hours of operation no negatively charged particle in the momentum interval 0.4–1.7 Bev/c was recorded as stopping in the absorber. This result has been used to show that the intensity of negative particles with strong nuclear interaction cannot amount to as much as 0.05 percent of the total intensity of negative particles in this momentum interval. It has been shown that the local production of negative mu mesons in the momentum interval 0.5–1.0 Bev/c is less than 8.8×10^{-5} particle/(cm^2 steradian hr meter). A lower limit of 6.9×10^5 g/cm^2 of lead has been set on the removal path length of mu mesons in the momentum interval 0.4–1.6 Bev/c.

I. INTRODUCTION

FROM many studies it is clear that the cosmic radiation at sea level and mountain altitudes consists principally of an electronic cascade component, positive and negative mu mesons, protons, and neutrons. Even at these low altitudes high-energy nuclear events occur which produce secondary particles not included in the above list. These are the pi mesons, V particles, and other types of mesons. Such particles have been detected only in association with highe-nergy nuclear events or when they chance to decay in cloud chambers or nuclear emulsions. With the possible exception of the pi meson, the net flux of these particles must be exceedingly small because of the low production rates and short decay times.

By improving a technique previously used to determine the intensity of protons at lower altitudes,[1,2] a careful search has been made at sea level for negatively charged particles of such nature as to be more readily absorbed than mu mesons. In the previous experiments the proton flux density was determined by using an experimental arrangement similar to that used in the present experiment (Fig. 1). The magnetic cloud chamber was triggered by an arrangement of counters designed to select those ionizing particles stopping in the absorber below the chamber. All particles selected in this way lie in the same range interval. By suitable choices of absorber thicknesses protons and mesons selected in this way will lie in well-separated momentum intervals because of the different range-momentum relationships of these particles. For ionization ranges of 0.5 to 5.5 cm of lead, well-resolved maxima corresponding to mesons and protons were obtained by plotting the number of particles as a function of momentum.[3]

While the negatively charged particles selected in this way were grouped strongly in the momentum interval to be expected for mu mesons on the basis of their ionization range, small numbers of negatively charged particles were recorded up to the highest momentum measured (2.5 Bev/c). In these observations the coverage of the anticoincidence tray was not nearly so complete as in the present experiment. This led to an error of inclusion in which mesons of momentum greater than that corresponding to the maximum ionization range were recorded as a result of being scattered outside the anticoincidence coverage. However, multiple scattering could not account for the negative particles recorded with momenta greater than 1 Bev/c. Inclusion of these high-energy negative particles was attributed to inefficiency of the anticoincidence Geiger tubes resulting from dead time. In later observations[2] with larger absorber thicknesses and much better anticoincidence coverage such high-energy negative particles were still recorded. At an altitude of 3.4 km and with an absorber thickness of 15 cm of lead the recorded intensity of negative particles above 1 Bev/c amounted to about 2.5 percent of the total negative meson intensity at the same momentum. In this case apparently neither scattering nor counter inefficiency could account for the inclusion of these negative particles. For similar observations[4] at sea level the corresponding percentage of negative particles was 0.4 percent, which can be accounted for by leakage due to dead time of the anticoincidence Geiger tubes.

In the present experiment the effects of scattering and counter inefficiency have been greatly reduced in order to place an upper limit on the total intensity of all negative particles (other than electrons) with momenta greater than 0.4 Bev/c and of such nature as to be absorbed in 10 cm of lead. In 1400 hours of operation at sea level, with the single exception of one heavily ionizing particle which seemed to be a backscattered deuteron, no negative particles with momenta

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* This work supported by the U. S. Office of Naval Research.

† A division of the Department of Physics.

[1] Miller, Henderson, Potter, Todd, and Wotring, Phys. Rev. 79, 459 (1950).

[2] G. R. Garrison *et al.* (to be published).

[3] Miller, Henderson, Potter and Todd, Phys. Rev. 84, 981 (1951).

[4] J. Todd, Jr. *et al.* (to be published).

greater than 0.4 Bev/c were found to stop. For the same momenta some 200 positive particles stopped in the absorber; these are assumed to consist almost entirely of protons.

II. APPARATUS AND EXPERIMENT

The experimental arrangement is shown schematically in Fig. 1. The chamber is expanded by C-A events in which Geiger tubes C_1 and C_2 are discharged in coincidence while none of the anticoincidence tubes in groups A_1 and A_2 are discharged. Therefore cloud-chamber photographs are obtained of those tracks produced by particles which pass through C_1 and C_2 and are absorbed in the 10 cm of lead below the chamber. The term "absorption" here refers to those events in which not only the incident particle but also all ionizing secondary particles are stopped in the absorber.

The cloud chamber has a diameter of 7 inches and an illuminated depth of 1 inch and is operated at a pressure of 1.8 atmospheres in a magnetic field of 8200 gauss. The coincidence tubes C_1 and C_2 that define the acceptance beam have copper cathodes $\frac{3}{4}$ inch in diameter and 6 inches long and are separated by a distance of 12 inches. The anticoincidence tubes below the absorber are $1\frac{1}{4}$ inches in diameter and 30 inches long. To insure complete coverage, the width and length of the anticoincidence tray are such that the tray extends several inches beyond the limits of the acceptance beam. The A tubes at the sides of the absorber prevent the recording of events due to wide angle scattering and reduce the probability of recording events in which high-energy charged particles entering the absorber from the side undergo nuclear collisions in the lead from which secondary particles pass upward through the cloud chamber and coincidence tubes. Errors resulting from the inefficiency of the anticoincidence tray because of counter dead time are eliminated by providing a blanking pulse which prevents the recording of any C-A events during the recovery time of the A tubes. Using the method described by Stever[5] the maximum recovery time of the A tubes used in this experiment was found to be about 450 microseconds. Following the discharge of any A tube a positive 600-microsecond pulse is applied to one side of a C-A mixer and prevents the recording of C-A events during the recovery time of the A tube. This blanking pulse was retriggered by each A pulse (even though the pulse occurred in the middle of a blanking cycle) so that no C-A pulse could be recorded for 600 microseconds following the last discharge of an A tube. The effect of introducing this blanking pulse is only to reduce the total time of observation by about 4 percent. During the effective time of observation it in no way reduces the probability of detecting those particles stopping in the absorber. To make sure that no events were recorded due to the failure of one or more A tubes, all tubes were scaled twice each day. Provision was made to do this without removing the tubes being checked from the anticoincidence circuit. During the experiment only one A tube had to be replaced, and all data were discarded which had been obtained between the previous check period and the detection of the bad tube.

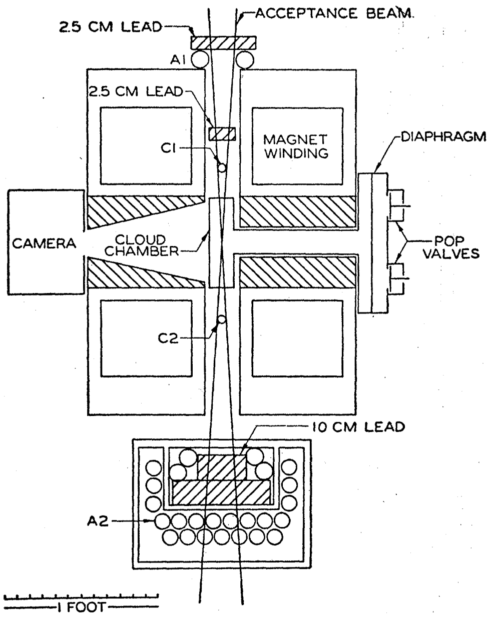

FIG. 1. Schematic diagram of the experimental arrangement.

Lead absorbers were placed above the chamber so that electrons would produce with a high probability cascade showers which would either trigger the anticoincidence tubes A_1 or be revealed by the presence of several time-coincident tracks in the cloud chamber.

As described in detail in a previous paper[1] the curvature of the cloud-chamber tracks was determined by comparing the track photographs with a set of standard curves.

The equipment was operated for 9 weeks during the summer of 1952 at Seattle, Washington, at an elevation of 20 feet above sea level.

III. RATE DETERMINATION

A. Track Selection

Since this experiment is primarily concerned with singly occurring nonelectronic particles that produce C-A events, only those photographs were retained in the pertinent data which showed a single track time-coincident with the chamber expansion. Of these tracks, those near the chamber wall are not suitable for accurate curvature measurement because of their short length and the turbulence of the gas near the wall. The curvature was determined only for those "single tracks" of length at least 75 percent of the

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[5] H. G. Stever, Phys. Rev. **61**, 38 (1942).

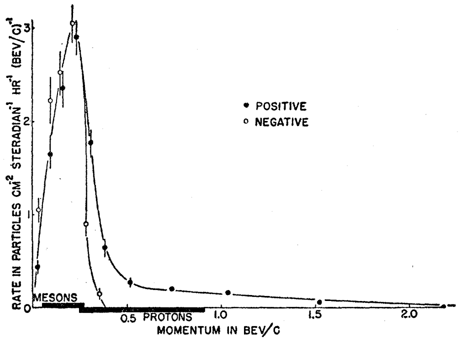

FIG. 2. Momentum spectra of those particles stopping in 147 g/cm^2 of lead equivalent at sea level plotted separately for positive and negative particles.

chamber diameter. These tracks constitute the "measured tracks." With the exception of the single track requirement, none of these criteria biases in any way the selection of particles of a specific type. The single track requirement does discriminate against electrons (which produce cascade showers) and those particles emitted from energetic nuclear collisions in the material immediately above the chamber since these particles are often accompanied by penetrating showers. Such discrimination is advantageous since we are concerned with the flux of nonelectronic particles in the atmosphere rather than with local production.

B. Normalization

As described in an earlier paper,[3] the absolute directional differential intensity is given by $I=(1/A)\times fr(n/m)(1/\Delta P)$, where A is the admittance of the counter telescope C_1 and C_2 in cm^2 steradian, f is the fraction of all C-A events associated with single tracks, r is the average hourly rate of C-A events and n/m is the ratio of the number of measured tracks in the momentum interval ΔP to the total number of measured tracks. This expression for the intensity depends only on the assumptions that the momentum distribution among measured tracks is the same as that among all single tracks and that the distribution of events producing C-A counts is the same whether or not the cloud chamber control circuits are in such a configuration that a C-A event would trigger a chamber expansion.

The admittance of the counter telescope computed from the effective length, width, and separation of tubes C_1 and C_2 is 0.97 cm^2 steradian. This value is in satisfactory agreement with the value 0.94 cm^2 steradian found in a separate experiment by a comparison of the intensity of the hard component as determined by this equipment with the absolute value determined by Rossi.[6]

IV. RESULTS

The experimental results obtained during 1400 hours of operation are listed in Table I and shown graphically in Fig. 2. Every track satisfying the criteria discussed under Track Selection is included in this table. The most significant feature of the results is that with one possible exception no negative particles with momenta greater than 0.4 Bev/c were recorded as stopping in the absorber. As will be shown later, the exceptional track was produced by a heavily ionizing particle which was probably positively charged and moving upward through the chamber; it is therefore omitted in the following discussion.

For particles with momenta near the maximum at which momentum measurement is attempted (2.5 Bev/c) there is a possibility that occasionally the sign of the charge of the particle will be mistaken because of turbulance in the cloud chamber or bias of the observer. Since relatively large numbers of high momentum positive particles were expected it was decided before the experiment was conducted that the quantitative results should be based only upon those particles with momenta less than 1.6 Bev/c in order to avoid even small numbers of errors of inclusion among the negative particles recorded. Therefore, even though no negative particles were recorded with momenta between 0.4 and 2.5 Bev/c, the results stated below are based on the momentum interval 0.4–1.6 Bev/c.

The exceptional track is track "a" of Fig. 3. Its curvature corresponds to a momentum of 0.54 Bev/c and the direction of curvature is such that if the particle moved downward through the chamber it must have been negatively charged. The density of the track has been estimated by comparing it with a large number of tracks produced by heavily ionizing positive particles, presumably protons. Tracks "b" and "c" are included in Fig. 3 as examples. Track "d" is a track of minimum ionization. All of the tracks of Fig. 3 were obtained within a period of 14 hours; the photographic treatment was therefore the same for all tracks, and the cloud-chamber conditions were at least approximately the

TABLE I. Momentum distribution at sea level of particles stopping in 147 g/cm^2 of lead.

	Positive particles		Negative particles	
Momentum interval in Bev/c	Number of particles	Intensity in particles per (cm^2 steradian hr Bev/c)	Number of particles	Intensity in particles per (cm^2 steradian hr Bev/c)
0.00–0.08	32	0.46±0.07	72	1.05±0.12
0.08–0.13	71	1.65±0.19	90	2.22±0.23
0.13–0.17	120	2.34±0.21	121	2.53±0.23
0.17–0.27	214	2.90±0.20	208	3.10±0.21
0.27–0.35	115	1.77±0.16	52	0.89±0.12
0.35–0.43	49	0.65±0.09	10	0.15±0.05
0.43–0.61	41	0.28±0.04	1	0.00
0.61–0.88	55	0.23±0.03	0	0.00
0.88–1.20	55	0.19±0.03	0	0.00
1.20–1.85	27	0.05±0.01	0	0.00
1.85–2.50	10	0.02±0.01	0	0.00

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[6] B. Rossi, Revs. Modern Phys. **20**, 537 (1948).

same. Track "c" was produced by a proton with a momentum of 0.54 Bev/*c* (the same momentum as particle "a") and track "b" corresponds to a momentum of 0.37 Bev/*c*. Much detail has been lost in the reproduction of these tracks, but a comparison of the tracks as they appeared on the original film shows that track "a" is much denser than track "c" and that it is at least as dense as and perhaps denser than track "b." It follows that particle "a" (if singly charged) has a mass at least $1\frac{1}{2}$ times that of a proton. This conclusion is consistent with the comparison of track "a" with other heavily ionizing tracks of positive curvature. Additional but perhaps less certain conclusions can be drawn from a comparison between the range required for a particle to traverse the chamber wall and trigger the second coincidence tube and the range of various heavy particles corresponding to the momentum indicated by the curvature of track "a." It is found that neither the triton nor the alpha particle of this curvature has sufficient ionization range to pass through the wall of the cloud chamber. It is conceivable that track "a" was produced by a negative particle, but since there is no reliable evidence for the existence of a negative particle of mass $1\frac{1}{2}$ times that of the proton, the most credible explanation of track "a" seems to be that it was produced by a deuteron emitted in an energetic nuclear event in the lower absorber and projected upward through the cloud chamber. It has therefore been omitted in the discussion of the experimental results.

With the possible exception just discussed, no negative particles in the momentum interval 0.4–1.6 Bev/*c* were found to stop in 147 g/cm^2 of lead. If the absolute intensity of such particles were such that on the average one would be detected during the experiment, the probability of the actual result (i.e., of detecting no such particles) would be 37 percent. An upper limit for the absolute intensity of such particles at sea level is computed on the basis that on the average one would be detected during the course of the experiment. In this way, using the normalization procedure mentioned above, an upper limit of 1.0×10^{-3} particle/(cm^2 steradian hr) is found. That is to say, the absolute intensity of negative particles in the momentum interval 0.4–1.6 Bev/*c* that are absorbed in 147 g/cm^2 of lead equivalent is $\left(0.0\begin{smallmatrix}+1.0\\-0.0\end{smallmatrix}\right)\times10^{-3}$ particle/(cm^2 steradian hr). Integrating Rossi's[6] sea level momentum spectrum for mu mesons over this momentum interval and taking 1.2 as the positive-negative ratio, it is found that the intensity of negative particles in the momentum interval that are absorbed in 147 g/cm^2 of lead is less than 0.02 percent of the total intensity of negative mu mesons in the momentum interval.

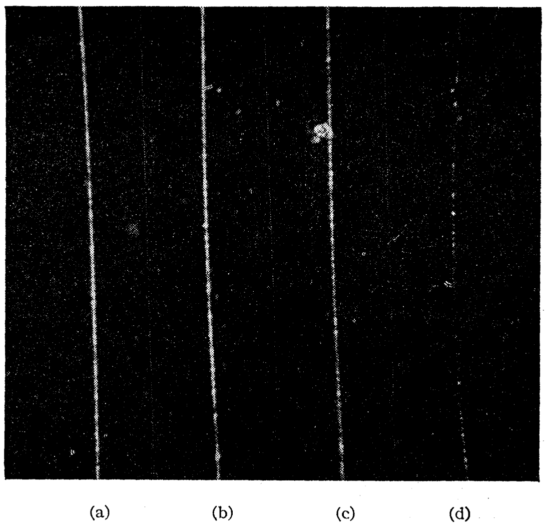

FIG. 3. Cloud-chamber tracks produced by (a) heavy particle showing negative curvature, (b) 0.37 Bev/*c* proton, (c) 0.54 Bev/*c* proton, (d) particle of minimum ionization.

In the same momentum interval 198 positive particles (presumably protons) stopped in the absorber, corresponding to an intensity of 0.36 particle/(cm^2 steradian hr) or 6 percent of the total intensity of positive particles in the momentum interval.

The results of this experiment may be compared with the results of a similar experiment by Mylroi and Wilson.[7] For the momentum interval 0.6–10 Bev/*c*, these authors found that of 1975 negative particles passing through the apparatus 4 were recorded as stopping in 1–10 cm of lead, none in 10–15 cm, and 8 in 15–20 cm. The 8 events for the range interval 15–20 were attributed to inefficiency of the anticoincidence tray. Two of the 4 events for 1–10 cm were attributed to erroneous information from the magnetic spectrometer, leaving two events that might have been due to electrons or absorption of negative particles with strong nuclear interaction. The authors therefore set an upper limit of 0.1 percent on the fraction of high-energy negative particles that are absorbed in 10 cm of lead.

V. DISCUSSION OF RESULTS

Since in the course of the present experiment no negative particles in the momentum interval 0.4–1.6 Bev/*c* were recorded, there is no necessity for a discussion of errors of inclusion. The detection efficiency for *C-A* events is considered to be 100 percent. Effects of dead times of the *C* counters are negligible for the present purpose. That the equipment was operating properly is shown by the detection of those mesons with range less than 147 g/cm^2 of lead with intensities in agreement with previous work of this and other laboratories.[4,6] In arriving at an upper limit for the intensities of specific types of negative particles assumptions will have to be made regarding the probability of such particles producing *C-A* events.

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[7] M. G. Mylroi and J. G. Wilson, Proc. Phys. Soc. (London) **A64**, 404 (1951).

A. Sea Level Intensity of Pi Mesons

In order to derive an upper limit for the intensity of negative pi mesons it is necessary to introduce a removal path length L, which is defined by the expression $J_0-J_x=J_0(1-e^{-x/L})$, where J_0-J_x is the intensity of particles that are "removed" in an absorber distance x, and J_0 is the intensity of particles incident at the top of the absorber. An event is recorded as a "removal" only if all ionizing secondary particles as well as the primary particles are stopped in the absorber. The removal path length is therefore always equal to or greater than the mean path for nuclear interaction.

The removal path length of the pi meson is assumed to be approximately equal to that of the proton. Experimental evidence for the validity of this assumption is given by the nuclear emulsion studies of Camerini *et al.* and others.[8] Within the statistical accuracy of these experiments the nuclear interaction cross section for fast pi mesons was found to be the same as that for protons, or approximately equal to the nucleon geometrical cross section. Furthermore the types of stars produced by pi mesons and those produced by protons were identical within the experimental accuracy. Previous work of this laboratory[2] has shown that the removal path length of protons in the momentum interval considered in the experiment is about 200 g/cm^2 of lead. This value has been assumed for the removal path length of pi mesons.

Since the nuclear collision of particles is a statistical process, not all pi mesons passing through the chamber would be absorbed in the lead below the chamber and some pi mesons interacting in the 60 g/cm^2 of material above the chamber would not be detected because of absorption or because of production of secondaries which would cause them to be rejected by the single track criterion. Taking account of these two effects and the loss of momentum as the particles pass through the material above the chamber, it is found that the intensity of pi mesons in the momentum interval 0.5–1.7 Bev/c at the top of the equipment is less than 2.5×10^{-3} particle/cm^2 steradian hr, or less than 0.05 percent of the total flux of negative mu mesons in this momentum interval.

In deriving this result the production of pi mesons in the absorber above the chamber was not considered. Pi mesons produced in the absorber and accompanied by secondary particles would be overlooked because of the single track criterion used in data selection. Those pi mesons produced locally but not accompanied by other particles would contribute to the observed intensity and have been included in the upper limit. This upper limit can be applied to each of the components contributing to the observed intensity and therefore is valid for the atmospheric intensity of singly occurring negative pi mesons in the momentum interval considered.

Although no negative particles were observed which could have been negative protons, the detection efficiency for such particles would probably be small because the energy released upon annihilation could produce secondaries penetrating the absorber.

B. Local Production of Mu Mesons

The preceding result can be used to set an upper limit on the local production of mu mesons. The fraction of pi mesons that decay in a distance x is given by $f=1-e^{-x/\gamma\beta\tau_0 c}$, where τ_0 is the proper mean lifetime, taken as 2.5×10^{-8} second. $\gamma\beta$ is the momentum of the pi meson in units of $m_\pi c$ and for this momentum interval has a mean value of about 8. The fraction of pi mesons in this momentum interval that decay in a distance of 1 meter is 0.016.

From the conservation of energy and momentum, it can be shown that pi mesons with momenta P_π decay to mu mesons with momenta P_μ in the interval $U_{\mu0}P_\pi-P_{\mu0}U_\pi<P_\mu<U_{\mu0}P_\pi+P_{\mu0}U_\pi$, where P_π and P_μ are in terms of $m_\pi c$ and $m_\mu c$. U_π is the energy of the pi meson in units of $m_\pi c^2$; $U_{\mu0}$ and $P_{\mu0}$ are the energy and momentum of a mu meson in the center-of-mass system of the parent pi meson. Only those pi mesons in the momentum interval 0.5–1.7 Bev/c can decay to mu mesons in the interval 0.4–1.0 Bev/c.

Applying the results of the previous section, it is found that the local production at sea level of mu mesons in the momentum interval 0.4–1.0 Bev/c is less than 8.8×10^{-5} particle/(cm^2 steradian hr meter).

C. Removal Path Length of Mu Mesons

In recent years many investigations have been made of the nuclear collisions of energetic mu mesons.[9–12] Most of these experiments have been conducted underground in order to reduce the number of events caused by nucleons and the soft component. Because of poor statistics and the diversity of techniques and event selection criteria only rough agreement is found among these experiments. The cross section for nuclear collisions (attributed to electromagnetic interaction) is found to be of the order of 10^{-29} cm^2/nucleon.

The results of the present experiment can be used to set a lower limit on the removal path length of mu mesons. From Rossi's absolute mu meson momentum spectrum and the effective admittance and operation time, it is found that 10 300 mu mesons in the momentum interval 0.4–1.6 Bev/c passed through the apparatus during the effective time of the experiment. Taking 1.2 as the positive-negative ratio, the number of

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[8] Camerini, Fowler, Lock, and Muirhead, Phil. Mag. **41**, 413 (1950).

[9] E. Amaldi and G. Fidecaro, Phys. Rev. **81**, 339 (1951).

[10] G. Cocconi and V. C. Tongiorgi, Phys. Rev. **84**, 29 (1951).

[11] E. P. George and P.T. Trent, Proc. Phys. Soc. (London) **A64**, 1134 (1951).

[12] Barrett, Bollinger, Cocconi, Eisenberg, and Greisen, Revs. Modern Phys. **24**, 133 (1952).

negative mu mesons in this momentum interval is 4700. Since none of these particles was absorbed in 147 g/cm^2 of lead the removal path length must be greater than 6.9×10^5 g/cm^2. The upper limit for the corresponding removal cross section is 2.4×10^{-30} cm^2/nucleon. The statistical significance placed on these limits is the same as that placed on the previously determined upper limit for the intensity of pi mesons.

This result is more direct than the results obtained by the earlier experiments in the sense that no corrections have to be made for instrumental errors or for nuclear events produced by particles other than mu mesons, e.g., pi mesons and protons in equilibrium with the mu meson flux. However, it should be pointed out that the cross section corresponding to a removal path length refers only to those collisions in which a large fraction of the incident energy is distributed among several heavily ionizing particles.

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Polarization of Nuclei in Metals

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A new method for polarizing nuclei, applicable only to metals, is proposed. It is shown that if the electron spin resonance of the conduction electrons is saturated, the nuclei will be polarized to the same degree they would be if their gyromagnetic ratio were that of the electron spin. This action results from the paramagnetic relaxation processes that occur by means of the hyperfine structure interaction between electron and nuclear spins. A shift of the electron spin resonance due to the same interaction will occur for large amounts of polarization and should provide a direct indication of the degree of polarization.

I. INTRODUCTION

A NUMBER of methods[1] have been proposed for producing polarization or alignment of nuclear spins. A new method, applicable to the nuclei of atoms of a metallic solid, is made possible by the existence[2] of the electronic spin resonance from electrons in the conduction band. The interaction between the electron spin magnetic moment $\boldsymbol{\beta}_e$ and the nuclear spin magnetic moment $\boldsymbol{\beta}_n$ that is responsible for the polarizing action is that of the hyperfine coupling of an S state,[3]

$$H=-(8\pi/3)\boldsymbol{\beta}_e\cdot\boldsymbol{\beta}_n\delta(\mathbf{r}). \tag{1}$$

Here, $\delta(\mathbf{r})$ is a delta function of the relative coordinate of the electron and nucleus under consideration. The polarization is produced when the metallic sample, in a constant magnetic field $\mathcal{H}_0$, is irradiated with a perpendicular microwave magnetic field, $2\mathcal{H}_1\cos\omega t$, of frequency such as to satisfy the electron spin resonance criterion,

$$\hbar\omega=2\beta_e\mathcal{H}_0. \tag{2}$$

The metal is then in a nonequilibrium condition, and we shall show that the dynamical processes which tend to restore the system to its equilibrium state induce nuclear transitions via Eq. (1) in predominantly one direction, with a resulting steady state nuclear polarization. This action cannot be attributed to a large Boltzmann factor for the energy separations of adjacent nuclear magnetic states, and the spin-temperature concepts, familiar in the literature of magnetic resonance, do not apply.

The magnitude of the polarizing effect depends upon the degree to which the electron resonance can be saturated, and hence upon the microwave power available, the paramagnetic relaxation time, and the resonance line width. A number of spin relaxation processes have been studied by the writer in a paper,[4] hereafter referred to as A, and the methods used for those calculations will be followed here. We shall consider first the problem of resonance absorption in the electron spin system.

II. ELECTRON RESONANCE ABSORPTION

If a metal is placed in a magnetic field $\mathcal{H}_0$, say in the z direction, the spin magnetic moments of the conduction electrons tend to line up parallel to the field. If N_+ and N_- are, respectively, the number of electrons per cc with spin up and down, the degree of bulk magnetization is proportional to the difference, $D=N_- -N_+$, and the equilibrium value of D is

$$D_0=3N\beta_e\mathcal{H}_0/2\epsilon_f. \tag{3}$$

If, in addition, the metal is subjected to a perpendicular, alternating magnetic field, $2\mathcal{H}_1\cos\omega t$, of frequency such

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[1] C. J. Gorter, Physica **14**, 504 (1948); M. E. Rose, Phys. Rev. **75**, 213 (1948); B. Bleaney, Proc. Phys. Soc. (London) **A64**, 315 (1951); R. V. Pound, Phys. Rev. **76**, 1410 (1949); A. Kastler, J. phys. et radium **11**, 255 (1950), Compt. rend. **233**, 1444 (1951).

[2] Griswold, Kip, and Kittel, Phys. Rev. **88**, 951 (1952).

[3] E. Fermi, Z. Physik **60**, 320 (1930).

[4] A. W. Overhauser, Phys. Rev. **89**, 689 (1953).

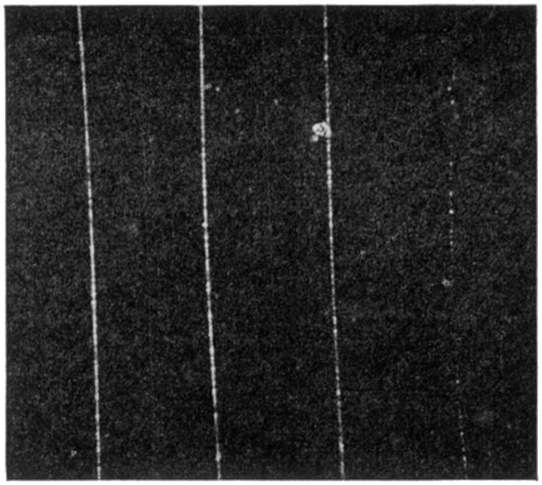

FIG. 3. Cloud-chamber tracks produced by (a) heavy particle showing negative curvature, (b) 0.37 Bev/*c* proton, (c) 0.54 Bev/*c* proton, (d) particle of minimum ionization.