THE SEARCH FOR A UNIT MAGNETIC POLE IN NUCLEAR EMULSIONS

by

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INTRODUCTION AND REVIEW OF LITERATURE

Theory

In 1931, Dirac (9), while investigating the admissable discontinuities in the phase of wave functions in an attempt to exnlain the fine-structure constant $\alpha = e^2/\hbar c = 1/137$, was led to a wave equation which could be interpreted only as the motion of an electron in the field of a single magnetic pole.

Dirac considered the formal representation of a wave function.[1] Suppose ψ_1 is an ordinary wave function with a definite phase everywhere. An equally ordinary wave function may be given as $\psi = \psi_1 e^{i\beta}$ where ψ differs from ψ_1 in the term $e^{i\beta}$. Dirac argued that ψ could be determined only to within some arbitrary phase. The actual value of the phase at a given point had no special significance, but the difference in phase between any two points could not be arbitrary. Then, the arbitrariness of the wave function resided in the factor $e^{i\beta}$. The preceding conditions required that β have no unique value for any given set of coordinates but that its derivatives, defined by $k_x = \partial\beta / \partial x$, $k_y = \partial\beta / \partial y$, $k_z = \partial\beta / \partial z$, must be specified. In general, $\partial k_x/\partial y \neq \partial k_y/\partial x$, etc.

By Stokes' Theorem, the change in phase around a closed

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[1] Dirac's paper is carried out in space and time coordinates but the time dependence is omitted here as it is not necessary in this simplified discussion.

path is
$$\oint \vec{K}\cdot d\vec{\lambda} = \int \vec{\nabla}\times\vec{K}\cdot d\vec{s}, \qquad (1)$$

where $\vec{K} = \vec{i}k_x + \vec{j}k_y + \vec{k}k_z$, since Ψ_1 does not enter into the phase change. In the above equation $d\vec{\lambda}$ is an element of the arc of the closed path, and $d\vec{s}$ is an element of the surface whose periphery is the closed path.

Following the quantum mechanical formalism, let us examine the result of operating on Ψ with the momentum operator. One obtains the relation

$$\vec{p}\Psi = e^{i\beta}(\vec{p} + \hbar\vec{K})\Psi_1 \qquad (2)$$

Thus if Ψ satisfies any wave equation involving the operator $\vec{p}$, Ψ_1 will satisfy any wave equation involving the operator $\vec{p} + \hbar\vec{K}$. Dirac assumed that Ψ satisfied the usual wave equation for a particle in free space. Then by analogy with the well known relation in classical mechanics

$$p_i = mu_i + (q/c)A_i$$

where p_i is the canonical momentum of a single particle in an electromagnetic field, mu_i is the canonical momentum normally expected in field free space, and A is some vector potential, Dirac found that Ψ_1 should satisfy the usual wave equation for a charged particle moving in an electromagnetic field.

If we make the identification, $\vec{A} = (\hbar c/q)\vec{K}$, we may identify the curl of the phase $\vec{A}$ with the magnetic field, for

$$\vec{\nabla}\times\vec{A} = \vec{H} = \vec{\nabla}\times(\hbar c/q)\vec{K},$$

from which we obtain

$$\vec{\nabla} \times \vec{K} = (q/\hbar c)\vec{H} \qquad (3)$$

Dirac further considered the fact that a phase can be determined only to an integral number of 2π's. Thus

$$\oint \vec{K}\cdot d\vec{\lambda} = \int \vec{\nabla}\times\vec{K}\cdot d\vec{S} = 2\pi n \quad (n = 0, \pm 1, \pm 2, \ldots).$$

Setting $q = e$, the electronic charge, and substituting for $\vec{\nabla}\times\vec{K}$ from Equation (3),

$$(e/\hbar c)\int \vec{H}\cdot d\vec{S} = 2\pi n. \qquad (4)$$

Let us shrink the path to an arbitrarily small one. Then the integral is to be taken over a nearly closed surface, and by Gauss' Theorem may be set equal to $4\pi g$, where g is the magnetic pole strength. Thus we find $eg = n\hbar c/2$ or taking $n = 1$,

$$eg = \hbar c/2. \qquad (5)$$

As seen here, a definite relation was found between the smallest electric charge e, and the smallest magnetic charge, g. The product eg is quantized. Since g occurs only in multiples of e, then g must also be quantized. Furthermore, the wave functions described here were found by Dirac to be quite proper for analysis by methods paralleling those of quantum mechanics. Quoting from Dirac (9), p. 71;

> . . . quantum mechanics does not really preclude the existence of isolated magnetic poles. On the contrary, the present formalism of quantum mechanics, when developed naturally without the imposition of arbitrary restrictions, leads inevitably to wave equations whose only physical interpretation is the motion of an

an electron in the field of a single pole. This new development requires no change whatever in the formalism when expressed in terms of abstract symbols denoting states and observables, but is merely a generalization of the possibilities of representation of these abstract symbols by wave functions and matrices. Under these circumstances one would be surprised if nature had made no use of it.

Dirac's theory is not the only work which has been done that indicates the possibility of the existence of isolated magnetic poles. As early as 1900, Thomson (?), while attempting to correlate mechanical and electromagnetic phenomena, considered the angular momentum of an electromagnetic field in vacuum composed of a pole-electron pair as shown in Fig. 1.

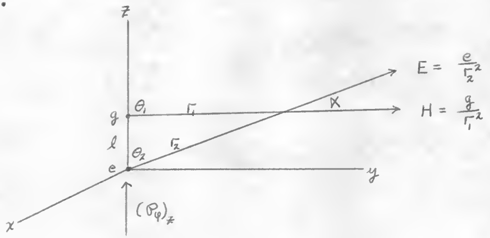

Fig. 1.

The linear electromagnetic momentum density $\vec{\rho}$ is given by

$$\vec{\rho} = (\vec{E}\times\vec{H})/4\pi c$$

The angular electromagnetic momentum density $\vec{\rho_\varphi}$ is then given by

$$\vec{\rho_\varphi} = \vec{r}_2 \times \vec{\rho},$$

with z component $(\rho_\varphi)_z = (eg/4\pi c)(r_2 \sin\theta_2 \sin\alpha / r_1^2 r_2^2)$.

After integrating over all space, Thomson's result for the total angular momentum in the z direction was

$$(\mathcal{P}_\varphi)_z = eg/c, \tag{6}$$

directed from a plus charge to a plus pole. According to quantum mechanical theory, any angular momentum must either be an integral or half-odd integral multiple of $\hbar$. Applying this requirement to Equation (6), Wilson (25) found in the case of the lowest half-odd integral quantization, $eg = \hbar c/2$, which is identical with Dirac's result of Equation (5).

Interaction with Matter

According to Dirac's theory, the unit magnetic pole strength is given by the relation $g = (\hbar c/2)e = (137/2)e$. Due to this large value, the magnetic poles are believed to interact strongly with matter through the electric fields which would be generated by a moving magnetic pole. In 1951, Bauer (1) and Cole (6) discussed this problem specifically for detection in cloud chambers and emulsion. Energy loss was found to be almost entirely due to inelastic collision and Bremsstrahlung as for any fast particles. Bauer suggested that since the value of g is so high, radiation reaction might be very important but is dependent upon the choice of mass M for the magnetic pole. The choice he made was

$$M = (g^2/e^2)m \approx 2.5m_p \tag{7}$$

where m is the mass of the electron and m_p is the mass of the proton. This choice of mass was made such that the ratio of inertial to radiation reaction forces is the same as for electrons. Cole, however, did not consider the loss of energy due to bremsstrahlung as being important as this effect takes place at extreme relativistic velocities. The loss due to bremsstrahlung is not considered in this paper for this reason.

For the loss of energy due to ionization, both Bauer and Cole utilized the semi-classical impact parameter method of Bohr (5, 6). The result for the total rate of energy loss due to inelastic collisions of a monopole of velocity v is given as

$$-dW/dx = (4\pi N e^2 g^2/mc^2)\log(mv^2\gamma c_1/J), \qquad (8)$$

where $\gamma = (1-v^2/c^2)^{-1/2}$, J is the mean binding energy of an electron of the absorber, N is the number of electrons per unit volume, and c_1 is a constant or order one. As compared with Bohr's results for charged particles, the only change that must be made between the rate of energy loss for heavy electrical particles and magnetic particles is a substitution of egv/c for Ze^2 in the relation for electrical particles. Equation (8) as further compared with that obtained for charged particles shows the startling difference that the ionization due to poles is independent of their velocity, except in the logarithmic term, whereas charged particles have a v^{-2} dependence in the dominant non-logarithmic term.

Just as a charged particle, a pole gives rise to two types of ionization. The primary ionization has already been discussed. The secondary ionization is the expulsion of other electrons of the absorber by those ejected in the primary collision. This type of loss cannot be treated by the theory of Bohr since the velocities of the expelled electrons are too small. Cole made the assumption that only the lightest bound electrons would be ejected as secondary electrons. Furthermore, if the binding energy were W, then a primary with an energy greater than sW and less than (s + 1)W will cause s additional ionizations where s is an integer. Based on these assumptions, Cole found the total number of ion-pairs produced per centimeter of path length to be

$$\Delta I/\Delta x = (2\pi N g^2 e^2/mc^2)(1/W_1) \sum_r \log(2m'^2 v^2/k^2 m W_r), \quad (9)$$

where W_1 is the ionization energy of the lightest bound electron, W_r is the ionization energy of the r^{th} electron, m' is the reduced mass of the pole and electron, v is the velocity of the pole, and k = 0.618. Figure 2, as reproduced from Cole, displays this relation for several poles and a corresponding relation for bare nuclei.

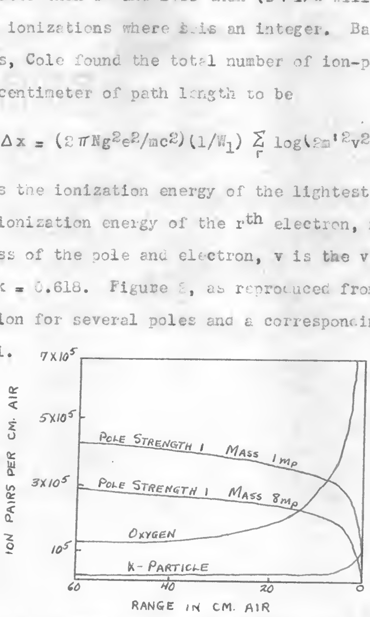

Fig. 2. Ionization vs. range for poles and nuclei.

From the results given by Bauer and Cole, the tracks of magnetic poles may be easily compared with those of heavy, charged particles. Fig. 2 shows that for equal distances except near the end of the track, the ionization per unit length is much greater for poles than for ordinary nuclei.

According to Cole, the distinguishing feature is the rapid decrease in ionization toward the end of the track for poles whereas it is just the opposite for nuclei. However, Cole neglected the capture and loss of charge by a nucleus at low velocity which reduces the ionization near the end of its range. It is a well known fact that the track of a heavy primary nucleus in cosmic radiation shows a characteristic taper or thin-down at the end of its range. This characteristic is predicted in the present thesis for magnetic poles also. Thus magnetic poles, which are also predicted to occur in cosmic radiation by Dirac, could be mistaken as heavy primary nuclei due to the similarity in tracks.

Heavy Nuclei

According to Bradt and Peters (5), there are, in general, three characteristic quantities of the tracks of heavy nuclei which may be measured. They are:

1. Range.
2. Track density or diameter of solid core of silver.
3. Delta-ray density.

From these three quantities, two different methods of charge determination are possible for highly sensitive emulsions.

These are:

1. The classical delta-ray method.
2. The thin-down-length method.

The Delta-ray Method. There are several methods of charge determination by means of delta-rays. The easiest and most frequently used for heavy, charged particles stopping in the emulsion is the range-delta-ray method. Bradt and Peters (5) first used this method with Mott's (18) relation for delta-ray densities given as

$$n_\delta = K(Z^2/\beta^2), \qquad (10)$$

where n_δ is the delta-ray density, Z is the atomic number of the incident nucleus, and β is a function of the range R and the atomic number Z. K is given by the relation

$$K = 2\pi N(e^2/mc^2)^2(mc^2/W_0 - mc^2/W_1),$$

where W_0 and W_1 are the minimum and maximum delta-ray energies to be counted respectively.

Two sets of criteria are normally used for delta-ray counting whereby the values of W_0 and W_1 may be obtained. One of these, called the grain criterion, requires that only those delta-rays having a number of grains between some chosen maximum and minimum number may be counted. The other, called the range criterion, requires that only those delta-rays having a projected horizontal range perpendicular to the track between some chosen maximum and minimum range may be counted. The values of W_0 and W_1 are obtained for the set grain and range limits respectively from the grain number-energy curves and range-energy curves for electrons as given by Voyvodic (26, 27).

Hoang (12) expressed the delta-ray density per one hundred microns from Mott's equation as the power law

$$n_\delta = AZ^{1.54}R^{-0.46}, \qquad (11)$$

where A is a constant depending upon the absorbing medium and the delta-ray criteria, and R is the residual range from the end of the track in grams per square centimeter.

Dainton, et al (8) also reported a power law variation except their law varies with $R^{-0.42}$. The Z^2/β^2 dependence as used by Bradt and Peters in Equation (10) results in a dependence on $Z^{1.42}R^{0.58}$. Of the three power laws given here, the most extensive work has been done recently with the relation of Hoang as given in Equation (11). His results were applied to the present problem.

<u>The Thin-down-length Method</u>. A heavy nucleus upon entering the atmosphere becomes stripped of its orbital electrons and remains so as long as its speed remains greater than that of the speed of its inner shell electrons. The thin-down process starts as the nucleus reaches the several velocities of its inner shell electrons as at this speed, the incident nucleus becomes capable of capturing electrons from the absorber. Hence, the track density and diameter diminishes as the effective charge of the nucleus approaches zero. The thin-down-length method was first derived and applied by Frier, et al (11). The derivation was made assuming the Bohr model of the atom for the calculation of the orbital velocities. Their result was

$$L = 0.5Z^2, \qquad (12)$$

where L is the thin-down length or the length of the track, in microns, from its end to the point at which the thin-down process begins, and Z is the atomic number of the nucleus.

Hoang and Morellet (13) found that, experimentally, the thin-down length L could be directly measured only to within about ten or twenty microns. They proposed that since the decrease in the square of the diameter at the end of the track is linear, a better choice of L might be made by the relation

$$t^2/R = t_o^2/L, \qquad (13)$$

where t is the diameter of the track at a range R near the end of the track and t_o is the diameter of the track immediately before it starts to thin-down. Experimental values of the thin-down-length L obtained by measurement of t, t_o, and R, and use of the above relationship as given in Equation (13), were found to be much greater than those predicted by the relation of Frier et al. as given in Equation (12). The work of Hoang and Morellet resulted in an empirical law of the form

$$L = aZ^{\alpha} , \qquad (14)$$

where a and α are constants with α being of order one in disagreement with Equation (12). However, when the energy corresponding to the thin-down-length for a given nucleus, as measured by Frier et al. and Hoang and Morellet, was compared with the energy at which thin-down was supposed to begin, it was found by Lonchamp (17) that neither the thin-down-length measured by Frier et al. nor Hoang and Morellet corresponded to the theoretical energy at which thin-down should occur. Lonchamp utilized the Thomas-Fermi model of the atom as an improvement over the Bohr model for the calculation of the theoretical energy. Perkins (18) had shown that there were two different types of thin-down. One was based on the decrease in the effective charge as originally assumed by Frier et al. (11) and was called the true thin-down. The other was based on the delta-ray density and was called the pseudo thin-down. Pseudo thin-down was based on the fact that delta-rays of feeble energies would often comprise part of the central core of the track and, as shown for several specific cases by Lonchamp (17), would at times form a veritable continuum or saturation of delta-rays as the core of the track. It is the point at which this saturation of delta-rays starts to decrease that the pseudo thin-down begins. Considering curves of the delta-ray density vs. velocity, as plotted from Mott's equation, Lonchamp (17) obtained the velocities at which pseudo thin-down began for several given particles at a set minimum delta-ray energy. From this, the energies of the particles were evaluated and found to be in excellent agreement with the energy values corresponding to the thin-down-lengths as calculated by Hoang and Morellet from Equation (13). It was this pseudo thin-down which was measured by Frier et al. and Hoang and Morellet when their respective equations were derived. Lonchamp's calculations showed the relation of Equation (14) as derived by Hoang and Morellet to be the correct one. The thin-down method of Hoang and Moliet was used in the present problem.

Purpose

Due to the similarity of the tracks of poles and heavy nuclei, it seemed a reasonable question that some of the common tracks which had been ascribed to heavy nuclei might, in reality, be tracks of magnetic poles. Two independent methods by which a measure of the supposed charge of a heavy nucleus causing a heavy track have been discussed. Any large discrepancy in the charge as measured by these two methods then indicates a loss of energy not expected for heavy nuclei. In such cases the tracks may be inspected for its agreement with the pole theories of Bauer and Cole. It was the purpose of this research to make such measurements as a means of searching out and identifying a unit magnetic pole.

To accomplish these aims it was necessary to prepare corrected ionization curves for heavy nuclei, displaying the thin-down at low velocities which had been neglected by Cole. It was also necessary to develop a simple delta-ray theory for magnetic poles in order that ionization discrepancies in the tracks of heavy particles might be used to characterize the properties of the pole.

PROCEDURE

All measurements pertaining to the two methods of charge determination were made with a Leitz Ortholux microscope under bright field illumination.

Five, 5X10 centimeter Ilford G-5 nuclear track pellicles arranged in a stack with no sandwiching, and exposed to cosmic radiation at an altitude of 100,000 feet in a balloon flight, were used in this experiment. The pellicles were developed at the University of Chicago, mounted on glass plates, and covered with a protective film of nail polish diluted 50-50 with nail polish remover to prevent stripping.

The desirous characteristic of this type of emulsion was its high sensitivity. This rendered the tracks of the heavily ionizing particles easily recognizable. Also, by virtue of this high sensitivity, diameter measurements for the thin-down-length method of charge determination were made quite readily as the track showed a solid core of developed silver. Unfortunately, it was found that the high sensitivity made delta-ray counting quite difficult in the case of the slower moving, highly charged particles.

The five plates were completely scanned for heavy tracks ending in the emulsion. The positions of all such tracks were recorded for later measurement. Measurements were carried out on only such tracks that showed a projected length of approximately 800 microns to insure reasonable accuracy in the limits of charge as found by the delta-ray method. Measurements were made as shown in Table 1.

Both the range criterion and the grain criterion were applied to delta-ray counting to determine which gave the most reproducible results. By far, the range criterion was the most suitable.

From the measurements outlined in Table 1, the following calculations were made as necessary:

Table 1. Measurements performed with appropriate objective and eyepieces as indicated.

Measurement	Objective Immersion	Eyepiece	Mag.
Scanning	10X air	10X	125
Projected horizontal range at which δ-ray count made.	20X air	Gaertner micrometer eyepiece 8X or Leitz micrometer eyepiece 12.5X	160 250
Projected horizontal range over which δ-ray count made. Approx. 100μ	97X oil	" " " " "	776 1112
All depth measurements.	97X oil	" " " " "	776 1112
δ-ray count. 3μ range criterion*	97X oil	Leitz micrometer eyepiece 12.5X	1112
All thin-down measurements	97X oil	Gaertner micrometer eyepiece 8X or Leitz micrometer eyepiece 12.5X	776 1112

*Only those delta-rays showing a projected horizontal length perpendicular to the track of 3μ or greater were accepted.

Range. $$R_o = \left[\ell^2 + S^2 z^2\right]^{\frac{1}{2}} \qquad (15)$$

where ℓ is the horizontal component of the track, z is the vertical component of the track length corrected for the index of refraction of the emulsion. (Thus $z = \eta \Delta y$, where Δy is the difference in depth of the ends of the range and $\eta = 1.50$ is the index of refraction as reported by Rotblat (20)). S is the shrinkage factor. (For Ilford G-5, S is reported as [illegible].7 by

Rotblat and Tai (21)).

Delta-ray density per one hundred microns.

$$n_\delta = \frac{\delta\text{-ray count}}{\text{Range } R_o \text{ over which count made}} \times 100 \qquad (16)$$

Values obtained by use of these two equations allowed a calculation of the charge Z which is for Ilford G-5 after Hoang (12)

$$n_\delta = 0.[illegible]5Z^{1.54}R^{-0.46} \qquad (17)$$

where $R = \rho R_o$ is the range in gm./cm.^{2} ($\rho = 3.8378$ gm./cm^3 as reported in correspondence from Ilford Inc.) A calculation for Z was made from Equation (17) at two separate points on the track. Each track was divided into five approximately equal parts giving four points at which a delta-ray count could be made. Counts were, in general, made at the first and last points in an attempt to obtain an upper and lower limit of the charge.

Thin-down length.

$$L = (t_o^2/t^2)R_o$$

A range R_o of about 10 to 20 microns was found to be the best for the measurement of the diameter t. After obtaining L, Z was computed after the empirical relation of Hoang and Morellet (12) as

$$L = 7.37Z^{1.07} \qquad (18)$$

Charges calculated by these two methods Equation (17) and Equation (18) were compared for agreement.

The preceding calculations were carried out on the basis of thin-down and delta-rays. However, the ionization curves of Cole given in Fig. 2, which display the difference between magnetic poles and nuclei, neglect the questions of thin-down and of delta-rays. Since nuclei do show a definite decrease in ionization at the very end of the range due to recombination or capture of electrons as previously discussed, a correction was made to these for α -particles and oxygen as shown in Plate I.

Range and ionization data for both alpha-particles and oxygen for ranges in excess of the range at which electron capture begins were taken directly from the curves of Cole. Points for the alpha particle curve over the range during which recombination takes place were easily obtained from the range-specific ionization curve for alpha-particles of Halloway and Livingston (14).

Similar range-ionization points for oxygen were not easily obtained. For these points, the velocity-range points for oxygen in Ilford C-2 emulsion given by Lonchamp (16) and the velocity-charge calculations of Fermi and Miranda as given graphically by Knipp and Teller (15) were used. The graph by Knipp and Teller gave the ratio i/Z of the effective charge i of an ion to its total charge Z as a function of $v_e/Z^{2/3}$, where v_e is the velocity of the electron for a given shell. It has been shown by Lonchamp (16) in his study of the energy loss of nuclei, that for oxygen, $v_e = 1.2v_i$, where v_i is the velocity of the ion. Using the values of v_i given by Lonchamp, the effective charges i at a range corresponding to given v_i's were found. The ionization due to the nucleus was then found by taking the product of the effective charge squared (i^2) times the ionization caused by a proton at the same velocity. Here it was necessary to utilize the curves of Blackett and Lees (2) for the range of protons as a function of their velocity and of Jentschke, as given by Evans (10), p. 655, for the ionization of protons as a function of their range. All these curves were given for air. Transformation to the G-5 emulsion was made by virtue of the Bragg-Kleeman rule given by Evans (10), p. 653. Transformation of the range points for oxygen given by Lonchamp (16) from the Ilford C-2 to the G-5 emulsion were not necessary as there is only a 1 per cent difference between corresponding ranges. The points at which pseudo and true thin-down start were noted on the resulting range-ionization curves.

EXPERIMENTAL RESULTS

Sixty-eight heavy particle tracks were found in the five pellicles. Of these, only 29 were suitable for measurement. The results of charge determination on these 29 tracks by both the delta-ray and thin-down method are tabulated in Table 2.

The charges as calculated by the two methods were found to be in good agreement except in the cases of tracks 14a24 and 14a26. For 14a24, reliable measurements could not be made as the track ending was beyond the working distance of the available oil immersion objective. Further checks were needed to decisively identify the track of 14a26 as either a nucleus or a pole. Before this check could be affected, it was found necessary to make an extension to the present energy loss theory. After this extension was made, 14a26 was decisively identified as that of a heavy nucleus as the passage through a maximum ionization, as described in the following section, was clearly observed.

AN EXTENSION OF THE THEORY

As previously stated, the curves for the ionization produced by nuclei as given by Cole in Fig. 2, are only valid for ranges in excess of that range at which recombination starts. Cole's curves have been corrected for α -particles and oxygen, as shown in Plate I. It is obvious that the ionization due to a nucleus does increase toward the end of the range but only to some maximum value and then drops rapidly to zero. It is this passage through a maximum ionization which definitely identifies the nuclear particle as distinguished from a magnetic pole.

As a nucleus shows both a true and pseudo thin-down, so should a magnetic pole. By following closely the discussion of Lonchamp (17) concerning pseudo thin-down of charged particles, the following theory for the pseudo thin-down of magnetic poles was developed.

The number of delta-rays per unit length of track having energies between W and $W + dW$ is given by Mott's equation for charged particles as

$$n_{\delta} = 2\pi NZ^2/\beta^2 \, (e^2/mc^2)^2 \left[mc^2/W_o - mc^2/W_1\right] .$$

Now taking $W_1 = 2mc^2\beta^2$, the maximum possible energy a delta-ray may acquire, the result may be expressed as

Table 2. Results of charge calculations.

Track no.	Charge limits by δ-rays	Charge by thin down	Track no.	Charge limits by δ-rays	Charge by thin down
14a1	9 13	10	17a5	15 14	16
14a6	8 13	12	17a8	17 17	15
14a11	4 5	4	17a10	11 14	15
14a24	12 15	8*	17a11	8 9	9
14a25	13 13	13	17a12	12 10	8
14a26	16 15	12	18a3	11 13	11
15a3	9 13	9	18a5	5 4	3
15a6	12 15	13	18a6	10 11	10
15a11	13 14	15	18a7	7 9	6
15a12	7 9	6	18a9	13 14	12
15a13	13 17	13	18a11	4 5	4
15a15	23 21	27	18a17	7 8	8
16a2	18 21	18	18a13	13 15	13
16a3	9 11	11	14a20	4 5	6
17a4	29 32	17			

*This determination was made with a 63X objective and is of doubtful value.

EXPLANATION OF PLATE I

Ion pairs versus range

for

several magnetic poles and nuclei

displaying corrections

to

Cole's theory

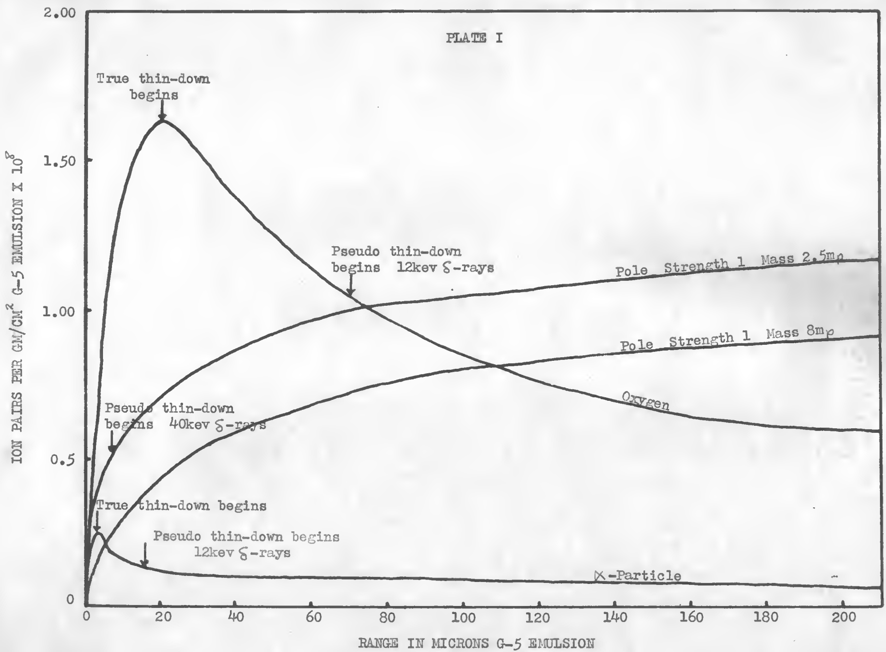
PLATE I
True thin-down begins
Pseudo thin-down begins 12kev δ-rays
Pole Strength 1 Mass 2.5m_p
Pole Strength 1 Mass 8m_p
Oxygen
Pseudo thin-down begins 40kev δ-rays
True thin-down begins
Pseudo thin-down begins 12kev δ-rays
α-Particle
ION PAIRS PER GM/CM² G-5 EMULSION X 10⁸
RANGE IN MICRONS G-5 EMULSION
2.00
1.50
1.00
0.5
0
0
20
40
60
80
100
120
140
160
180
200

$$n_\delta = 2\pi NZ^2/\beta^2 \, (e^2/mc^2)^2 \left[510/W_o - 1/(2\beta^2)\right] .$$

where W_o is expressed in kev. However, the production of delta-rays (23) is by the same process as in the primary energy loss derivations of Bauer and Cole. The same simple substitution of egv/c for Ze^2 may be made to find a result for poles. Then for a pole of unit strength, $g = (137/2)e$,

$$n_\delta = 2\pi N(e^2/mc^2)^2 \;\; (137/2)^2 \left[510/W_o - 1/(2\beta^2)\right] . \quad (19)$$

The constant term $N = N_o\rho Z'/A$; where N_o is Avagadro's number, ρ is the density of the absorber and Z' and A are the atomic number and atomic weight of the absorber respectively; may be evaluated for Ilford G-5 utilizing the values of Z'/A as reported by Voyvodic (26) and ρ as given previously. Finally, for Ilford G-5, $n_\delta = 24.07 \left[510/W_o - 1/(2\beta^2)\right]$. (20)

This equation is displayed by the curve of Plate II for W_o equals 12 and 15 kev.

Pseudo thin-down-length has been defined as that length from the end of a track at which the delta-ray density starts to decrease from the saturation for a particular delta-ray energy. Taking into account the mean diameter of the grains of the G-5 emulsion, the computed value of this saturation was 275 delta-rays per 100μ. This limit is indicated on Plate II. The small arrows specify the points for two common delta-ray energies at which a definite thin-down should be observed in the track of a monopole. For comparison, the delta-ray density curve of oxygen was also shown.

EXPLANATION OF PLATE II

Delta-ray density versus velocity

for

magnetic poles

and

oxygen

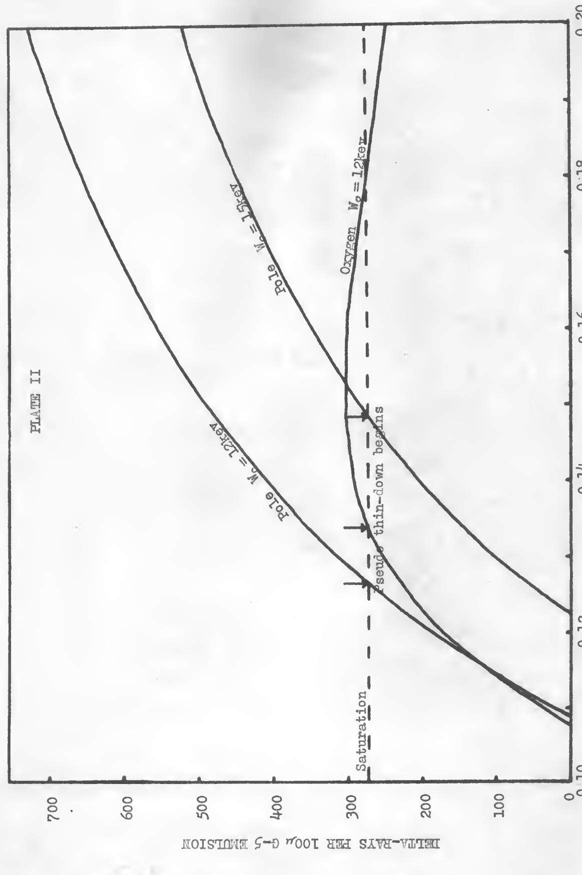
PLATE II
Pole $W_o = 12$kev
Pole $W_o = 15$kev
Oxygen $W_o = 12$kev
Saturation
Pseudo thin-down begins
DELTA-RAYS PER 100μ G-5 EMULSION
β
0
100
200
300
400
500
600
700
0.10
0.12
0.14
0.16
0.18
0.20

However, further calculations showed that for common delta-ray energies of from 10 to 20 kev., the pseudo thin-down-length for poles with mass of the order of $2.5m_p$ was less than one micron. If a reasonable pseudo thin-down-length is to be measured, delta-ray energies of the order of 30 to 40 kev. must be observed.

From Plate I, one can infer that the track of a monopole will look distinctly different from the track of a charged particle. The track of the pole is wedge shaped from the end of its range until near relativistic velocities. The track increases in blackness to a maximum and then diminishes to zero ionization. The point at which pseudo thin-down begins for a pole of mass $2.5m_p$, considering a delta-ray energy of 40 kev. is shown for comparison with nuclei in Plate I.

If the track of a monopole is identified, then Plate II or a similar curve for the delta-ray energy chosen may be used to set up one relation between pole strength and velocity for the point at which thin-down begins for delta-rays of a given energy. Having the velocity, the mass may be determined from the range. The assigned pole strength is implicit in the determination of mass. As in the case of mesons, the charge must be assumed.

The curves of Plate II also show the validity of the method used in this search for a magnetic pole in the emulsion, especially for short tracks. As may be seen, at a given point, the delta-ray density for a magnetic pole and a nucleus may be identical for the same value of W_0. However, it is highly improbable that agreement would be obtained if comparison were made with the calculations of the charge by the thin-down method. For long tracks, the delta-ray method would suffice as the delta-ray density for a nucleus decreases with increasing range whereas the opposite is true for a magnetic pole. However, the decisive characteristic still is the increase to a maximum ionization just before thin-down for a charged particle as compared to the absence of this increase in ionization for a magnetic pole.

CONCLUSIONS

Of the 29 tracks upon which measurements were made, none were found to disagree with the behavior expected for primary nuclei in the cosmic radiation.

The delta-ray method of charge determination and the thin-down-length method of charge determination, when compared, furnish a reliable method of differentiation between poles and charged particles, especially for short tracks. The delta-ray method is sufficient for long tracks if measurements are made at widely separated points.

<u>The decisive method</u> whereby a pole may be identified as compared to a charged nucleus is by virtue of the absence of a rise to a maximum ionization just before thin-down takes place. Highly sensitive emulsions such as the Ilford G-5 emulsion used in this experiment are recommended as this passage through a maximum ionization was clearly visible in all of the tracks

except those which had a high angle of dip. This information may be used by scanners surveying cosmic ray plates to identify tracks suitable for further study.

The delta-ray density for a magnetic pole is proposed to be $n_\delta = 2\pi N(e^2/mc^2)^2 (137/2)^2 [mc^2/W_o - mc^2/W_1]$, for a unit Dirac monopole.

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THE SEARCH FOR A UNIT MAGNETIC POLE
IN NUCLEAR EMULSIONS

by

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It has been suggested that tracks due to free magnetic poles might be mistaken as those of bare nuclei common in the primary cosmic radiation. It was shown theoretically that at the end of the range, a magnetic pole should show a rapid decrease in ionization where it is just the opposite for a nucleus if charge capture by the nucleus is neglected. Charge capture cannot be neglected as it is by this process that a nucleus shows well known tapering or decrease in ionization at the end of its range.

Due to the similarity in tracks, it was the purpose of this research to make such measurements on the tracks of heavy particles that they could be identified as either nuclei or magnetic poles. To achieve this, it was necessary to prepare corrected ionization curves for heavy nuclei, displaying the decrease in ionization at the end of the range due to charge capture which has previously been neglected. Such corrections were made for alpha-particles and oxygen from existing data. It was further necessary to develop a simple delta-ray theory for magnetic poles in order that ionization discrepancies in the tracks of heavy particles might be used to characterize the properties of a pole. The result for the delta-ray density per 100μ for a unit Dirac monopole was

$$n_{\delta} = 2\pi N(e^2/mc^2)^2 \ (137/2)^2 \left[mc^2/W_o - mc^2/W_1\right] .$$

Measurements were made on 89 heavy tracks ending in the Ilford G-5 emulsion such that two independent charge determinations could be carried out by the delta-ray and thin-down length methods. Comparison showed one track which differed widely enough in the charge calculations to be further checked. The corrected ionization theory decisively proved the track to be that of a nucleus.

Introduction of the correction to the ionization due to nuclei and the simple delta-ray theory for poles resulted in a decisive method whereby the tracks of heavy nuclei and magnetic poles may be more easily differentiated. This method is by virtue of the fact that a nucleus passes through a maximum ionization just before the rapid decrease in ionization whereas a magnetic pole does not. It is inferred that the track of a monopole is actually wedge shaped from the end of its range until near relativistic velocities. This information may be used by scanners surveying cosmic ray plates to identify tracks suitable for further study.