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Determination of Mass of Slow Charged Particles in Photographic Plates

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The accuracy of various methods of determination of the masses of slow charged particles stopped in photographic plates is examined. It is shown that for reliable identification of an individual particle it is not sufficient to determine its mass by only one method. Distributions in mass of slow charged particles ($E < 30$ Mev) produced by ~ 460 Mev protons are presented, the masses being determined by different methods. The mass and charge sign distributions have been obtained by the magnetic deflection-range method for slow particles ($E < 50$ Mev) created by cosmic rays at an altitude of ~ 9.5 km.

INTRODUCTION

THE DISCOVERY OF NEW unstable particles – heavy mesons and hyperons – in cosmic rays has made exceedingly important the determination of mass, charge, and fractional yield of the various particles. In connection with this, work on a systematic study of charged particles assumes great importance. Many investigations,[1-15] carried out with emulsions, Wilson cloud chambers, counters, or stripped emulsions have been devoted to a systematic study of the mass as of the stopped charged particles. The basic defect of these investigations was that particle identification was made on the basis of a single method of mass measurement, as a result of which experimental errors could lead to incorrect mass determinations in individual cases. An example of this is seen in Ref. 3 where a wide range of particle masses was obtained using emulsions.

With the aim of clarifying the dependability of various methods of mass determination of slow charged particles stopped in emulsions, and to find the conditions under which certain particle indentification may be made, we performed an experiment in which a C, emulsion was bombarded by 460 Mev protons, and studied the secondary particles which stopped in the emulsion.

The masses of slow charged particles were determined by three methods: a) using magnetic deflection and range (magnetic analysis, ρ and r); b) using grain counts and range (N, r); c) using scattering and range (α, r).

In examining the nature of slow charged particles created by cosmic rays at 9.5 km altitude, the basic method chosen to determine mass was magnetic analysis.[4] The principal advantage of this method, besides the higher accuracy in mass determination, is that the sign of the charge can be obtained independent of what happens at the end of the range. The use of emulsions sensitive to relativistic particles allowed observation of particles of arbitrary velocity. Whenever an "intermediate" mass ($m_\pi < m < m_p$) was found by magnetic deflection and range, the mass was determined in addition by two other methods – ionization and range, and scattering and range. This procedure turned out to be exceedingly important for reliable identification of the particle.

EXPERIMENTAL SETUP

Ilford C_2 plates with an emulsion thickness of 100 μ and a size 5 × 8 cm were bombarded by protons of ~ 460 Mev (first series of experiments). NIKFI-R plates with an emulsion thickness of 200 μ and a size 7.8 × 7.8 cm were bombarded by cosmic rays at altitude 9.5 km (second series of experiments). Photographic plates were bombarded in a magnetic field; control plates were bombarded without such field.

The setup used was similar to that described by Franzinetti.[4] Two plates were placed into a special container, emulsions facing each other at a distance of 3 mm, and located between the poles of an electromagnet in such a way that the field was perpendicular to the emulsion plane. During cosmic ray bombardment an 8 cm lead filter was placed above the plates and served as a meson generator. The temperature of the container during the experiment was held at 15 ± 5° C. The magnet provided a field of 27,000 Oersted. The maximum error in magnetic field measurement was 1%. Variations of the magnetic field during bombardment never exceeded

± 0.4%. The magnetic field was very homogeneous right out to the pole tips. If edge effects occurred, they were at less than 5 mm from the pole tips.

There were two aims in developing the emulsions: minimum distortion, and uniform development in depth. The C_2 plates were developed by the two bath method, the NIKFI-R plates by the temperature method. Before drying, the type R plates were soaked in 5% glycerine solution for two hours at 18° C. Drying took place in a closed cabinet at 18° C. These methods resulted in plates developed almost uniformly in depth, with only small distortions (noticeable distortions were observed less than 5 mm from the edges of the C_2 plates, and less than 10 mm from the edges of the R plates).

Scanning and track following was done with an MBI-2 microscope with magnification $10 \times 10 \times 1.5 = 150$. Notice was taken of all stopped particle tracks coming from the surface of the emulsion. The basic difficulty in microscopic examination of plates is finding the continuation of stopped particle tracks. In contrast to previous work[4-5] our search for the continuation of stopped particle tracks was made with a rotating table, which reduces the time by a factor of 3 – 4.

ERRORS IN THE DETERMINATION OF MASS BY VARIOUS METHODS

a) *Mass Determination by Magnetic Analysis and Range*

An analysis of the errors of this method is given in Ref. 4. The main sources of errors in this mass determination is the measurement of radius of curvature; the error in measurement of magnetic field strength is 1%, and the error in particle-range measurement is usually 2 – 3% and always less than 5%.

The radius of curvature can be expressed as:

$$\rho = R/2 \sin (\beta/2),$$

where R is the projection of the particle path in the space between the emulsions onto the emulsion plane, and β is the angle between the projections of tangents to the particle trajectory at the points of entry and exit from the emulsion onto a plane perpendicular to the magnetic field (or onto the emulsion plane). The error in the radius of curvature is determined by the error in measurement of β since $\Delta R/R \approx 0.01$. The error in β depends on distortion of the emulsions, scattering in the air space between emulsions, and scattering in the surface layers of the emulsion.

Under our experimental conditions the error in β due to the emulsion distortion gives an uncertainty of 0.1 – 0.3°. Since the C_2 plates were bombarded at normal atmospheric pressure, while the R plates were bombarded at 300 g/cm², the mass error caused by air scattering between the emulsions was 2 – 5% in the former case and 1 – 3% in the latter case. Most of the error in β is caused by multiple scattering of the particles in the surface layers of the emulsion. To reduce this error the direction of particle motion in the emulsion was measured with optimum cell length,[16] which for a range of 100 – 1500 μ is 8 – 25 μ and 14 – 40 μ for mesons and protons respectively. If one considers that the error in β is caused only by multiple scattering in the surface layers of the emulsion, then a theoretical value for the error can be obtained from the expression $\Delta\beta = \sqrt{2}\alpha_t$ where α_t is the theoretical value for the average multiple scattering angle between chords on a path length $t\mu$. To investigate the correspondence of this theoretical value and experiment we examined tracks in plates that had been bombarded without a magnetic field. In one pair of such plates there were 17 stopping tracks, in another pair there were 28 of which 6 were mesons. For each particle we obtained the ratio $\Delta\beta_{\mathrm{exp}}/\Delta\beta_{\mathrm{calc}}$, and then determined the average value of this ratio. It turned out that $\overline{\Delta\beta_{\mathrm{exp}}/\Delta\beta_{\mathrm{calc}}} = 0.6$ for the first case (17 tracks) and $\overline{\Delta\beta_{\mathrm{exp}}/\Delta\beta_{\mathrm{calc}}} = 0.7$ for the second case (28 tracks).* The error in β is thus determined by the expression

$$\Delta\beta = \sqrt{2} \times 0.7\, a_t \approx a_t.$$

It is important to note that all errors in β are contained in $\Delta\beta_{\mathrm{exp}}$.

The mean-square values of mass errors for protons, deuterons and π-mesons as a function of range under the conditions of the present experiment are given in Table 1. The value of $\Delta m/m$ for $r = 10\ 000\ \mu$ was calculated under the assumption that $\overline{R} = 4$ cm; for all other ranges the experimental value of $\overline{R}$ was used. It is seen from Table 1 that in mass determination by the ρ, r method the error decreases with increasing range, since in general

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*The ratio $\overline{\Delta\beta_{\mathrm{exp}}/\Delta\beta_{\mathrm{calc}}}$ deviates from unity because the track direction is measured at the center of gravity of the grain, while in the calculated $\Delta\beta$ the multiple scattering angle is taken between chords.

the longer range corresponds to a larger value of R.

b) *Mass Determination by Ionization and Range*

The method is discussed in detail in Ref. 17.

For the C_2 plates mass was determined by examining the integral curves of the grain number $N(r)$ as a function of range. A calibrating curve was constructed from 13 proton tracks whose mass identification had been reliably made by the magnetic analysis-range method. The grains in a track were counted twice. Repeated measurement of the number of grains in a particular track by the same observer (a proton track of range 500 μ has about 550 grains) gave results which differed by 3 – 5%. Results of different observers differed by 5%. If a measurement was repeated after a long time interval, the spread in the number of grains reached 10%. Thus large subjective errors enter into the grain count. The total error in mass determination by grain count and range under the conditions of our experiments (range of examined particles 300 $\mu < r < 3000\ \mu$) is 35 – 25%.

TABLE I.

Range r, μ		100—500		500—1000		1000—2000	>2000	10000
$\bar{R}$, cm		0.5	1.0	1.0	1.4	1.8	> 2	4
$\frac{\Delta m}{m}\%$	p	—	~ 30	—	~ 22	~ 18	<16	~ 5
	d	—	~ 13	—	~ 13	~ 12	<12	~ 8
	π	~ 30	—	~ 15	—	~ 10	< 7	~ 4

In the type R plates ionization was measured either by the length density of gaps along the track or by a photometric device. The gap density was measured with a special apparatus constructed by A. I. Galaktionov, and the photometric measurements were made on a narrow slit instrument constructed along the ideas of A. E. Chudakov.*

In making measurements of the gap density for tracks inclined more than 20° in the undeveloped emulsion, a correction for the angle of the track was included.[18] In the photometric measurements corrections were applied for depth of the track in emulsion. The photometric method is an objective way of determining the relative ionization, although it can be used only for tracks inclined less than 5° in the emulsion.

Under the conditions of our experiments, fading and uneven development in depth of the emulsion had practically no effect. To eliminate variations due to emulsion sensitivity or development procedure, the calibrating track was always taken in the same plate as the unknown track. In selecting tracks for calibration it must be borne in mind, as shown by our data, that one-third of all heavy slow charged particles which stop in the emulsion are deuterons. (This holds also for particles coming from a single ray star produced in the emulsion.)

It is essential to note that in a steep track measurement of the ionization can differ considerably from the true value. For example if the track angle is 35° in the undeveloped emulsion then for a gap density measurement of 0.1 the actual value is 0.23, *i.e.*, almost 2.5 times larger. By using electron-sensitive emulsions, the (I, r) method allows under the best circumstances a proton mass determination of 6% for a 10 000 μ range, and for a heavy meson with $m = 1000\ m_e$ a mass determination of 10 – 7% for the range interval 5 – 10 mm.[17]

The method has poor sensitivity for separating the heavy stopped particles, since protons, deuterons and tritons have almost the same track density for ranges of a few millimeters.

c) *Mass Determination by Scattering and Range*

The multiple scattering along the track of a stopped particle was measured by the coordinate method. In the first series of measurements we used the constant cell method,[19] and in the second series the variable cell method.[2]

The error in mass determination of stopped charged particles is determined by the statistical error in the multiple scattering angle, and ranges from 50 to 20% under the circumstances of this experiment (300 $\mu < r < 3000\ \mu$). Independent mass de-

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*Articles in collaboration with these authors are in press (Prib. Tekhn. Experim.).

termination for μ-mesons using the constant-cell method gives an average mass value

$$\overline{m_\mu} = (211 \pm 26)\, m_e$$

(10 μ-mesons from a $\pi - \mu$ decay).

In determining second differences by the variable cell method, we used for steep tracks third differences,[21] which allowed elimination of effects of emulsion distortion. The accuracy of various methods of mass determination for stopped charged particles as a function of particle range in electron sensitive emulsion is given in Table 2.

TABLE II. Relative error (in %) in mass determination of protons and π-mesons of various ranges in the emulsion.

Range r, μ	Protons			π-mesons		
	ρ, r	α, r	I, r*	ρ, r	α, r	I, r
100		—			—	
300	~30	50		30	50	
500		45			40	~20
1000	22	35		15	30	
2000	18	30		10	25	~15
3000	<16	25		< 7	20	~10
5000		22	~15		17	~ 7
10000	~5	17	~ 6	~ 4	13	~ 5

*Mass error depends significantly on emulsion sensitivity.

From a comparison of the various methods of mass determination for stopping charged particles it follows that the best accuracy for ranges less than 10 000 μ is given by the magnetic analysis – range method. Although the (I, r) method errors are comparable with the (ρ, r) method errors for ranges ~ 10 000 μ, the errors listed in the table for the I, r method were obtained with tracks inclined less than 10°, and the calibration was carried out with several tens of tracks. Under ordinary circumstances the error of the (I, r) method will be much greater, since it is necessary to examine much steeper tracks which pass through a series of emulsion layers. In such a case additional errors come about because of inclination, possible variation of sensitivity in different emulsion layers, variation in development, and errors in the calibration of each layer.

The magnetic analysis – range method is also very effective for the separation of heavy particles – protons, deuterons, and tritons. The mass determination error for deuterons and tritons in the (ρ, r) method depends only weakly on range, and is about 10 – 15%. The errors for the (ρ, r) method indicated in Table 2 can be reduced by increasing the space between emulsions, or by increasing the magnetic field strength. The range interval can be increased by using thicker emulsions. The time efficiency of the apparatus can be improved by increasing the dimensions of the polepieces.

EXPERIMENTAL RESULTS

First Series of Experiments

The mass of 48 particles was determined by the magnetic analysis – range method. Particles with ranges greater than 100 μ and with a projection of the path between emulsions onto the emulsion plane of more than 8 mm were examined. The mass of most of these particles was also determined by the grain count – range and scattering – range methods.

The distribution of particles by mass obtained by the various methods is shown in Fig. 1. As can be seen from Fig. 1, the mass determination error of slow charged particles ($E < 20$ Mev) using the magnetic analysis – range method is much smaller than with the other methods. This data is for particles with $m > m_p$. In Ref. 4 the analogous result is obtained for light mesons. The average values for proton and deuteron mass obtained by the (ρ, r) method are respectively $\overline{m}_p = (1850 \pm 70)\, m_e$ (27 particles) and $\overline{m}_d = (3630 \pm 130)\, m_e$ (14 particles).

The (N, r) and (α, r) methods were used to deter-

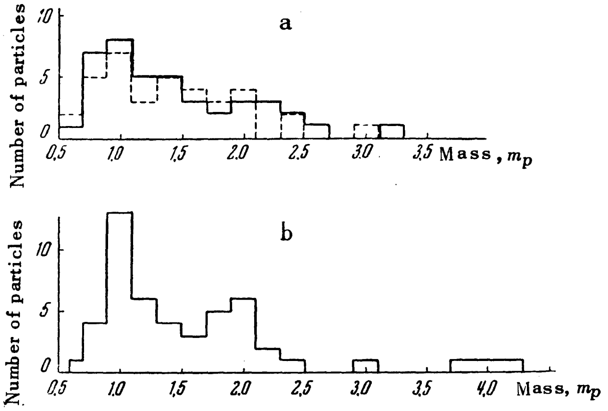

FIG. 1. Mass distribution of particles (first series of experiments): *a* – solid line – grain count and range; dashed line – scattering and range; *b* – magnetic deflection and range

mine the masses of 191 particles (only particles of range > 300 μ were examined). Analysis of the mass determination results by the three methods shows that the determination by magnetic deflection – range allows a positive identification of particle type in approximately 95% of the cases. If however the mass for a slow charged particle ($r < 2000$ μ) is determined by one of the methods [(N, r) or (α, r)], then the number of false identifications is 10 – 15%. Table 3 gives results for some of the cases where the mass determination by one method did not agree with that made by the other two methods.

It follows from the mass values and errors indicated in Table 3 that the probability that the particle is a deuteron is less than 1% for track 63, and less than 0.2% for track 158. A number of single scatterings were observed along track 209 which most likely raised the measured scatterings angle, and therefore lowered the mass. It therefore follows that positive identification of a particle requires mass measurement by more than one method. If two methods give the same result, the identification of the particle is almost positive. This applies to cases where the particle is brought to a stop by ionization loss. The results of the first series of experiments are given in Table 4, where the number and distribution of particle types found is shown.

TABLE III.

Track No.	Mass value (in m_p) obtained by the various methods			Range μ	Identification
	ρ, r	N, r	α, r		
63	1.12±0.33	1.85±0.45	0.81±0.36	560	*p*
158	1.82±0.50	1.00±0.25	0.91±0.40	553	*p*
209	1.90±0.60	1.79±0.50	0.370±0.20	460	*d*

TABLE IV.

Particle type	Mass determination method			
	ρ, r; α, r; N, r		α, r and N, r for r > 300 μ	
	No. of particles*	% of all particles	No. of particles*	% of all particles
p	27 (5)	56.3	118±9 (37)	61.5
d	14 (5)	29.2	58±9 (16)	30.5
$m > m_d$	6 (2)	12.5	8±1 (2)	4.3
μ and π	1	2	7	3.7

*The quantities in parentheses indicate the number of particles coming from stars in the emulsion.

Second Series of Experiments

The masses of 276 particles were determined by magnetic deflection and range. A histogram of the mass distribution is given in Fig. 2. The angular distribution of particles is given in Fig. 3. Let us examine each particle group in the histograms.

1. *Heavy Particles.* All positively charged parti-

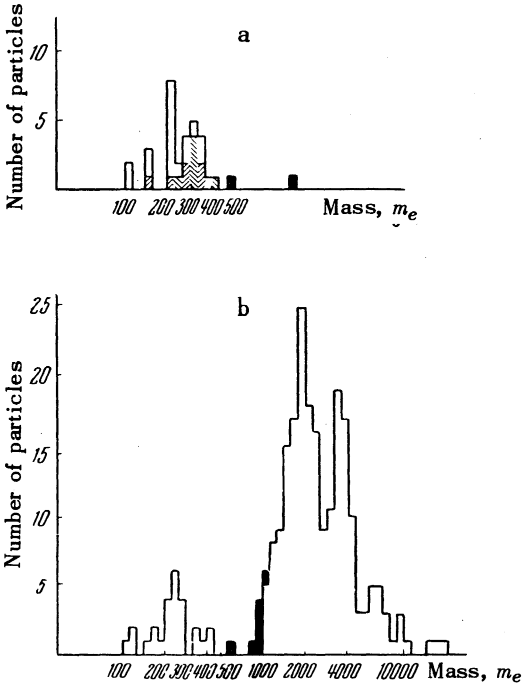

FIG. 2. Mass distribution of particles (second series of experiments): *a* — negative particles, *b* — positive particles. The crosshatched sections are negative π-mesons, the blackened section — particles with mass $m_\pi < m < m_p$.

cles with mass in the interval 11 — 2800 m_e were considered protons, particles with 2800 — 4600 m_e were considered deuterons, and particles with mass 4600 — 6600 m_e were considered tritons. Particles with mass > 6600 m_e were considered heavier than tritons.* Average mass values obtained for protons, deuterons and tritons are respectively:
$\bar{m}_p = (1860 \pm 40)\, m_e$ from 120 cases,
$\bar{m}_d = (3610 \pm 50)\, m_e$ from 51 cases, and
$\bar{m}_t = (5700 \pm 180)\, m_e$ from 11 cases. The angular distribution of heavy particles is not isotropic. Examining the angular and energy distributions of the heavy particles it follows that most are knocked out of a nucleus by an incident nucleon, and do not come from an evaporation process.

2. *Light Particles.* Light particles are identified by taking account of the decay products, and can all be classified $\mu^\pm$ and $\pi^\pm$ mesons. The average mass values obtained are: $\bar{m}_\pi = (294 \pm 13)\, m_e$ (25 cases: 7 π^+ and 18 π^-) and $\bar{m}_\mu = (207 \pm 12)\, m_e$ (32 cases: 19 μ^+ and 13 μ^-).

3. *Particles of "Intermediate" Mass.* Seven positive and two negative particles were found by the magnetic deflection — range method to have a mass larger than the π-meson and smaller than the proton. All these cases were studied in great detail. The track characteristics with indicated decay modes and masses obtained by various methods are shown in Table 5.

We include some additional data for this table. By "track pair" is meant tracks of the examined particle in two plates.

Pair 150. The ionization measured on the primary particle track contradicts the mass value obtained by the (ρ, r) and (α, r) methods. Since the question of existence of particles with mass 500 — 600 m_e is exceedingly important this case was studied further. Let us assume that the case represents the decay of a π-meson in flight. The angle between the π and μ mesons is 34 ± 5°. Grain density of the secondary particle track is (60 ± 5)/100 μ. Such a density in a μ-meson track corresponds to a range of 2500 ± 500 μ. In order for an in-flight decay to yield a μ-meson of this energy, the π-meson must decay some 200 — 300 μ from the end of its range.

If one assumes that the π-meson has decayed in flight some 300 μ before the end of its range, then: 1) the ionization of the primary particle agrees with the assumption of a π-meson: 2) primary particle mass determined by the (α, r) method is $(175 \pm 90)\, m_e$; 3) primary particle mass determined by the (ρ, r) method is $(470 \pm 190)\, m_e$. Owing to the above, the case has been identified as decay of a π meson in flight. Under the conditions of the experiment, the probability of an in-flight π decay $\sim$ 300 μ before the end of range is about 1.5%.

It is essential to note that in the case of a decay or interaction of a particle in flight, the (α, r) method gives a mass value that is too high. This is also true for the (ρ, r) method. In such a case the additional method of mass determination must make use of the ionization.

Pair 23. The particle is identified as a proton. The probability of a proton having a measured mass 840 m_e [obtained by the (ρ, r) method] under the conditions of the experiment [$m_p = (1860 \pm 40)\, m_e$, 120 cases], is 0.8%, *i.e.*, one case in 120, as actually observed.

Pair 30. The closeness of the particle mass to that of a proton, together with its negative charge, forced us to give this track pair very careful study. Measurement of scattering and ionization along the track showed that the direction of particle motion

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*The boundaries of these intervals were chosen in such a manner that experimental error made it equally probable for a particle to be assigned to one group or the other near the boundary.

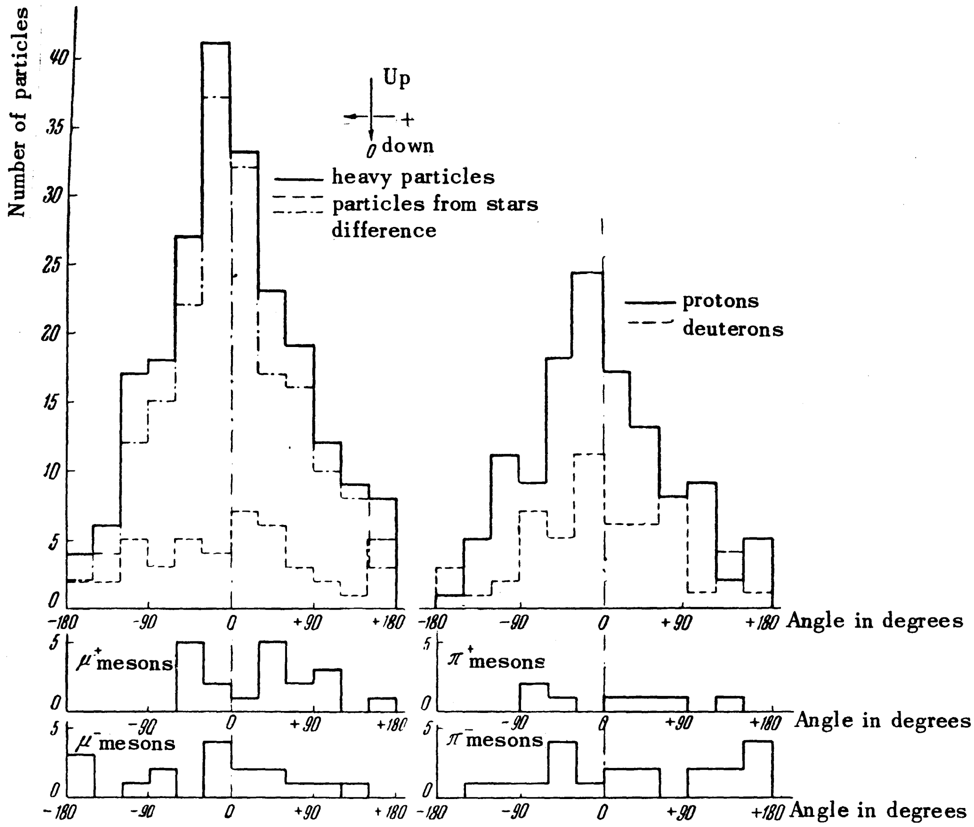

FIG. 3. Angular distribution of charged particles created by cosmic rays at an altitude of 9.5 km.

was opposite to that which had been assumed in the mass determination. In that case the particle charge will be positive.

Thus out of nine cases examined, only three particles turn out to be heavy mesons, all with positive charge and initial mass 900 – $1000m_e$. It is possible to indicate several reasons for incorrect mass determination by the magnetic deflection – range method: scattering in the surface layers of the emulsion and in the space between emulsions, decay or interaction of the particle in flight near the end of its range, incorrect determination of particle motion direction (which is important for particles with $m \gg m_p$), and false coincidence (each member of a pair belongs to different particles).

Table 6 shows the number and fraction of each type of particle with allowance for definite identification in the "intermediate" mass region.

DISCUSSION OF THE RESULTS

1. *On the Certainty of Individual Particle Identification*

It follows from the experimental results of the present work that reliable identification of an individual particle can be made only if its mass is determined by several methods. This is particularly important in the identification of rare events (heavy mesons, or "new" particles). An analogous conclusion can be drawn from experiments performed with Wilson cloud chambers or counters. In Ref. 13, where a mass spectrometer was used, the sorting of particles by momentum and range produced three particles with mass in the interval 450 – $650\,m_e$. However, additional mass determinations of these particles made by ionization and momentum showed that these particles were π-mesons which interacted in flight. The use of the additional ionization – range measurement together with the basic mass spectrometer method allowed a significantly higher certainty in the identification of heavy mesons, as well as a reduction in the experimental uncertainty for the fraction of such mesons.[15] It should also be noted that in many cases the estimated accuracy of mass determination should be reevaluated to disclose erroneous results or incorrect conclusions. We shall give some examples.

In Ref. 3, where photo emulsions were used, the number of charged particles with mass 600 – $1000m_e$

TABLE V.

Pair No.	No. or pair and plate symbol		r, μ	Total path length in both tracks	β°	R, cm	ρ, cm	Mass value (in m_e) ρ, r	α, r	I, r	$\overline{m}$	Decay products	Minimum grains per 100 μ	Identification
1	114* III, IV	+	217	525	5°	0.650	7.45	944±300	770±300	900±300	880±210	—	17	K-meson
2	145 III, IV	+	234	750	4°30′	0.610	7.76	1018±300 or 1018±780, if $m = m_\pi$	220±85	$m < m_\pi$		Relativistic particle	17	μ-meson
3	181 XI, XII	+	775	1520	6°11′	1.225	11.30	946+215	964±275	890±300	930+190	Relativistic particle	21	K-meson
4	150 XIX, XX	+	458	742	4°53′	0.480	5.64	580±145 or 580±215, if $m = m_\pi$	590±270	$m < m_\pi$	—	Gray decay particle track	22	Decay in flight π-meson
5	242 XIX, XX	+	452	987	5°	0.975	11.20	1200±420	710±270	$m_\pi < m < m_p$	955±250	Relativistic particle	22	K-meson
6	18 XXXVa, XXXVIa	—	123	404	7°6′	0.495	4.00	556+150 or 556+325, if $m = m_\mu$	245+90	$m \sim m_\pi$	—	3 prong star	31	π-meson
7	52 XXXVaXXXVIa	+	440	825	5°	0.750	8.60	870±365	Measurements of α and I show that the parts of the pair belong to different particles			—	31	False coincidence**
8	23 XIIIa, XIVa	+	385	883	6°	0.840	8.85	840±270	1875 ± 700	$m \sim m_p$		—	20	Proton
9	30 XIa, XIIa	—	296	592	3°	0.69	11.8	1625±740	Measurements of α and I along track show that particle has opposite direction of motion			—	20	—

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*Absence of secondary particle tracks is due to low grain densities in tracks of relativistic particles and the high background on the plate.

** The probability for accidental coincidence under the conditions of the experiment is less than 0.5%, *i.e.*, 1 case in 276 tracks, as indeed observed.

TABLE VI.

Particle type	No. of particles	No. of particles created in emulsion	% relative to all particles	Remarks
p	124±3	29	45	
d	50±3	12	20.5	
$m > m_d$	28	5	10	
π^+	9	—	3	All particles suffer μ decay; one particle decays in flight
π^-	20 (±1)	1	7.5	15 particles form stars
μ^+	22	4	8	20 cases of electron decay observed
μ^-	14 (±1)	—	5	7 cases of electron decay observed
K^+ $(m \sim 950 m_e)$	3	1	~1	2 cases of a relativistic decay particle observed

was greater than the total number of π and μ mesons, a result which was not confirmed by further experimentation. The error of this result is due to overestimating the accuracy of mass determination by grain count and range (particles with range > 200 μ were examined). Independent mass determinations by the (l, r) and (α, r) methods, for heavy mesons formed by cosmic rays and stopped in the emulsion, gave results from 600 to $1700 m_e$ in individual cases; the mass-determination uncertainties given by the authors assumed the existence of several types of heavy mesons of different masses. However, it has since been well established that all heavy mesons have a mass $\sim 965 m_e$, with a maximum spread due to the different types of mesons of less than 0.5%.

The conclusions of the authors of Ref. 11, who used two cloud chambers and observed particles of mass 100 and $600 m_e$ in the soft component of cosmic rays 300 m above sea level, are in our opinion incorrect. This error is due to overestimating the accuracy with which the mass was determined by the (l, r) method under the conditions of their experiment

2. *Proportion of Heavy Mesons*

It is seen from Table 6 that at an altitude of 9.5 km positively charged heavy mesons with mass $\sim 1000 m_e$ comprise 2.5 ± 1.5% of the number of protons, or 10 ± 5% of the number of π-mesons.

In Franzinetti's work[4] (360 particles examined at $\sim$ 3500 m) 7 particles were observed with $m_\pi < m < m_p$. The author states that all these cases may be due to experimental error. The use of only one method of mass determination did not allow the author to make positive identification in each case, and did not allow the separation of known heavy mesons from the 7 cases of "intermediate" mass particles with $m_\pi < m < m_p$. In work with emulsion stacks exposed in the stratosphere, taking account of the emulsion efficiency for the registration of heavy meson tracks (which according to Ref. 10 is 25 – 30%) the number of heavy mesons is 2.5 – 3% of the π-mesons.[9,10] These data pertain to particles stopped in the emulsion.

In Ref. 7 using a mass-spectrometer and a Wilson cloud chamber (mass was determined by two methods: momentum and range, and ionization and range), it was found that at 3200 m with a 9 cm lead filter the number of positively charged heavy mesons was 2.5% of the number of protons of the same range (range interval 2.5 – 4.5 cm Pb). In Ref. 12, using two cloud chambers (particle mass was determined by momentum and range), it was found that at 3250 m under an 8 cm lead filter the number of heavy mesons was 6 ± 4% of the number of π-mesons (range interval 10.5 – 22.5 g/cm^2).

Thus, from different experiments carried out at various altitudes it follows that at low and medium energies the number of stopped heavy mesons with mass $\sim$ 1000 m_e is 1 – 5% of the number of protons, and 3 – 10% of the number of π-mesons.

Alikhanian *et al.*[6,7,15] report observations of particles with mass $\sim 550 m_e$. According to the most recent of these investigations,[15] done with a mass spectrometer and two cloud chambers, the number of particles of mass $(560 \pm 60) m_e$ is less than one percent of the number of μ-mesons in the same range interval. No stopped charged particles with mass

$500-600m_e$ were found in photoplates and emulsion stacks. If one assumes that such particles do exist in very small numbers, and if a positive particle decays to a slow π-meson, while a negative particle interacts and gives a star similar to a σ star from π-mesons, it is obviously very difficult to establish their existence from the decay products.

In our opinion the search for particles with mass $\sim 600m_e$ should be made in emulsions placed in a magnetic field. Since magnetic analysis allows higher accuracy for mass determination than other methods for slow charged particles, and besides results in a determination of particle mass and charge that is independent of decay processes, the use of the (ρ, r) method together with occasional use of the other methods will allow positive particle identification in the $600m_e$ region if such particles do exist. The use of plates will at the same time allow a study of the decay products.

3. *Proportion of Deuterons*

As indicated above, the magnetic deflection method allows the separation of heavy particles – protons, deuterons and tritons. From the data of the present work, the number of deuterons among slow particles stopped in the emulsion is 45 – 50% of the number of protons, and the number of tritons is $\sim$ 10% of the number of protons. From the data of Refs. 4 and 22, the number of deuterons stopped in the emulsion is 40 – 45% of the number of protons.

According to Refs. 23 – 25, where deuterons and tritons were not separated, the deuterons and tritons comprised $\sim$ 30% of the singly charged particles emitted from stars. Calculations by Le Couteur based on evaporation theory[26] give a similar number. However, the apparent agreement between experiment and evaporation theory is not necessarily real. For example, if one takes into account that the number of tritons is about 20% of the number of deuterons, then the actual number of deuterons as reported by all sources is about 40 – 50% of the number of protons; Le Couteur's figure is $\sim$ 20%.

The large emission of deuterons can possibly be explained as the result of non-evaporative processes where the particle is the result of a direct interaction between a nucleon and one or more nucleons in a nucleus. In this case an important part of deuteron formation is due to pickup of a nuclear nucleon by either the incident or scattered nucleon.[27,28] On the other hand, it has been shown by Migdal[29] that taking account of nucleon interactions in an evaporation process significantly increases the deuteron emission.

CONCLUSIONS

1. The mass determination error for slow charged particles stopped in an emulsion ($r < 10\ 000\ \mu$) is less for the magnetic deflection – range method than for the ionization – range method or the scattering – range method. Moreover, the magnetic field allows the particle charge to be determined.

2. In determining the mass of charged stopped particles by the magnetic deflection – range method, the errors were such that more than half (6 out of 9) the particles with "intermediate" ($m_\pi < m < m_p$) mass were incorrectly identified. If the mass of a slow charged particle is determined by another method – ionization – range or scattering – range, then identification of an "intermediate" mass is still more unlikely. From the analysis of our and other data, it follows that to identify reliably charged particles that constitute a very insignificant fraction of all particles observed (on the order of a few percent or less), the mass of such particles must be identified by several methods. Only if the results coincide can the identification be complete. In general, to find the proportion of heavy mesons, or to observe particles of unusual mass it is essential to determine the mass by several methods.

3. At an elevation of 9.5 km under 8 cm of lead the number of mesons with mass $\sim 1000m_e$ from among the stopped secondary particles caused by cosmic rays is 2.5 ± 1.5% of the number of protons. Particles with mass $500-600m_e$ are not observed. From the statistical information given in this paper it follows that the number of such particles, if they do exist, is less than 1% of the number of protons.

4. From both the 460 Mev proton data and the cosmic ray bombardments at 9.5 km it is seen that a large number of deuterons occurs among the slow charged secondary particles ($E < 50$ Mev). The number of deuterons is about half the number of protons.

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Interaction of Nitrogen and Gold Nuclei

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The dependence of the cross sections on the energy of nitrogen ions has been determined for the reactions Au(N, 4*n*), Au(N, 5*n*) and Au(N, 6*n*). The irradiation was carried out at the internal test chamber of the cyclotron with monoenergetic ions accelerated up to 115 Mev. In accord with the theory of competitive processes, curves with pronounced peaks were obtained.

IRRADIATION OF GOLD WITH N^{14} ions, accelerated up to 100 – 130 Mev, produces highly excited Rn^{211} compound nuclei. The excitation energies involved amount to ∼ 75 – 100 Mev. Such excitation of the nucleus should lead either to its disintegration into fragments, or to the "evaporation" of a certain number of nucleons – chiefly neutrons. In the latter case there are produced a number of isotopes of Rn, At, Po etc., which are either α-active or disintegrate through *K*-capture. In 1954 Burcham,[1] while studying the reaction products resulting from the irradiation of Au^{197} with accelerated ions of N^{14} and C^{13}, identified several Rn, At, and Po isotopes. He used the 150-cm cyclotron of the University of Birmingham to accelerate the N^{14} and C^{13} ions. Beams of accelerated multicharged ions with a continuous energy spectrum, decreasing sharply in the direction of higher energies, were obtained in this cyclotron. The maximum energies of the N^{14} and C^{13} ions at the ultimate radius were