A SEARCH FOR THE DOUBLE PROTON.

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In his paper on 'Elementary heavy particles with any integral charge', Bhabha (1940) comes to the conclusion that heavy elementary particles can exist in states of all integral charge, positive, negative or zero; the different states having different rest masses. The states with charge zero (neutron) and charge $+e$ (proton) are taken to have the lowest rest masses, while the proton states of charge $-e$ and $+2e$ are assumed to have slightly larger masses. In the foregoing paper, Bhabha has given a detailed description of the mechanism and probability of production of these particles, their mass, life, etc. According to him, the most probable processes for the formation of the new particles are the following:—

$$P_1+P_1 \longrightarrow P_2+N \quad \ldots \quad (1)$$

$$N+N \longrightarrow P_{-1}+P_1 \quad \ldots \quad (2)$$

P_1 denotes an ordinary proton, N a neutron, P_2 and P_{-1} protons of charge $+2e$ and $-e$ respectively. The collision cross-sections for production of such particles are calculated to be of the order of 10^{-25} cm.^{2} and the colliding proton or neutron should have at least the kinetic energy of 35 mev. The masses of these particles, P_2 and P_{-1}, are calculated to be about 2% higher than that of an ordinary proton. Such particles can also be produced by mesons and photons but in these cases, the collision cross-section is of the order of 10^{-29} cm.^{2}

The lifetime of these particles is of the order of $\frac{1}{6}$ sec., so that it is quite probable, if Bhabha's arguments are correct, that these particles might have occurred amongst the Wilson chamber photographs of cosmic rays, which have been so far secured by investigators in different parts of the world. So before undertaking new experiments for detecting such particles, it was suggested by Dr. Bhabha that a search might be made for them in the photographs of heavy tracks that have already been published.

A negative proton has almost the same mass as the ordinary proton, so that ionisation and range of both being the same for a given energy, they can be distinguished from each other only when Wilson chamber tracks are taken in a magnetic field, for their curvatures will be in the opposite directions. Searches have already been made for the antiproton (which, though not exactly Bhabha's negative proton, is experimentally indistinguishable) but it has not been found so far. So it was not considered worth while to look for it in the photographs already published. Therefore, the photographs were searched only with the aim of finding the doubly charged proton.

Identification of ionising particles.

The ionisation produced by a particle varies as the square of its charge. It is practically independent of its mass, and depends essentially on its velocity. Therefore, for a given velocity, a double proton ionises four times more than an ordinary proton. But in the Wilson chamber, the velocity of a particle is not measured, but its curvature ρ : the magnetic field being known, the experiment directly gives $H\rho$. Now for the same value of $H\rho$ if the particle is a proton it has a certain momentum p, if a double proton it has the momentum $2p$. As a result, if we plot ionisation against $H\rho$, the ionisation of a double proton is only some 30–50% higher than that of an ordinary proton for non-relativistic velocities, so that very accurate measurements are required to distinguish between them. But for a given $H\rho$ the range of these particles are very different. Hence if varying thicknesses of lead sheets are placed in the Wilson chamber, it may be possible to distinguish between the particles by observing how the curvature changes before and after traversal through lead blocks, or whether they are stopped in lead. On account of these and other difficulties it is necessary to scrutinise critically the current methods for identification of ionising particles. Let us now discuss these methods.

It is well known that in order to identify a particle completely, we should know its rest mass, charge, energy and if possible spin. The principal means by which the mass can be determined (assuming charge to be known) are the following:—

(1) Range and curvature in a magnetic field.
(2) Ionisation and curvature.
(3) Ionisation and range.
(4) Close elastic collision with extra-nuclear electrons of the atom.
(5) Deflection by combined electric and magnetic fields.

The last method is hardly applicable in the case of high energy particles in cosmic radiation. The 4th method is also rarely used; only in a very few cases has this method been employed by Anderson and Neddermeyer (1939), Leprince-Ringuet and Crussard (1937). They determined the energy of the knocked-out electron and its angle of projection from which the identity of the colliding cosmic ray particle was determined. The first three methods are based on the same principle, viz., the relationship between the loss by ionisation per cm. of path and the velocity of the particle. The ranges of these particles can be calculated from the same relationship. The calculation of energy loss by electrons, mesons and protons, etc. (as are of interest in cosmic rays) has so far been carried out for the cases shown in the table below:—

Author.	Particle.	Work.	Remarks.
Blackett and Occhialini, 1933	Electron and Proton	Energy loss in water	$<10^8$ ev.
	Proton and α-particle.	Range in air	For five different values of velocity.
Anderson and Neddermeyer, 1939.	Singly charged particles.	Energy loss in lead and air also Range (found by graphical integration).	For different velocities.
Euler and Heisenberg, 1938.	Electron, Proton and Meson.	Energy loss in water and lead.	They have plotted the loss against $H\rho$.
Bhabha, 1938 ..	Proton and Meson	Energy loss in lead and water.	
1940 ..	Proton, Double Proton and α-particle.	Ranges in air	For four different values of energy.
Bhattacharya (this paper).	Meson, Proton, Double Proton, Deuteron and α-particle.	Energy loss in air	10^6–10^9 ev.
	,,	Range in air and lead.	10^6–10^8 ev.

Calculation of energy loss.

The total ionisation loss per cm. path in a substance of atomic number Z by a particle of charge ze moving with a velocity $v = \beta c$ and having a total energy E is given by the Bloch formula (Bhabha, 1938).

$$-\left(\frac{dE}{dx}\right)_{\text{coll}} = 2\pi N Z r_0^{\,2} \frac{mc^2}{\beta^2} z^2 \left[\log_e \frac{mc^2\beta^2 W_m}{(1-\beta^2)I^2Z^2} + 1 - \beta^2\right] \quad .. \quad (3)$$

where N is the number of atoms per c.c. of the substance,

$$r_0 = \frac{e^2}{mc^2},$$

m, e being the mass and charge of the electron respectively. IZ is the mean ionisation potential of the atom and according to Bloch it is given by

$$IZ = 13{\cdot}5\, Z \text{ ev.}$$

W_m is the maximum energy that can be transferred to an initially stationary electron in a free collision. It is given by the following expression :—

$$W_m = \frac{2mM(\gamma+1)}{m^2+M^2+2mM\gamma}(E-Mc^2),$$

where M is the mass of the heavy particle, and

$$\gamma \equiv \frac{E}{Mc^2} = 1 + \frac{T}{Mc^2},$$

T being the kinetic energy of the particle.

In order to calculate the ionisation loss in different substances by different particles, equation (3) can be transformed conveniently into the following form:—

$$-\left(\frac{dE}{dx}\right)_{\text{coll}} = \frac{Az^2}{\beta^2} NZ \left[\log_{10} \frac{2{\cdot}8 \times 10^3}{Z^2} + C\right] \quad \cdots \quad \cdots \quad (4)$$

where $A = 2{\cdot}303\ (2\pi r_0{}^2\, mc^2) = 5{\cdot}77 \times 10^{-19}$ ev.

$$C = \log_{10} W_m + \log_{10} \frac{\beta^2}{1-\beta^2} + \frac{1-\beta^2}{2{\cdot}303}.$$

Thus C depends only on the energy and nature of the particle.

Let us now see how 'β^2' needed in formula (4) can be obtained from the experimental work. From the Wilson chamber photographs in a magnetic field we obtain ρ, the curvature of the tracks. The magnetic field H is known. The momentum p is obtained from the equation:

$$pc = (ze)\, H\rho \quad \cdots \quad (5)$$

$= 300\ H\rho$ ev. for $z = 1$, i.e. for protons, electrons, deuterons and mesons.

$= 600\ H\rho$ ev. for $z = 2$, i.e. for α-particles and double protons.

Thus for a given '$H\rho$' the momentum of the double proton will be twice the momentum of the proton.

From pc, we obtain β and E using the formulae:—

$$\frac{\beta}{\sqrt{1-\beta^2}} = \frac{p}{Mc}$$

$$E = \sqrt{p^2c^2 + (Mc^2)^2} \quad \cdots \quad \cdots \quad \cdots \quad (6)$$

$$= \frac{Mc^2}{\sqrt{1-\beta^2}}. \quad \cdots \quad \cdots \quad \cdots \quad \cdots \quad (7)$$

For singly charged particles, we have, from equations (5) and (6):—

$$H\rho = \frac{\sqrt{T(T+2Mc^2)}}{300} \text{ Gauss-cm.}$$

and for doubly charged particles

$$H\rho = \frac{\sqrt{T(T+2Mc^2)}}{600} \text{ Gauss-cm.}$$

'T' and 'Mc^2' must be expressed in electron volts.

A table of T and $H\rho$ values for different particles is given below, and the corresponding $\log_{10} T$ vs. $\log_{10} (H\rho)$ curves are given in fig. 1.

TABLE I.

Relation between kinetic energy and Hρ of various particles.

T	'$H\rho$' in Gauss-cm.				
Kinetic energy in ev.	Meson ($Mc^2 = 8\times10^7$ ev.)	Proton ($Mc^2 = 10^9$ ev.)	Double Proton ($Mc^2 = 1{\cdot}02\times10^9$ ev.)	Deuteron ($Mc^2 = 2\times10^9$ ev.)	α-particle ($Mc^2 = 4\times10^9$ ev.)
1×10^6	$0{\cdot}42\times10^5$	$1{\cdot}49\times10^5$	$0{\cdot}75\times10^5$	$2{\cdot}11\times10^5$	$1{\cdot}49\times10^5$
2×10^6	0·60 ,,	2·11 ,,	1·07 ,,	2·98 ,,	2·11 ,,
4×10^6	0·85 ,,	2·98 ,,	1·51 ,,	4·22 ,,	2·98 ,,
6×10^6	1·05 ,,	3·66 ,,	1·85 ,,	5·17 ,,	3·65 ,,
8×10^6	1·22 ,,	4·23 ,,	2·13 ,,	5·97 ,,	4·22 ,,
1×10^7	1·37 ,,	4·73 ,,	2·39 ,,	6·67 ,,	4·71 ,,
2×10^7	2·00 ,,	6·70 ,,	3·38 ,,	9·45 ,,	6·67 ,,
4×10^7	2·98 ,,	9·52 ,,	4·81 ,,	$1{\cdot}34\times10^6$	9·45 ,,
6×10^7	3·83 ,,	$1{\cdot}17\times10^6$	5·91 ,,	1·65 ,,	$1{\cdot}16\times10^6$
8×10^7	4·62 ,,	1·36 ,,	6·86 ,,	1·91 ,,	1·34 ,,
1×10^8	5·37 ,,	1·53 ,,	7·71 ,,	2·13 ,,	1·50 ,,
2×10^8	8·94 ,,	2·21 ,,	$1{\cdot}12\times10^6$	3·06 ,,	2·13 ,,
4×10^8	$1{\cdot}58\times10^6$	3·27 ,,	1·65 ,,	4·42 ,,	3·06 ,,
6×10^8	2·25 ,,	4·16 ,,	2·10 ,,	5·54 ,,	3·78 ,,
8×10^8	2·92 ,,	4·99 ,,	2·51 ,,	6·52 ,,	4·42 ,,
1×10^9	3·59 ,,	5·77 ,,	2·91 ,,	7·46 ,,	5·00 ,,
2×10^9	6·93 ,,	9·43 ,,	4·74 ,,	11·55 ,,	7·49 ,,

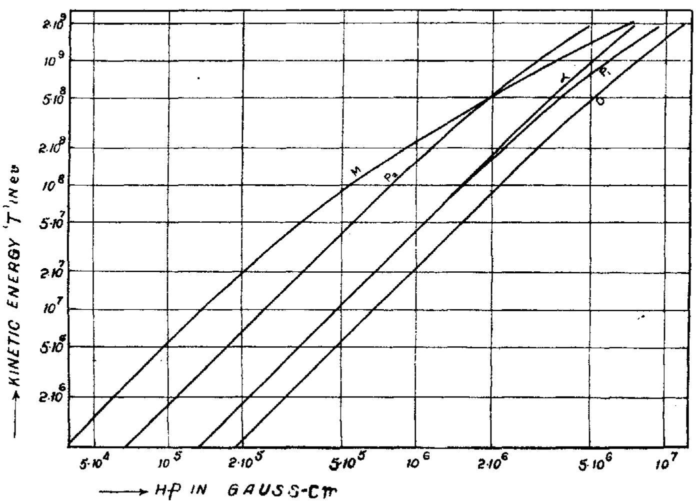

FIG. 1. Relation between Kinetic Energy and $H\rho$. M denotes → Meson, P_2 → Double Proton, P_1 → Proton, D → Deuteron, α → α-particle.

These curves are very useful in an analysis of this kind; because some authors mention only the kinetic energy of the particles. From these curves we can at once find out the corresponding '$H\rho$' and hence the ionisation and range.

The energy loss per cm. path by different particles having various kinetic energies has been calculated (Table II) and then the energy loss plotted against $\log_{10}(H\rho)$ for these particles (fig. 2).

TABLE II.

Collisional energy loss in air at N.T.P.

Thousands of electron volts per centimetre.

T	Meson ($Mc^2 = 8 \times 10^7$ ev.)	Proton ($Mc^2 = 10^9$ ev.)	Double Proton ($Mc^2 = 1{\cdot}02 \times 10^9$ ev.)	Deuteron ($Mc^2 = 2 \times 10^9$ ev.)	α-particle ($Mc^2 = 4 \times 10^9$ ev.)
1×10^6 ev.	45·2	302	..	..	..
2×10^6 ,,	25·9	205	817·5	380·3	..
4×10^6 ,,	14·8	115·2	459·5	215·0	..
6×10^6 ,,	10·8	85·6	341·6	145·1	..
8×10^6 ,,	8·7	68·2	272·7	117·8	..
1×10^7 ,,	7·4	55·0	225·1	96·2	659·2
2×10^7 ,,	4·68	31·2	127·4	54·5	384·7
4×10^7 ,,	3·28	17·8	72·6	31·4	218·1
6×10^7 ,,	2·83	12·9	52·7	22·5	158·1
8×10^7 ,,	2·62	10·3	42·1	17·8	124·8
1×10^8 ,,	2·52	8·7	35·6	14·9	103·9
2×10^8 ,,	2·41	5·4	21·8	8·9	59·9
4×10^8 ,,	2·49	3·6	14·7	5·4	35·0
6×10^8 ,,	2·59	3·0	12·3	4·2	26·2
8×10^8 ,,	2·63	2·8	11·2	3·6	21·6
1×10^9 ,,	2·75	2·6	10·6	3·3	18·8
2×10^9 ,,	2·82	2·4	9·7	2·6	13·2

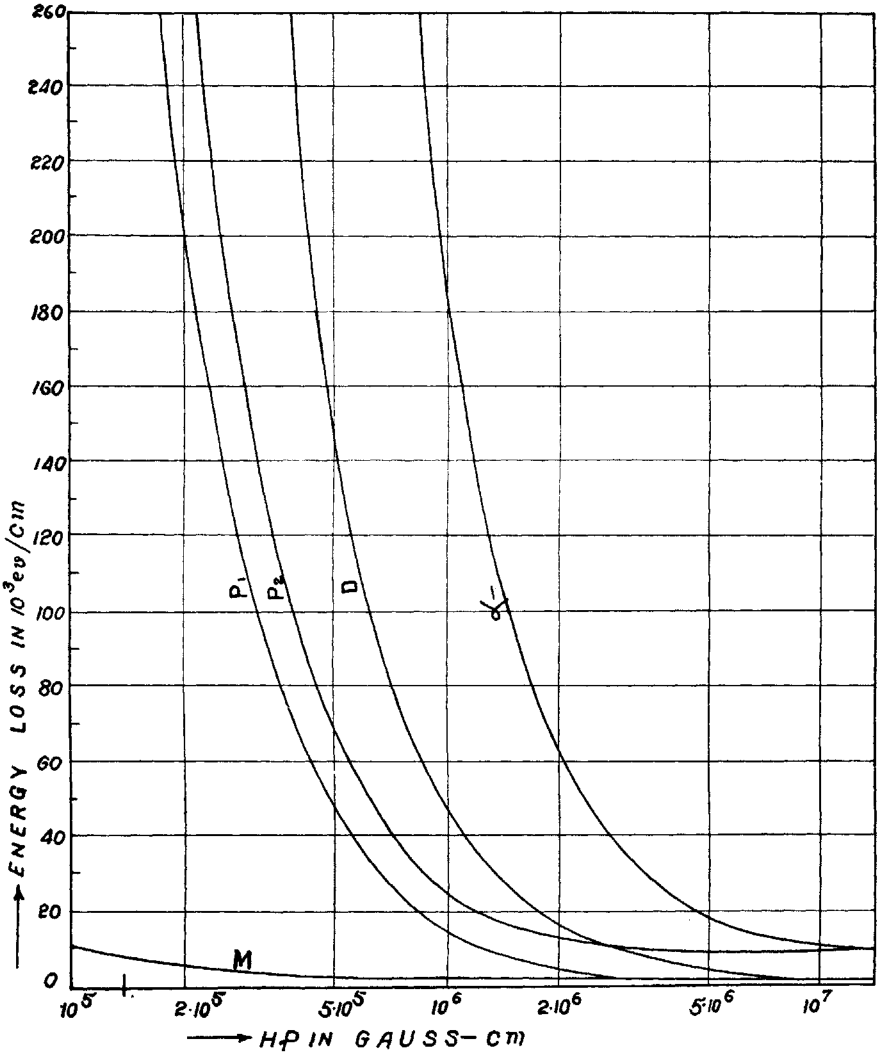

FIG. 2. Energy loss in air at N.T.P. M denotes → Meson, P_1 → Proton, P_2 → Double Proton, D → Deuteron, and α → α-particle.

Range.

For the calculation of range of heavy particles moving with *non-relativistic* velocity, following Bhabha (1940), the equation (3) may be written as

$$-\left(\frac{dT}{dx}\right)_{\text{coll}} = \frac{\pi N Z e^4 z^2 M}{mT} \log\left(4\frac{m}{M}\frac{T}{\bar{I}}\right)^2$$

or

$$dx = -\frac{m}{\pi N Z e^4 z^2 M} \frac{T\,dT}{\log\left(4\frac{m}{M}\frac{T}{\bar{I}}\right)^2} \quad \ldots \quad \ldots \quad (8)$$

or range

$$R = \int_0^R dx = \frac{1}{a}\int_{\epsilon_0}^{\epsilon} \frac{d\epsilon}{\log \epsilon}$$

or

$$aR = Ei\left(\log_e \epsilon\right) - Ei\left(\log_e \epsilon_0\right) \quad \ldots \quad \ldots \quad \ldots \quad (9)$$

where

$$a = \frac{32\pi N Z e^4 z^2 m}{M \bar{I}^2} \quad \text{and} \quad \epsilon = \left(4\frac{m}{M}\frac{T}{\bar{I}}\right)^2.$$

$Ei(x)$ is the well-known exponential integral and has been tabulated (*e.g.*, B.A. Math. Tab., Vol. 1, or Jahnke-Emde).

$\bar{I} = IZ$ is the average ionisation potential of the substance traversed. In the case of air we may take $Z = 7$ (i.e. for nitrogen alone), and $\bar{I} = 94{\cdot}5$ ev.

In this paper, the ranges of different particles have been calculated taking the value of ϵ_0 such that $Ei\,(\log_e \epsilon_0) = 0$. Tables III and IV give the ranges of various heavy particles in air (at N.T.P.) and lead respectively; figures 3 and 4 give the corresponding curves.

TABLE III.

Range in Air.

T in ev.	Meson.	Proton.	Double Proton.	Deuteron.	α-particle.
1×10^6	12·25 cm.	2·18 cm.	0·52 cm.	1·46 cm.	0·25 cm.
2×10^6	43·17 ,,	6·76 ,,	1·64 ,,	4·34 ,,	0·56 ,,
4×10^6	152·8 ,,	21·2 ,,	5·42 ,,	13·45 ,,	2·05 ,,
6×10^6	323·1 ,,	44·4 ,,	10·9 ,,	26·7 ,,	4·06 ,,
8×10^6	..	72·7 ,,	18·55 ,,	43·8 ,,	6·95 ,,
1×10^7	..	109·8 ,,	26·50 ,,	64·6 ,,	9·74 ,,
2×10^7	..	384 ,,	93·6 ,,	219·8 ,,	32·64 ,,
4×10^7	..	1358 ,,	336 ,,	770 ,,	109·9 ,,
6×10^7	..	..	704 ,,	1612 ,,	229·7 ,,
8×10^7	..	..	1120 ,,	2728 ,,	388·9 ,,
1×10^8	..	..	..	..	580·4 ,,

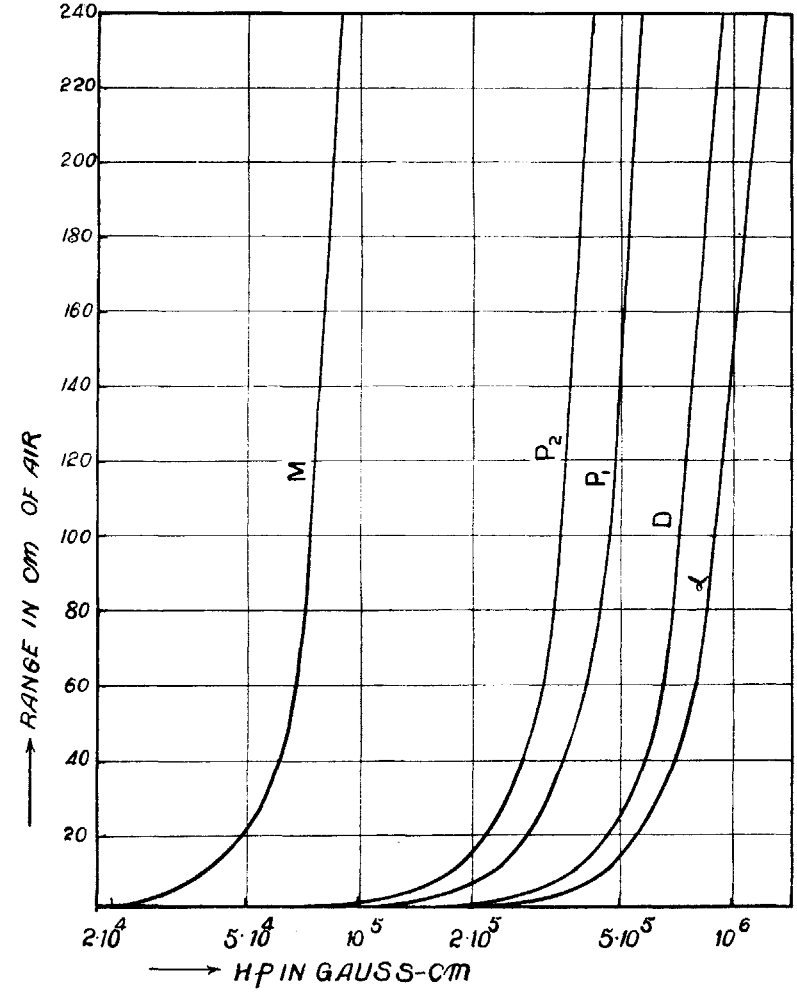

FIG. 3. Range in Air. M denotes → Meson, P_2 → Double Proton, P_1 → Proton, D → Deuteron, α → α-particle.

TABLE IV.

Range in Lead.

T in ev.	Meson.	Proton.	Double Proton.	Deuteron.	α-particle.
1×10^6	0·036 mm.	0·01 mm.	0·002 mm.	..	..
2×10^6	0·11 ,,	0·03 ,,	0·007 ,,	0·02 mm.	..
4×10^6	0·36 ,,	0·08 ,,	0·019 ,,	0·058 ,,	0·01 mm.
6×10^6	0·73 ,,	0·14 ,,	0·036 ,,	0·10 ,,	0·019 ,,
8×10^6	1·2 ,,	0·23 ,,	0·058 ,,	0·16 ,,	0·029 ,,
1×10^7	1·8 ,,	0·33 ,,	0·081 ,,	0·22 ,,	0·04 ,,
2×10^7	6·3 ,,	1·01 ,,	0·25 ,,	0·67 ,,	0·11 ,,
4×10^7	22·7 ,,	3·2 ,,	0·81 ,,	2·03 ,,	0·33 ,,
6×10^7	48·2 ,,	6·6 ,,	1·63 ,,	4·01 ,,	0·64 ,,
8×10^7	80·9 ,,	10·9 ,,	2·72 ,,	6·6 ,,	1·02 ,,
1×10^8	..	15·7 ,,	4·03 ,,	9·7 ,,	1·4 ,,
2×10^8	..	56·6 ,,	14·04 ,,	32·7 ,,	4·9 ,,
4×10^8	..	..	49·4 ,,	113·6 ,,	16·5 ,,
6×10^8	..	..	..	..	33·9 ,,
8×10^8	..	..	..	..	57·3 ,,
1×10^9	..	..	..	..	85·4 ,,

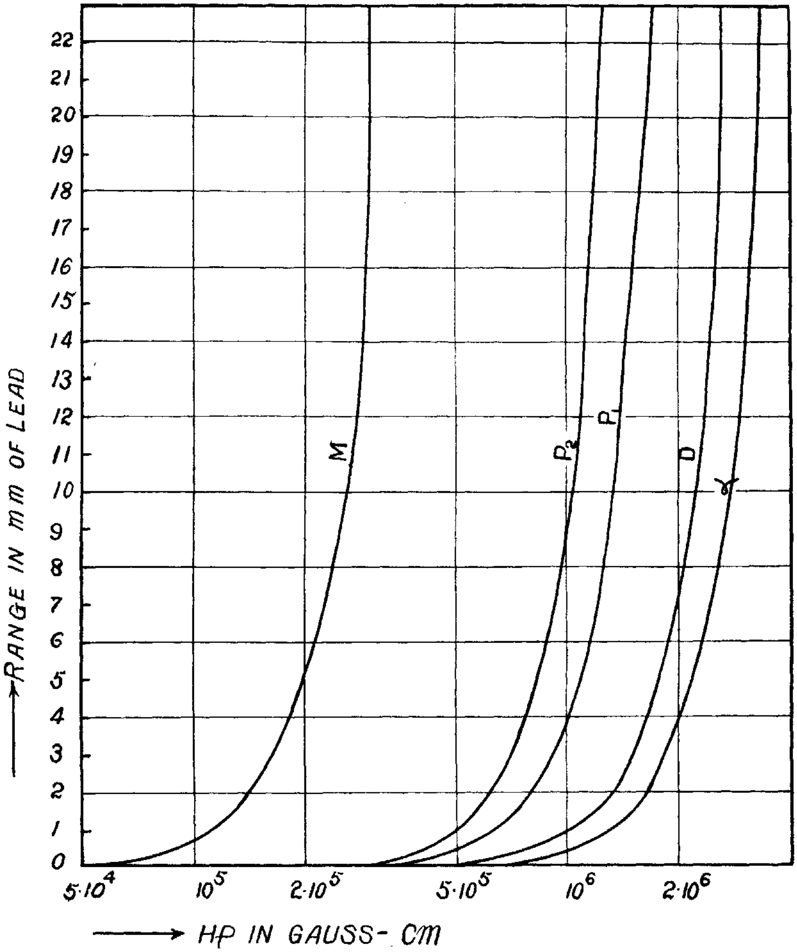

FIG. 4. Range in Lead. M denotes → Meson, P_2 → Double Proton, P_1 → Proton, D → Deuteron, α → α-particle.

Analysis.

With the help of these energy loss and range curves the heavy tracks in the photographs published by the following authors have been examined:

Anderson and Neddermeyer, 1932, 1936, 1938, 1939.
Blackett and Occhialini, 1933.
Blackett, 1934.
Brode and co-workers, 1936, 1938.
Herzog, 1941.
Herzog and co-workers, 1935, 1941.
Johnson and co-workers, 1940.
Kunze, 1933.

Leprince-Ringuet and Crussard, 1937.
Locher, 1937.
Maier-Leibnitz, 1938, 1939.
Nishina and co-workers, 1939.
Street, 1939.
Street and Stevenson, 1937.
Williams and Roberts, 1940.

In the scrutiny of tracks, special attention has been given to the heavy tracks found at high altitudes because it is only here that energetic protons are available in large numbers. Moreover, Auger (1939), in his interesting work on extensive air showers, has shown that the core of these showers contains large numbers of penetrating particles (probably very energetic photons and electrons) and also heavy tracks. These tracks can be recognised as being due to heavy and probably multiply charged particles which probably have their genesis in the explosion of the nucleus (of the constituents of Wilson chamber gas) caused by the above-mentioned energetic photons and electrons. An abnormally high number of slow proton tracks was also found by Auger in the nuclear disintegrations taking place in the core of the air showers. A detailed investigation of the core of the air showers with a Wilson chamber appears to be very promising for finding out experimental confirmation of Bhabha's reactions, but such an undertaking involves time and organisation. The 'unusual' tracks found by Anderson and Neddermeyer (1936) in their high altitude experiments (Pikes Peak, 14,000 ft. above sea level) were therefore scrutinised very carefully.

As the result of analysis, a few heavy tracks have been found which were ascribed by the original authors to protons; but according to the present analysis they may be due to the double proton as well.

In fig. 13, of *Phys. Rev.*, 50, p. 270, there is one 'unusual' track coming out of the lead plate (0·35 cm. thick) in the chamber. It is associated with an extensive air shower and its $H\rho$ is 'at most $1{\cdot}4 \times 10^5$ Gauss-cm. and the curvature shows that the particle is positively charged. Its range is more than 5 cm. in the chamber', but the particle has apparently gone beyond the illuminated portion of the chamber. If this particle is a proton, its range should be about 2 cm. (*vide* fig. 3); but if it is a double proton its range would be about 5 cm. in air at N.T.P. So considering range and $H\rho$ this particle could be interpreted as a double proton but not as a proton. But the ionisation presents some difficulty. As seen from fig. 2, a double proton of this $H\rho$ should ionise about 150 times the minimum for an electron, whereas a glance at the track in question shows that the ionisation can hardly be more than 5 times the minimum ionisation. The pressure in the chamber is not mentioned. If it is 1·8 atmospheres of Argon (see fig. 7 of the same paper) the range in standard air will be $\sim$9 cm. With the aid of their mass energy nomograph the mass of this particle was determined by Corson and Brode (1936) on the assumption that it is a singly charged particle and was found to be about 1000 m. This value is therefore too small for a particle of protonic mass. This particle, therefore, cannot be a proton, but there are difficulties in interpreting it as a double proton and, indeed, if the pressure in the chamber is 1·8 atmospheres of Argon even this interpretation must be rejected.*

The tracks published by Johnson and co-workers (1940) have also been examined critically but the information given there is not sufficient to allow us to come to a definite conclusion. Their experimental arrangement is very favourable for the detection of the double proton.

The search for the existence of the double proton amongst the published photographs has not, therefore, led to any definite positive result as yet. But it will be rather premature to predict on the strength of this search that the particle does not exist. From the curves in fig. 4, it will be seen that, if the '$H\rho$' of a particle is 10^6 Gauss-cm., a lead block of 4 mm. will be sufficient to stop a proton but a double proton of this '$H\rho$' will penetrate about 9 mm. of lead; the ranges of α-particles and deuterons are extremely small while the range of mesons is very large ($\sim$14 cm. of lead). In order to eliminate mesons an anticoincidence circuit should be used with a few centimetres of lead just above the 'anti' counter. If the 'anti' counter with the lead above it is placed just below a counter controlled Wilson chamber, then the tracks obtained in this arrangement may be due to protons, double protons or deuterons. A lead block of 5 mm. thickness will be sufficient to cut off protons, deuterons and α-particles and only double protons will be able to come out of the lead block. The probability of getting tracks in this arrangement, particularly those ending in the chamber, will be small at sea level but at high altitudes it will be fairly good.

In conclusion, the author wishes to record his sincere thanks to Dr. H. J. Bhabha, F.R.S., at whose suggestion this search was undertaken, and who has helped him with his criticisms and suggestions. He is also indebted to Prof. M. N. Saha, F.R.S., for his kind interest and helpful discussions during the progress of the work.

Summary.

Energy loss per cm. of air at N.T.P. by mesons, protons, double protons, deuterons and α-particles and their ranges in air and lead have been calculated and plotted against $\log_{10}(H\rho)$. With the help of these range and energy loss

* Before the publication of this note the present writer came to know that Heitler and Ma (1941) have also discussed this very track which they ascribe to a double proton. They have expressed the opinion that the ionisation by a double proton of $H\rho = 1{\cdot}4 \times 10^5$ Gauss-cm. is the same as that of an ordinary proton of this $H\rho$. But they have not compared the ionisations of double protons or protons at this $H\rho$ to ionisation minimum of fast particles. In the case of double protons it should be about 150 times the minimum ionisation. For this and other difficulties already discussed, it seems to the author that this particle cannot be interpreted as a double proton.

curves, a search has been made to find out the double proton predicted by Bhabha (particle with charge $+2e$ and mass 2% higher than that of an ordinary proton) amongst the published photographs of cosmic ray heavy particles. The result so far obtained is negative. A full discussion of the various ways of continuing the search for the particle is given.

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