The 2, 4 and 7 m.e.v. lines can be correlated with differences in energy of proton groups observed by Cockroft and Walton,[1] which indicate lines at 2.2, 4.5 and 6.8 m.e.v. The reaction producing the protons, and hence also these gamma-ray lines is probably

$$B^{10}+H^2\rightarrow B^{11}+H^1. \qquad (1)$$

The 5.5 m.e.v. line has been found associated with the formation of C^{12} in the case of beryllium bombarded with alpha-particles,[2] and therefore it seems reasonable to ascribe it also in this case to the reaction in which C^{12} is produced:

$$B^{11}+H^2\rightarrow C^{12}+n^1. \qquad (2)$$

Alpha-particles are produced, by the reaction

$$B^{10}+H^2\rightarrow 3\,He^4 \qquad (3)$$

with a large excess of energy, and it is probable that this is responsible for the component of radiation observed at 10 m.e.v. or higher. There has already been an indication that the alpha-particle has an excitation level at about 12 m.e.v.,[3] and the present observations furnish confirmation of this hypothesis.

The absorption coefficient in lead which we previously determined for the gamma-radiation from boron bombarded with deutons[4] is entirely consistent with the above combination of lines, if we keep in mind the fact that the absorption coefficient for lead has a minimum at about 3 m.e.v. and rises for energies higher than this.[5]

Also the ratio of positive to negative electrons (0.05) from the thin lead absorber is the same as would be produced by a single gamma-ray line of about 5 m.e.v., and is therefore consistent with the mixed radiation in question.

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December 1, 1934.

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[3] Lauritsen and Crane, Phys. Rev. **46**, 537 (1934).
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Capture of Charged Particles by Nuclei Due to Emission of Gamma-Radiation

According to the experiments of Lea[1, 2] and more definitely according to Chadwick and Goldhaber[3] a proton and a neutron may unite to form a deuton emitting a γ-ray in the process. It appears probable that a nucleus and a proton may unite also in other cases, and that the excess energy may be emitted as γ-radiation. Thus, the formation of N^{13} by proton bombardment of C may perhaps be due to the reaction $C^{12}+H^1\rightarrow N^{13}+\gamma$. We calculated the probability of such processes, and we can account without difficulty for collision cross sections of the order of 10^{-30} cm^2 and higher for 500 kv protons supposedly captured by C with the emission of approximately 7×10^6 e.v. γ-rays. We discuss first an approximate formula for the effective collision cross section σ at a given velocity v of the protons

$$\sigma=5.08(c/v)(1+\eta^2)(R^5/\lambda^3\Lambda^2)P^2\cdot\pi R^2\xi/(e^{\xi}-1). \qquad (1)$$

Here

$$P=1+(5/12)\kappa R\eta+(1/14)(\kappa R\eta)^2(1-1/\eta^2)+(1/144)(\kappa R\eta)^3(1-7/2\eta^2)+\cdots,$$

$$\eta=Zc/\text{``}137\text{''}v,\quad \xi=2\pi\eta,\quad \kappa=2\pi/\Lambda,\quad \Lambda=h/mv.$$

λ = wave-length of γ-rays, Λ = wave-length of incident protons, R = nuclear radius. This formula is rough, but is often useful in estimating σ. Two approximations are involved in its derivation: (1) that of neglecting the effect of the nuclear potential well on the wave function of the proton before capture, (2) that of taking the wave function of the proton after capture to be constant through a sphere of radius R and zero outside that sphere. The values of σ obtained from this formula for 520 kv protons incident on carbon for $h\nu=14mc^2\cong 7\times10^6$ e.v. are:

σ(cm^2)
$=1.3\times10^{-28}$ 2.2×10^{-29} 2.3×10^{-30} 1.0×10^{-31} 6.1×10^{-34}

for R(cm)
$=1.0\times10^{-12}$ 0.8×10^{-12} 0.6×10^{-12} 0.4×10^{-12} 0.2×10^{-12}.

The dependence on v is primarily determined by $e^{-\xi}$. The mean collision cross section for solid targets is

$$\bar{\sigma}=v^{-3}\int_0^v 3\sigma(v)v^2dv.$$

For $R=0.4\times10^{-12}$ cm. The ratio $\bar{\sigma}/\sigma$ has the approximate values 0.26 at 1020 kv and 0.34 at 520 kv.

The above formula is simple but not accurate. Without approximations except those inherent to a central field treatment one finds for the dipole radiation due to a transition to a captured s state:

$$\sigma=3.36\frac{c}{v}\frac{1+\eta^2}{(\kappa\lambda)^3}\frac{\xi}{e^{\xi}-1}\cdot\frac{1}{\kappa^2}\left|\int_0^\infty \rho\Psi(\rho)\bar{f}_1(\rho)d\rho\right|^2, \qquad (2)$$

where Ψ represents the captured state, $\rho=\kappa r$, $\int\Psi^2(\rho)d\rho=1$ and $\bar{f}_1$ is the function which replaces the regular power series solution in a Coulomb field beginning with ρ^2 for $l=1$. If the well is absent $\bar{f}\rightarrow f=\rho^2(1+\cdots)$. The ratio $|\bar{f}/f|^2$ at boundary of well is $[(1-FG\delta)^2+F^4\delta^2]^{-1}_{r=R}$, where F, G are, respectively, the regular and irregular radial functions asymptotic at ∞ to $\sin(\rho+\epsilon)$, $\cos(\rho+\epsilon)$. The quantity $\delta=(F'/F-\bar{f}'/\bar{f})$.

Formula (2) gives larger values of σ than Eq. (1). Thus for a well with a depth of about 20×10^6 e.v. and a radius $R=0.33\times10^{-12}$ cm the approximate values of σ are as follows:

Energy (kv)	900	730	580	440
σ(10^{-30} cm^2)	3.9	2.7	1.7	0.94

The more accurate Eq. (2) gives a less rapid decrease of the probability with decreasing velocity and thus $\bar{\sigma}/\sigma$ is somewhat larger than for Eq. (1).

A yield of 500 disintegrations per 2 microamperes at 900 kv corresponds to $\bar{\sigma}=2.8\times10^{-31}$ cm^2. There appears thus to be no difficulty in accounting for either the Cambridge[4] or the Pasadena[5] results on C on the basis of γ-radiation. Since the γ-radiation itself has not been detected and since the alternative explanation of Lauritsen and Crane $C^{13}+H^1\rightarrow N^{13}+n$ appears to be also possible we do not attempt to draw a definite conclusion as to the way in which N^{13} is formed.

Hafstad and Tuve[6] found a very intense induced radioactivity when C was bombarded by deutons at 1000 kilovolts but were able to show that the effect with protons at the same voltage (using magnetic analysis of the beam) was less than 1/8000 of the deuton effect. They have recently informed us[7] that preliminary observations using more intense proton beams indicate a real proton effect of 1/7000 to 1/14,000 of the deuton effect at 900 kilovolts, and estimate that a 2 microampere beam of protons at 900 kilovolts gives rise to an equilibrium emission of roughly 1000 positrons per second in the total solid angle 4π. There is thus qualitative agreement as to order of magnitude of the effect between the three groups of experimenters.

We made use above of some unpublished calculations of Dr. John A. Wheeler giving F and G in tabular form, and we are very much indebted to him for making these tables available to us. We are also very grateful to G. Gamow, M. A. Tuve and L. R. Hafstad for a discussion of the theoretical and experimental evidence for $C+H^1\rightarrow N^{13}$.

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University of Wisconsin,
December 3, 1934.

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A Criticism of Dr. L. G. H. Huxley's Theory of the Origin of Cosmic Rays

In a recent paper, L. G. H. Huxley[1] has developed in detail a theory of the origin of cosmic rays in which the rays are treated as charged particles, distributed uniformly at infinity and starting with negligible velocity, which move in the field of an earth which is a uniformly magnetized sphere carrying an electric charge opposite in sign to the charge of the particles. The suggestion of a charged Earth attracting the particles, and thus accounting for their huge energies, has been previously put forward by Johnson.[2] Apart from difficulties of a general nature such as are suggested by Huxley himself which this theory would have to meet, it appears to the writer that Huxley's analysis is incorrect, and the object of this note is to point out this fact.

Taking, with Huxley, polar coordinates (r, θ, ϕ) at the Earth's center, with the polar axis the Earth's magnetic axis, and employing special relativity dynamics, the velocity v of the particle and the azimuthal velocity ϕ are easily expressed as functions of r only by means of well-known integrals of the equations of motion. The assumption is then made that *at the Earth's surface the component of velocity $r\dot{\theta}$ is negligibly small compared with the other two components*. The expressions for v and $\dot{\phi}$ mentioned above then enable the velocity and direction of motion of the particle at the Earth's surface to be found in terms of the latitude and the constants defining the particle and the Earth. Most of Huxley's results relating to intensity of the radiation, etc., depend on the above assumption. Concerning this, Huxley merely says (Reference 1, p. 977): "as, however, the particles approach the Earth radially over the greater part of their orbits, it is evident that $\dot{r}\ll r\dot{\theta}$ throughout the motion."[3] However, this hardly seems enough; certainly the *initial* motion is radial, but the action of the magnetic field will gradually impart θ- and ϕ-components to the velocity, and there does not seem to be any evident reason why the former should be negligible compared with the latter.

We can, in fact, show that the assumption is in general wrong in the following manner: the complete equations (after elimination of $\dot{\phi}$) can be reduced to the form

$$\dot{r}^2+r^2\dot{\theta}^2=c^2[1-(m_0/m)^2]-(e\mu\sin\theta/cr^2m)^2, \qquad (1)$$

$$d(mr^2\dot{\theta})/dt=-e^2\mu^2\sin\theta\cos\theta/c^2r^4m, \qquad (2)$$

where
$$m=m_0+eQ/c^2r, \qquad (3)$$

in which e, m_0 are the charge and rest-mass of the particle, and Q, μ the charge and magnetic moment of the Earth. These equations are given implicitly by Huxley.

We further assume, with Huxley,

$$|Q|>|\mu|/a\ll m_0c^2a/|e|, \qquad (4)$$

where a is the Earth's radius; the first part of (4) is necessary for particles to reach the magnetic equator, and the second part is true for electrons or (less so) for protons. We now integrate (1) and (2) approximately under the assumption $r\dot{\theta}\ll\dot{r}$. We may then neglect $\dot{\theta}$ in (1). Then writing $d/dt=\dot{r}d/dr$ in (2) and substituting for $\dot{r}$ from (1), we obtain

$$d(mr^2\dot{\theta})/dt=-(e^2\mu^2\sin\theta\cos\theta/cr^2)$$
$$\times[e^2Q^2r^2+2m_0c^2eQr^3-e^2\mu^2\sin^2\theta]^{-\frac{1}{2}}. \qquad (5)$$

Denoting by a suffix E the value of a quantity taken at the Earth's surface $(r=a)$, $(mr^2\dot{\theta})_E$ is then given by integrating the righthand side of (5) with respect to r from ∞ to a. In this integration, θ may be given an approximately constant mean value because of our assumption $r\dot{\theta}\ll\dot{r}$, and further (4) shows that the second term in the square root