Further Evidence for a Single Component in the Primary Cosmic Radiation

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In former communications,[1–4] the writer has given reasons to suppose that there is *no electron component to the primary cosmic radiation*, that the mesotrons are secondary to primaries, and that the only electrons in the atmosphere are secondary to the mesotrons.[5] He has pointed out, moreover, that insofar as mean life considerations are more potent than energy loss in determining variation of mesotron intensity with altitude, such variation in intensity should follow approximately an exponential law with a *single coefficient* when plotted against *true distance*. When intensity is plotted against *water equivalent* distance, the curve becomes compressed parallel to the distance axis in such a manner that the result is an apparent increase of absorption coefficient with altitude.[3]

The purpose of the present communication is to add further evidence in support of the foregoing views. Our interest concerns that region of the atmosphere which lies below the altitudes at which the approach to a maximum is felt.[6]

Figure 1 gives measurements made by W. F. G. Swann and W. E. Danforth.[7] In curve A, $\log_{10} I/I_0$, the logarithm of the ratio of intensity to that at sea level is plotted against *true altitude in kilometers*. In curve B, $\log_{10} I/I_0$ is plotted against water equivalent altitude. The constancy of the slope of A bears out the conclusions cited above, and the change of slope of B shows how, on a water equivalent basis, the existence of an increase of absorption coefficient with altitude, and a consequent existence of more than one component, is simulated.

If x represents true altitude in kilometers, and $I=I_0 \exp[-\mu x]$ we obtain, from the slope of A, $\mu=0.156 \times 2.3=0.36$. Now if v is the velocity of the mesotrons, and t the time to travel the distance x, we may write $\mu x=\mu vt =0.36\times 3\times 10^5 t=10^5 t$ where we have assumed v equal to the velocity of light for purely kinematical purposes. Thus $I=I_0 \exp[-10^5 t]$.

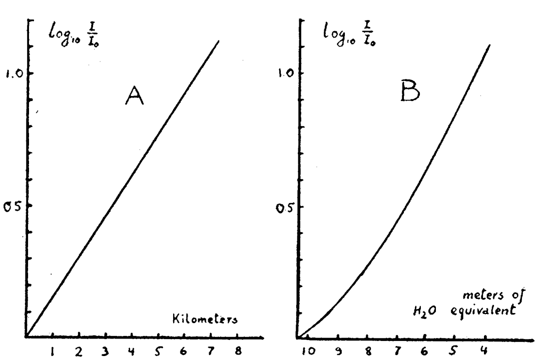

Fig. 1. A—intensity variation *vs.* true altitude; B—intensity variation *vs.* water equivalent altitude.

If the rays disappeared simply by mean life considerations, we should have $I=I_0 \exp[-t/\tau]$ where τ is the mean life. A comparison of these two expressions gives $\tau=10^{-5}$ sec. If the mean life for a stationary mesotron is 10^{-6} sec., this tells us that the mesotrons would have to have a mass 10 times the rest mass, which would give them an energy of 10^9 ev. If we should assume Yukawa's value 5×10^{-7} sec. for the mean life for a mesotron at rest, the corresponding energy would be 2×10^9 ev. This value is sufficiently near the probable average value of the energy of the mesotrons to provide support to the foregoing views. A distribution of energy introduces a distribution of apparent absorption coefficients, but high energies give small absorption coefficients, and the story provided by energy distribution for high energies concerns increase of hardness for great depths, where, of course, disappearance of rays by energy absorption becomes more important.

[1] W. F. G. Swann, Phys. Rev. **56**, 209 (1939).
[2] W. F. G. Swann, Rev. Mod. Phys. **11**, 242 (1939), (see in particular pp. 251–254).
[3] W. F. G. Swann, Phys. Rev. **58**, 200 (1940).
[4] W. F. G. Swann, Phys. Rev. **59**, 770 (1941).
[5] Further evidence to support these views has also been supplied by M. Schein, W. P. Jesse and E. O. Wollan, Phys. Rev. **59**, 615 (1941).
[6] The maximum becomes accounted for on the old and new views, but in slightly different fashion.
[7] W. F. G. Swann and W. E. Danforth, J. Frank. Inst. **228**, 43 (1939).

The Stable Isotopes of Nickel

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The relative abundances of the nickel isotopes have been measured by a large number of workers.[1–5] In these results discrepancies exist either between the various values of the ratio $Ni^{61} : Ni^{64}$, or between the atomic weight calculated therefrom and the chemical value.

The present results were obtained in August 1940, with the type of mass spectrometer in which an initially monoenergetic ion beam is passed through a semicircular magnetic momentum analyzer, the emergent ion current being proportional to the isotopic abundance. Ions were

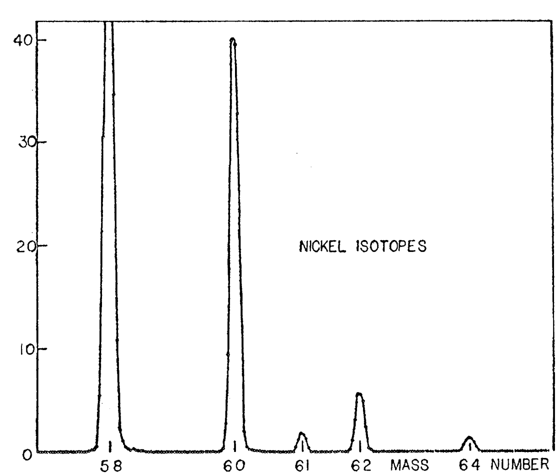

FIG. 1.

formed by electron bombardment of a beam of Ni vapor obtained from a hot, nickel-plated platinum wire. The nickel was especially purified for the experiment.

Figure 1 shows a typical mass spectrum of nickel and serves to demonstrate that no corrections were necessary due to incomplete resolution. The values obtained are:

Ni	58	60	61	62	64
	67.4	26.7	1.2	3.8	0.88

From the nickel masses of Okuda *et al.*[6] and the oxygen ratio 1.000275,[7,8] the value 58.71 ± 0.02 is obtained for the chemical atomic weight. This agrees within the experimental error with the chemical value 58.69 ± 0.01.[9] The ratio Ni^{61} : Ni^{64} obtained here is in agreement with the recently published value of Straus,[5] and in approximate agreement with the photographic results of Dempster.[4]

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Radiative Collision of Neutrons with Protons

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As is well known, capture with radiative emission and elastic scattering are the principal collision processes of neutrons with protons. Although the capture process is known to be predominant only in the narrow range of very slow neutron energies, elastic scattering will probably play an important role over a wide range in the primary neutron energy owing to the larger contribution to the cross section of the partial waves with relatively high angular momenta. For very high neutron energies, however, we must consider the possibility of radiative emission in the collision of neutrons with protons, since the protons set in motion during the collision are capable of emitting radiation. In order to find the order of magnitude of the cross section, we have worked out such a radiative collision of heavy particles. The process is similar to that of the radiative scattering (bremsstrahlung) of charged particles in an atomic field. The calculation, therefore, has been treated in a similar manner to that of the bremsstrahlung of charged particles.

For the nuclear interaction between neutron and proton we have assumed, as usual, a static potential with an exchange operator of short range,

$$V = -V_0(e^{-\lambda r}/r)\mathrm{O}, \tag{1}$$

in which O is the exchange operator (Heisenberg's or Majorana's), r the mutual distance, $\lambda = mc/\hbar$ the reciprocal Compton wave-length of a meson, and V_0 the constant dependent upon the depth of the potential. As a preliminary, the motion of heavy particles has been treated nonrelativistically,[1] the radiative emission induced by the magnetic dipole moment of a neutron being neglected, and, further, we have used Born's approximation.

For the case that the neutrons with a given momentum $\mathbf{p}_N{}^0$ and an energy $E_N{}^0$ impinge upon protons initially at rest, we have obtained the following expression for the differential cross section:

$$d\phi = \frac{1}{\pi^2}\frac{e^2}{\hbar c}\left(\frac{V_0}{c}\right)^2 \frac{d\hbar\nu}{\hbar\nu} d\Omega_\nu d\Omega_P \frac{\sin^2\theta}{p_N{}^0} \times \left\{ p_P{}^5 \Big/ \left[p_P{}^2 - M\hbar\nu\left(1 + \frac{\hbar\nu}{2Mc^2} - \frac{p_N{}^0}{Mc}\cos\theta'\right)\right] \left(1 - \frac{\hbar\nu}{2Mc^2} - \frac{p_P}{Mc}\cos\theta\right)^2 \times (\lambda^2\hbar^2 + p_N{}^{02} - 2M\hbar\nu - p_P{}^2)^2 \right\}, \tag{2}$$

in which $\hbar\nu$ = the emitted quantum, M is the mass of a heavy particle, $\cos\theta = (\mathbf{k}_\nu \cdot \mathbf{p}_P)/k_\nu p_P$, $\cos\theta' = (\mathbf{k}_\nu \cdot \mathbf{p}_N{}^0)/k_\nu p_N{}^0$ $\cdot \hbar\mathbf{k}_\nu$ and $\mathbf{p}_P$ represent the momenta of the photon and recoil proton, respectively. $d\Omega_\nu$ and $d\Omega_P$ are their elements of solid angle. According to the conservation equations of energy and momentum, p_P is found to depend upon θ, φ and θ' if the primary energies of the colliding neutron and of the emitted quantum are known. For the special case that $\hbar\nu/Mc^2 \ll 1$ and $p_N{}^0/Mc < 1$, the bracket expression in (2) may be shown to depend on the angles through the function p_P only.

For an estimate of the order of magnitude of the total cross section ϕ_ν for the emission of a quantum between $\hbar\nu$ and $\hbar\nu + d\hbar\nu$, it is sufficient, in the above approximation, to consider the average value $[2M(E_N{}^0 - \hbar\nu)]^{-\frac{1}{2}} \cdot g$ of the reduced bracket expression in $d\phi$, taking into account that p_P varies from 0 to $(p_N{}^{02} - 2M\hbar\nu)^{\frac{1}{2}}$.

Then, integrating $d\phi$ over all angles, we get

$$\phi_\nu \sim \frac{e^2}{\hbar c}\left(\frac{V_0}{c}\right)^2 \frac{1}{2M}\frac{d\hbar\nu}{\hbar\nu}\frac{g(E_N{}^0, \hbar\nu, mc^2)}{E_N{}^0}\left(1 - \frac{\hbar\nu}{E_N{}^0}\right)^{-\frac{1}{2}}, \tag{3}$$

where g is a rather lengthy expression dependent upon $E_N{}^0$, $\hbar\nu$ and mc^2, which reduces to $(E_N{}^0 - \hbar\nu)/(m^2c^2/2M)$ for $E_N{}^0 \gg \hbar\nu$.

For neutrons of 10^8 electron volts energy, the above formula gives a cross section of less than 10^{-30} cm^2 for the emission of γ-rays of 10^6 electron volts. The corresponding cross section for the bremsstrahlung of an electron in the Coulomb field of a proton is found to be less than 10^{-25} cm^2, being very large compared with that of the former process. This is to be expected owing to the very short range of the nuclear force and the relatively large mass of a proton. Since the cross section for elastic scattering becomes[2] approximately 10^{-26} to 10^{-27} cm^2 for these neutron energies, the radiative collision of heavy particles may be reasonably neglected in the study of neutron scattering by protons. In connection with cosmic-ray phenomena, however, it seems desirable to calculate the cross section of this process for extremely high neutron energies.[1]

[1] The relativistic calculation, based upon the present meson theory, of the radiative collision of heavy particles is now in progress; a full account will be published elsewhere, together with details of this work.

[2] H. A. Bethe and R. F. Bacher, Rev. Mod. Phys. **8**, 122 (1936).