Radioactivity of Be^7

As reported at the Washington meeting of the American Physical Society[1] we have obtained evidence for the formation of Be^7 in the reaction $Li^6+H^2\rightarrow Be^7+n$. At that time we had found that there was no radioactive emission of charged particles. We have since discovered a gamma-ray radioactivity with a 43-day half-life in lithium targets which have been bombarded by deuterons. Further experiments indicate that the gamma-ray activity originates in K electron capture by Be^7 which leaves the residual Li^7 nucleus in the 450-kv excited level.

The activity was first observed in a LiF target which had been bombarded a month previously with 35 microampere hours of 1000-kv deuterons. Similar activity was subsequently produced by bombarding a lithium metal target with 20 microampere hours of 1000-kv deuterons. The activity was followed for a month and showed a half-life of 43 ± 6 days. The absorption-coefficient in lead was 0.169 g cm^{-1}. No charged particles could be detected either by thin-walled counters, by ionization chambers, or by placing the sample in a cloud chamber, although the gamma-ray counting rate indicated the emission of more than 100 quanta per second.

The surface of the target (in which the activity was concentrated) was scraped off and subjected to a chemical separation, carried out by Dr. M. H. Van Horn of George Washington University. The activity was concentrated in the final precipitation of 100 micrograms of beryllium carbonate which had been added as a carrier. The separation would not, however, remove iron or aluminum. As iron also shows a 40-day period, we bombarded an iron target and looked for a similar gamma-ray. The iron impurity necessary to produce the observed gamma-rays from the lithium targets is greater than 100 percent.

Although we were not able to detect the alpha-particle group produced in the reaction[1] $B^{10}+H^1\rightarrow Be^7+He^4$, we have since observed a long period gamma-ray activity from a B_4C target which had been bombarded with 11 microampere hours of 950-kv protons. The intensity of the radiation was 25 percent less than that produced in the lithium metal target. Its absorption-coefficient was also 0.169 g cm^{-1}. We therefore ascribe both this activity and that produced in the lithium targets to Be^7.

This unusual type of radioactivity could originate in two nuclear reactions. Either a positron is emitted with so little energy that it does not ionize appreciably and is detected only by the annihilation radiation, or a K electron is captured and the residual nucleus is left in an excited state. In the latter case the average number of quanta per disintegration is less than one because there exists the alternative process of capture in which the nucleus is left in the ground state. Assuming as usual that a neutrino is emitted, these reactions may be written:

$$Be^7\rightarrow Li^7+e^++\eta$$
$$e^++e^-\rightarrow h\nu+h\nu \qquad h\nu=0.5 \text{ Mev}$$
$$Be^7+e_k^-\rightarrow Li^7+\eta \qquad \text{neutrino energy}=E \text{ Mev}$$
$$Be^7+e_k^-\rightarrow Li^{7*}+\eta \qquad \text{neutrino energy}=E-0.45 \text{ Mev}$$
$$Li^{7*}\rightarrow Li^7+h\nu \qquad h\nu=0.45 \text{ Mev}$$

The absorption-coefficient in lead of the gamma-rays from the lithium targets and of the annihilation radiation of the positrons from N^{13} were measured under idential conditions and were observed to be 0.169 ± 0.008 and 0.130 ± 0.002 g cm^{-1}, respectively. This indicates that the energy of the radiation is 425 ± 25 kv, which agrees well with the energy expected from K electron capture but differs from the energy of annihilation radiation.

A comparison of the numbers of quanta observed per neutron emitted from the carbon and lithium targets gives additional information about the process. Li^6 and Li^7 are (per atom) equally effective in producing neutrons at 800 kv and the yield curves for the two reactions are known.[2] The energy distribution of the neutrons from Li^6 shows that approximately one atom of Be^7 is formed for every two neutrons emitted. In carbon one neutron is emitted for each N^{13} atom formed. The comparison of the number of neutrons emitted by lithium and carbon has been made by Amaldi, Hafstad, and Tuve.[3] Thus the relative numbers of Be^7 and N^{13} atoms can be calculated. Assuming two quanta per N^{13} we find that, on the average, one quantum is emitted for each 10 Be^7 atoms produced. Positron-emission should lead to a gamma-ray intensity 20 times greater than that observed. On the other hand the data are consistent with the hypothesis of K electron capture, because in this case transitions to the ground state should be more probable than transitions to excited levels.

As a final check we have looked for double coincidence counts. No appreciable change in the background rate of 0.8 per minute was observed although the simultaneous emission of two quanta at 180°, which would be expected if positron annihilation occurred, should increase the rate by at least a factor of three.

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[1] R. B. Roberts and N. P. Heydenburg, Abstract No. 78, 1938 Washington Meeting American Physical Society.
[2] L. H. Rumbaugh, R. B. Roberts, and L. R. Hafstad, to be published shortly in Phys. Rev.
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The Transmutations of the Cosmic-Ray Electrons and the Nuclear Forces

The "transmutations of mass" (i.e., the changes of the rest mass) of the electrons probably play an important role in the passage of cosmic rays through the atmosphere. Thus according to Blackett[1] the cosmic-ray particles at sea level are heavy when energetic, but change their mass suddenly when slowed down below a critical energy of about $2\text{–}3\cdot10^8$ ev and become ordinary electrons. According to Bowen, Millikan and Neher[2] the penetrating heavies are mainly secondaries produced in the atmosphere by incoming electrons and photons. However this conclusion, does not necessarily follow from the data of the authors mentioned;

these data are consistent also with the assumption of a primary character of the penetrating heavies.

No adequate mechanism has been suggested up to now for these transmutations of mass. The suggestions of Jauncey[3] and Bhabha[4] can be shown to be untenable. The creation of heavy pairs by photons does not account for the disappearance of the slowed down heavies. Youkawa's hypothesis of a spinless heavy electron seems to lead to difficulties[5] and will not be considered by us.

Considerations connected with the principle of detailed balance and also with the probable dependence of the cross section for transmutation on the atomic weight of the substance traversed, seem to indicate, that the heavies are stable in absence of atomic nuclei and that the transmutation of mass can be induced only by a nonelectromagnetic short range interaction of an electron with protons and neutrons.

Let us assume, that this interaction is of the δ-type and corresponds to terms of the form

$$\psi_k^x \psi_e \Psi^x \Psi \tag{1}$$

in the Hamiltonian, where ψ_k and ψ_e are the wave functions of electrons of mass km_0 and lm_0, respectively, and Ψ the wave function of a proton or a neutron.

Consider an electron of mass m_1 and energy E hitting a nucleus and scattered by it with a modified mass m_2. If the recoil of the nucleus is neglected

$$E = c(m_1^2c^2 + p_1^2)^{\frac{1}{2}} = c(m_2^2c^2 + p_2^2)^{\frac{1}{2}}, \tag{2}$$

where p_1 and p_2 are the momenta of the incident and the scattered electrons.[6]

The cross section σ for the transmutation $m_2 \rightarrow m_1$ differs from that for the transmutation $m_1 \rightarrow m_2$ by the factor

$$\frac{p_1^2}{p_2^2} = \frac{E^2 - m_1^2c^4}{E^2 - m_2^2c^4},$$

so that it is sufficient to consider only the case for which (for instance) $m_1 < m_2$. In this case σ vanishes for $E < m_2c^2$ and then increases with increasing E somewhat faster than E^2. But when the wave-length of the electron becomes comparable with the nuclear radius ($E \backsim A^{-\frac{1}{3}} \cdot 7 \cdot 10^7$ ev, where A is the atomic weight) the interference of the partial waves scattered by different particles of the nucleus makes σ tend with increasing E to a constant "stationary" value σ_{st} and also ensures the preponderance of the forward scattering. σ_{st} is proportional to $A^{4/3}$. But if E exceeds about $2 \cdot 10^8$ ev the recoil of the nuclear particles can no longer be neglected, since the recoil energy exceeds their binding energy (if the angle of scattering is not very small). In consequence σ will again begin to increase in proportion to E^2. Hence, as long as σ has at $E = 10^{10}$ ev any reasonably moderate value, its value at $E \lessapprox 5 \cdot 10^8$ ev must be quite negligible.

However, in the domain of very high energies the validity of the above calculations becomes questionable. It is known, that interactions of the type considered lead to divergent results even in such approximations, which can be satisfactorily treated by the present quantum electrodynamics. Thus the interaction under consideration implies the possibility for a neutron or a proton to create a pair, the electron and the positron of the pair having eventually different masses. Hence there must exist certain forces between neutrons and protons which correspond to the exchange of pairs between these particles. But if one tries to evaluate in the first approximation the energy $\vartheta(r)$ of this interaction one gets a divergent result, even if the separation r of the interacting particles is finite.[7]

In absence of any better theory let us introduce in the interaction operator (1) some "guillotine factor," e.g. the factor $e^{-\tau(p_k+p_l)}$; p_k and p_l are the momenta of the electrons of mass km_0 and lm_0, measured in that reference system, in which the nucleus is at rest. This factor makes the energy $\vartheta(r)$ finite: at large distances $\vartheta(r)$ varies as r^{-5}, but tends to a finite value $\vartheta(0)$ as r tends to zero.

But the guillotine factor will affect also the cross section for the scattering of electrons with transmutation of mass. No such factor is needed in the case of the Coulomb scattering since for the latter only distant encounters are essential, while the guillotine factor accounts in some very crude manner for the finite size of the interacting particles. On account of this factor the probability of transmutations of energetic electrons will become very small, but, if $\tau = 400\ m_0c$, it will rapidly increase as the electrons are slowed down to about $3 \cdot 10^8$ ev and at $E \backsim 2 \cdot 10^8$ ev σ will reach the "stationary" value defined above. This is in accordance with Blackett's measurements.

With this value of τ one gets for the energy of interaction of nuclear particles a reasonable estimate $\vartheta(0) \backsim -3N^2(\sigma_{st}^{\text{air}} \cdot 10^{25}) \times 10^6$ ev where σ_{st}^{air} is the "stationary" value of σ in air expressed in cm^2, and N the number of allowed values of the mass km_0 of an electron. The sign and the spin dependence (if any) of $\vartheta(0)$ are correct.

The possibility of explaining the nuclear forces by the exchange of pairs between neutrons and protons has already been suggested by Gamow and Teller[8] and by Wentzel,[9] who, however, considered only ordinary electrons ($m = m_0$) and were unable to establish any connection between the proposed explanation of nuclear forces and other physical phenomena. As pointed out by these authors, the forces due to the exchange of pairs do not depend on the electric charge of the nuclear particles and are consistent with Wick's explanation of the magnetic moment of the neutron. The only serious difficulty is that they apparently do not possess saturation properties.

A more detailed communication will appear in *Comptes Rendus Acad. Sci. U. S. S. R.*

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[1] Blackett, Proc. Roy. Soc. **164**, 1 (1938).
[2] Bowen, Millikan and Neher, Phys. Rev. **53**, 217 (1938).
[3] Jauncey, Phys. Rev. **52**, 1256 (1937).
[4] Bhabha, Proc. Roy. Soc. **164**, 257 (1938).
[5] Serber, Phys. Rev. **53**, 211 (1938).
[6] In lectures held in Moscow and Leningrad in February I suggested that some of the cloud chamber tracks which apparently violate the conservation of energy may be explained on the basis of Eq. (2) Afterwards I learned that Zwicky also suggested a similar explanation cf., Phys. Rev. **53**, 315 and 611 (1938).
[7] Although the integration may be arranged in such a way as to give a finite result at finite r's, still if one performs the integrations in a somewhat different succession the integrals do diverge even at finite r's. The reason at the bottom of this is that the interaction corresponds to the exchange of *pairs* of particles, and not of separate particles.
[8] Gamow and Teller, Phys. Rev. **51**, 289 (1937).
[9] Wentzel, Helv. Phys. Acta **10**, 107 (1937).