Excitation of Nuclei by Bombardment with Charged Particles

Charged particles are able to excite nuclei without penetrating into the nucleus by means of the action of their electric field upon the nucleus when they pass nearby. The cross section for such a process can be calculated and is surprisingly large. An approximate expression for the cross section for the excitation of a transition from a level A with the orbital momentum $l=0$ to another level B with $l=L\geqq 2$ is given by

$$\sigma_L \cong \frac{16\pi^2}{(2L+1)}\frac{L}{(2L-1)(2L-2)} \cdot \frac{1}{Z^2}\frac{E'^2}{E^2}\left(\frac{\hbar v'}{2zZe^2}\right)^{2L-4}\frac{(Q_{AB})^{2L}}{\lambda\lambda'^{2L-3}}. \quad (1)$$

Here E and $2\pi\lambda$ are the energy and wave-length of the incident particle of charge ze; E', $2\pi\lambda'$, v' are its energy, wave-length and velocity after the nuclear excitation. Ze is the charge of the nucleus, and Q_{AB} is given by:

$$(Q_{AB})^L = \sum_i \int \phi_A{}^* r_i{}^L \phi_B d\tau,$$

where r_i are the radial coordinates of the nuclear protons and ϕ_A and ϕ_B are the eigenfunctions, respectively, of the nuclear states A and of one of the $2L+1$ degenerate states B.

The expression (1) is valid only so long as E is less than the potential barrier: $E<E_0=zZe^2/\rho$ (ρ nuclear radius). If E is greater than that limit, σ_L is to be multiplied by

$$\frac{(2L-1)}{(2L-2)}\left(\frac{E_0}{E}\right)^{2L-2}\left(1-\frac{E_0}{(2L-1)E}\right). \quad (2)$$

The exact formula for σ_L contains rather complicated expressions with E, E' and L and will be presented together with the derivation of (1) in a paper by M. S. Plesset and the present author which will appear shortly in the *Physical Review.*

The cross section σ_2 for the excitation of *one* quadrupole transition with an excitation energy of 1 Mev in a nucleus $Z=50$ by means of a proton of 6 Mev is according to (1): $\sigma_2=0.5\cdot 10^{-26}$ if one assumes $Q_{AB}=5\cdot 10^{-13}$. The cross sections for $L>2$ are much smaller. The dipole transitions which are not included in (1) are also very weak because of the smallness of nuclear dipole moments. The numerical values obtained by (1) are extremely sensitive to the value of Q_{AB}. The order of magnitude of Q_{AB} is deduced from γ-ray evidence.

It is possible to estimate the total excitation cross section; i.e., the sum of all cross sections for any possible excitation in a heavy nucleus. If the density of levels with $l=2$ is given by $\omega(E)$, the total cross section for excitation of a nucleus by means of a charged particle of an energy E is approximately (apart from the factor (2) if $E>E_0$)

$$\sigma_2{}^{\text{total}} = 5^{1/2}\pi^{5/2}\frac{1}{Z^2}\frac{E'^2}{E^2}\frac{Q^4}{\lambda\lambda'}T(E)\cdot\omega(E-E').$$

Here $E'=(5/2)T(E)$ and $2\pi\lambda'$ is the corresponding wave-length. The temperature $T(E)$ is given by $1/T=d\lg\omega/dE$ and $(E-E')$ is the average excitation energy of the nucleus after collision. Q is to be considered as the average value of the quadrupole moments corresponding to all possible transitions. One gets for the total excitation cross section of a nucleus with $Z=50$ with α-particles of 14 Mev: $\sigma_2{}^{\text{total}}\cong 3\cdot 10^{-25}$ and a mean excitation energy of 10 Mev. An expression is used here for the level density given by Bethe[1] and Weisskopf,[2] and Q is taken equal to $0.4\cdot 10^{-13}$. This value of Q is computed from the radiation breadth of neutron capture levels. These results have to be considered as a rough estimate of the order of magnitude because of the uncertainty of the value of Q and $\omega(E)$.

The process described here may be of some interest for the investigations of nuclear excitation levels. Furthermore, after bombardment of nuclei with charged particles of high energy ($E>8$ Mev) one should expect that the excited nucleus emits a particle so that one gets processes of the kind $(p-p, n)$, or $(p-2p)$. This effect may be of some importance in bombardments of heavy nuclei; processes such as $(p-p, n)$, $(d-d, n)$, $(\alpha-\alpha, n)$ are not to be expected after penetration of the projectile into the nucleus since the re-emission of a charged particle by the compound nucleus is much less probable than the emission of neutrons.[2, 3] These reactions could, however, be produced in the way described here.

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[1] H. A. Bethe, Phys. Rev. **50**, 332 (1936).
[2] V. F. Weisskopf, Phys. Rev. **52**, 295 (1937).
[3] E. J. Konopinski and H. A. Bethe, Phys. Rev. in press.

Heavy Electrons and β-Decay

Yukawa[1] has shown that nuclear forces of the correct magnitude and range can be accounted for by assuming the existence of new charged particles of mass about 137 times that of an electron and of zero spin. These heavy electrons have recently been observed[2] in expansion chamber photographs of cosmic rays and have consequently brought Yukawa's theory to general notice. If the heavy electron were formed from an electron and a mass-less neutrino it should be extremely unstable and should dissociate with the liberation of energy equal to 136 mc^2. It is difficult to see how it could ever exist long enough to be observed in cosmic rays. We can get over this difficulty by assuming the heavy electron to be formed from an electron and a "heavy neutrino" of mass 136 and spin $\frac{1}{2}$. It might now be possible to do away entirely with the conception of the mass-less neutrino, for it is evident that the emission of one of these heavy electrons obeying Bose statistics in β-disintegration would satisfy the statistical requirements of the nucleus. If this heavy electron then disintegrated into an electron and a heavy neutrino while still close enough to the nucleus to interact with it the continuous energy distribution of the β-rays would be qualitatively accounted for.

Bhabha[3] has pointed out that if the disintegration of the heavy electron is spontaneous it may be regarded as a "clock," and hence it follows merely from relativity considerations that the time of disintegration is longer the greater the velocity of the particle. A heavy electron of mass 137 formed as suggested above from an electron and a heavy neutrino of mass 136 would be just on the point