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 ½. 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 of instability since it would have no mass defect. It is of interest, therefore, to see if its much greater velocity in cosmic rays would increase its time of dissociation sufficiently to enable it to be observed.

If t_0 is the time of disintegration of the particle at rest and t the time when it is moving with velocity $v=\beta c$ we have

$$t=t_0/(1-\beta^2)^{\frac{1}{2}}.$$

From the relativistic energy equation

$$eV=300\ mc^2[(1-\beta^2)^{-\frac{1}{2}}-1],$$

it follows that the relative times of disintegration of two particles having energies V_1 and V_2 e-volts is given by

$$t_2=t_1\frac{V_2+300\ mc^2/e}{V_1+300\ mc^2/e},$$

where m is the mass of the particle, here equal to 137 times the mass of an electron, and $300\ mc^2/e=7\times10^7$. The relative distances traveled before disintegration is then given by $d_2=d_1v_2t_2/v_1t_1$.

Taking the mean energy of the end-points of β-decay spectra to be 10^6 e-volts I find that the ratio of the distance traveled by a cosmic heavy electron of 10^{12} e-volts energy to that traveled by a β-decay heavy electron before spontaneously disintegrating is 10^5. To account for the continuous energy distribution of β-rays the heavy electron would have to dissociate while still close enough to the nucleus to interact with it, so that this figure of 10^5 is hardly great enough to allow the heavy electron to be observed in cosmic rays, unless the interaction with the nucleus caused the slower β-ray heavy electron to be dissociated in a time much shorter than its time of spontaneous disintegration. Crane[4] has reported that in the course of some cloud chamber experiments a few β-particles appeared to behave in an anomalous way for which no satisfactory interpretation could be found. Zwicky[5] also has drawn attention to some peculiar cloud chamber tracks which, in his view, may be due to the electron suddenly changing its rest mass. This is just what would be observed if a β-decay heavy electron disintegrated spontaneously outside the atom, the probability of dissociation of the particle by interaction while it is still close to the nucleus is not quite unity.

Corben[6] has suggested that the heavy electron may be formed by the combination of an electron with one of Eddington's neutral particle ($\frac{1}{4}$ of a scalar particle) which has a mass 135.9. He considers this occurs with the emission of a neutrino. In Eddington's theory,[7] however, the neutral particles have no objective existence: they form a background consisting of the unspecified particles of the universe. The highest energy level of this background represents the ground level of the "object system" to which the vector wave functions of quantum theory apply: the scalars apply to the background which forms the reference frame. The neutral particles of the background, which are all below the ground level of the object system, are therefore in negative energy states. It is a *vacancy or hole* in the background that manifests itself as a particle in the object system.

If the neutron→proton transition in the nucleus interacts with the background as I have suggested,[8] and causes an electron to be created, the hole left in the background will represent the creation of a neutral particle with spin $\frac{1}{2}$, which could then combine with the electron to form a heavy electron which obeys Bose statistics, as is suggested above. The hole must represent an uncharged particle of spin $\frac{1}{2}$ for charge and spin to be conserved among the particles of the object system. On this view the heavy electron is created by the neutron→proton transition in the atom.

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May 14, 1938.

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Some Results of the Search for Super-Novae

Some time ago Baade and I discussed the existence of a new class of novae which surpass the common novae in luminosity by a factor of one thousand.[1,2] We proposed to call these new stars *super-novae*, a designation which is now in general use. It should be emphasized, however, that super-novae in some respects differ fundamentally from ordinary novae.

In our original communications[1,2] we made a first tentative attempt to estimate how often super-novae appear in an average nebula. From a considerable, though very heterogeneous set of records from various sources extending over the past fifty years we concluded that the frequency of occurrence of super-novae in an average nebula is of the order of one per several centuries. We also suggested that the study of super-novae promises to throw new light on the problem of the generation of energy in stars and perhaps on the origin of the cosmic rays. In conjunction with considerations concerning the tremendous liberation of energy in super-novae we suggested the formation of *collapsed neutron stars*[1,2] as the most powerful source of energy.

These suggestions clearly reveal the great potentialities of a study of super-novae. We decided that no effort should be spared to track down and to study in detail as many as possible of these rare objects. Several seasons of unsuccessful work with unsatisfactory telescopic equipment preceded a period in which the greatest advance was made with the aid of the 18-inch $f:2$ Schmidt telescope which had been built in the meantime with the authorization of the observatory council of the California Institute of Technology.

In the period from September 5, 1936 until January 31, 1938, about six hundred excellent photographs covering seventy square degrees each were obtained with the Schmidt telescope. The resulting search is equivalent to the continuous control during one year of about 1800 nebulae whose apparent brightness is greater than $m=15$. Since three super-novae were discovered in the period mentioned, the resulting frequency is one *super-nova per average nebula* of our collection *in a period of six hundred*