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TRANSMUTATIONS OF ATOMIC NUCLEI[1]

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It has been pointed out on an earlier occasion[2] that in order to understand the typical features of nuclear transmutations initiated by impacts of material particles it is necessary to assume that the first stage of any such collision process consists in the formation of an intermediate semi-stable system composed of the original nucleus and the incident particle. The excess energy must in this state be assumed to be temporarily stored in some complicated motions of all the particles in the compound system, and its possible subsequent breaking up with the release of some elementary or complex nuclear particle may from this point of view be regarded as a separate event not directly connected with the first stage of the collision process. The final result of the collision may therefore be said to depend on a competition between all the various disintegration and radiation processes from the compound system consistent with the conservation laws.

A simple mechanical model which illustrates these features of nuclear collisions is reproduced in Fig. 1, which shows a shallow basin with a number of billiard balls in it. If the bowl were empty, then a ball which was sent in would go down one slope and pass out on the opposite side with its original energy. When, however, there are other balls in the bowl, then the incident one will not be able to pass through freely but will divide its energy first with one of the balls, these two will share their energy with others, and so on until the original kinetic energy is divided among all the balls. If the bowl and the balls could be regarded as perfectly

[1] Abstract of lectures given in the spring of 1937 at various universities in the United States. The illustrations are reproductions of three slides shown in these lectures.
[2] N. Bohr, *Nature*, 137: 344, 1936.

smooth and elastic, the collisions would continue until a sufficiently large part of the kinetic energy happened again to be concentrated upon a ball close to the edge. This ball would then escape from the basin, and if the energy of the incident ball were not very large, the remainder of the balls would be left with insufficient total energy for any of them to climb the slope. If, however, there were even a very small friction between the balls and the basin or if the balls were not perfectly elastic, it might very well happen that none of the balls would have a chance to escape before so much of the kinetic energy were lost as heat through friction that the total energy would be insufficient for the escape of any of them.

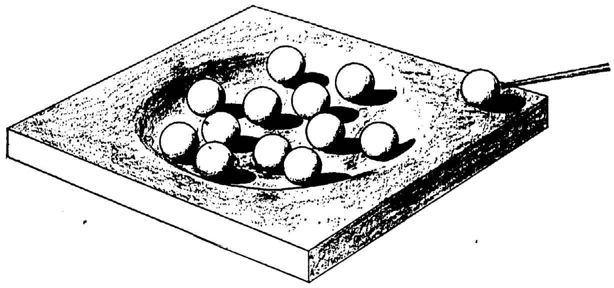

FIG. 1

Such a comparison illustrates very aptly what happens when a fast neutron hits a heavy nucleus. On account of the large number of particles which in this case constitute the compound system and their strong interaction with one another, we must in fact expect from this simple mechanical analogy that the lifetime of the intermediate nucleus is very long compared with the time taken by a fast neutron to cross a nucleus. This explains, first of all, that although the probability for a heavy nucleus to emit electromagnetic radiation in such a time is extremely small, nevertheless there is on account of the long life of the compound nucleus a not quite negligible probability that the system instead of releasing a neutron will emit its excess energy in the form of electromagnetic radiation. Another experimental fact, which is easily understood from such a picture, is the surprisingly large probability of inelastic collisions, resulting in the emission of a neutron with a much smaller energy than the incident one. Indeed from the above considerations it is clear that a disintegration process of the compound system, which claims a smaller amount of energy concentrated on one single particle, will be much more likely to occur than a disintegration, in which all the excess energy has to be concentrated on the escaping particle.

At first sight such simple mechanical considerations might be thought to contradict the fact, so well established from the study of the radioactive γ-ray spectra, that nuclei like atoms possess a discrete distribution of energy levels. For in the above discussion it was essential that the compound system would be formed for practically any kinetic energy for the incident neutron. We must realize, however, that in the impacts of high-speed neutrons we have to do with an excitation of the compound system far greater than the excitation of ordinary γ-ray levels. While the latter at most amounts to a few million volts, the excitation in the former case will considerably exceed the energy necessary for the complete removal of a neutron from the normal state of the nucleus, which from mass defect measurements can be estimated to be about eight million electron volts.

Fig. 2 then illustrates in a schematic way the general character of the distribution of energy levels for a heavy nucleus. The lower levels, which have a mean energy difference of some hundred thousand volts, correspond to the γ-ray levels found in radioactive nuclei. For increasing excitation the levels will rapidly come closer to one another and will for an excitation of about 15 million volts, corresponding to a collision between a nucleus and a high-speed neutron, probably be quite continuously distributed. The character of the upper part of the level scheme is illustrated by the two lenses of high magnification placed over the level diagram, one in the above-mentioned

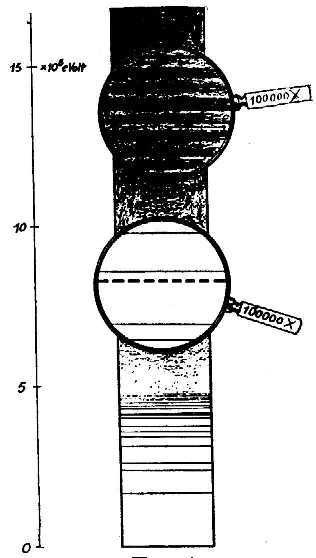

FIG. 2

region of continuous energy distribution and the other in the energy region corresponding to the excitation which the addition of a very slow neutron to the original nucleus would give for the compound system thus formed. The dotted line in the middle of the field of the lower magnifying glass represents the excitation energy of the compound nucleus when the kinetic energy of the incident neutron is exactly zero, and the distance from this line down to the ground state is therefore just the binding energy of the neutron in the compound system.

Information about the level distribution in the energy region near this line can be obtained from experiments on the capture of very slow neutrons with energies of a fraction of a volt. Thus if the kinetic energy of the incident neutron just corresponds to the energy of one of the stationary states of the compound system, quantum mechanical resonance effects will occur, which may give effective cross sections for capture of the neutrons several thousand times larger than ordinary nuclear cross sections. Such selective effects have actually been found for a number of elements, and it has further been found that the breadth of the resonance region in all these cases is only a small fraction of a volt.[3] From the relative incidence of selective capture among the heavier elements and from the sharpness of the resonances, it can be estimated that the mean distance of levels in this energy region is of the order of magnitude of about 10–100 electron volts. In the field of the lower magnifying glass in Fig. 2 there are indicated a number of such levels, and the circumstance that one of these levels is very close to the dotted line corresponds to the possibility of selective capture for very slow neutrons in this particular case.

The distribution of energy levels indicated in Fig. 2 is of a very different character from that with which we are familiar in ordinary atomic problems where on account of the small coupling between the individual electrons bound in the field round the nucleus the excitation of the atom can in general be attributed to an elevated quantum state of a single particle. The nuclear level distribution is, however, just of the type to be expected for an elastic body, where the energy is stored in vibrations of the system as a whole. For, on account of the enormous increase in the possibilities of combination of the proper frequencies of such motions with increasing values of the total energy of the system, the distance between neighboring levels will decrease very rapidly for high excitations. Indeed, considerations of the above character are well known from the discussion of the specific heat of solid bodies at low temperatures.

Thermodynamical analogies can also be applied in a fruitful way for the discussion of the disintegration of the compound system with release of material particles. Especially the case of emission of neutrons, where no forces extend beyond proper nuclear dimensions, exhibits a very suggestive analogy to the evaporation of a liquid or solid body at low temperature. In fact, it has been possible from the approximate knowledge of the level system of nuclei at low excitations to get an estimate of the "temperature" of the compound nucleus, which leads to evaporation probabilities for neutrons consistent with the lifetimes for the compound system in fast neutron collisions derived from the analysis of experiments.[4]

Fig. 3 illustrates the course of a collision between a fast neutron and a heavy nucleus. To follow the simple trend of the arguments, an imaginary thermometer has been introduced into the nucleus. As the figure shows, the scale on the thermometer is in billions of degrees centigrade, but in order to get a more familiar measure for the temperature energy, one has also added another scale to the thermometer showing the temperature in millions of electron volts. The figures give the different stages of the collision process. To begin with, the original nucleus is in its normal state and the temperature is zero. After the nucleus has been struck by a neutron with about ten million volts kinetic energy, a compound nucleus is formed with 18 million volts energy, and the temperature is raised from zero to

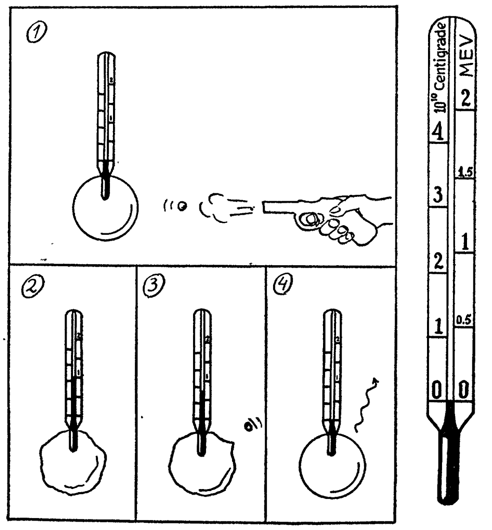

FIG. 3

roughly one million volts. The irregular contour of the nucleus symbolizes the oscillations in shape corresponding to the different vibrations excited at the temperature in question. The next figure shows how a neutron escapes from the system and the excitation, and accordingly the temperature, is somewhat lowered. In the last stage of the process the remaining part of the energy is emitted in the form of electromagnetic radiation and the temperature drops down to zero.

The course of the collision described above is the

[3] The phenomenon of selective capture of slow neutrons, which shows an interesting formal analogy with optical resonance, has especially been studied in a paper of G. Breit and E. Wigner (*Phys. Rev.*, 49: 642, 1936). Estimates from experimental evidence of the breadth of the levels were first given by O. R. Frisch and G. Placzek (*Nature*, 137: 357, 1936) and have been discussed in details in a recent paper by H. Bethe and G. Placzek (*Phys. Rev.*, 51: 450, 1937).

[4] The idea of applying for the probability of neutron escape from compound nuclei the usual evaporation formula was first proposed by J. Frenkel (*Sow. Phys.*, 9: 533, 1936). A more detailed investigation on the basis of general statistical mechanics is given in a paper by V. Weisskopf (*Phys. Review*, in print).

most probable one if the energy of the incident neutron is large, but for lower energies of the neutron the probabilities of escape and of radiation will become of the same order of magnitude, giving rise to a considerable probability for capture. If we finally go down to the region of very slow neutrons it is known experimentally that the probability for radiation is even very much larger than the probability of escape. It will, however, be clear that in this case the analogy between neutron escape and evaporation will be quite inadequate, because the mechanism of escape, like the formation of the compound system, involves here specific quantum mechanical features which can not be analyzed in such a simple way.

A quantitative comparison between ordinary evaporation and neutron escape can in fact be carried through only in case of excitation energies of the compound system, very large compared with the energy necessary for the removal of a single neutron, for only in this case will the excitation of the residual nucleus left after the escape of a neutron be nearly equal to that of the compound system, as is assumed in the usual evaporation phenomena where the change in the heat content of the bodies concerned during the escape of a single gas molecule is negligibly small. The above considerations can therefore be applied in this simple form only when the change in the temperature in going from the second to the third stage in Fig. 3 is comparatively small.

Although the conditions for the application of the evaporation analogy are in general not strictly fulfilled in the experiments on fast neutron impacts so far carried out, there are still a great number of more qualitative consequences derivable from the analogy, which are very useful in the discussion of such collision processes. For instance, the above-mentioned large probability of energy loss in collisions between fast neutrons and nuclei just corresponds to the fact, that the molecules released in ordinary evaporation do not take the whole energy of the hot body, but that they in general come off with the much smaller energy per degree of freedom corresponding to the temperature of the evaporating body. It should further be expected from the thermodynamic analogy that the released particles would have an energy distribution around this mean value which corresponds to the Maxwellian distribution. If the energy of the incident neutron is several times larger than the binding energy per particle, it can moreover be predicted that not one single particle but several particles, each with an energy small compared to that of the incident particle, will leave the compound system in successive separate disintegration processes. Nuclear reactions of this type have actually been experimentally found to take place in a number of cases.

The above considerations can also be applied to the release of charged particles like protons and α-particles from the compound system, but it must be kept in mind that in this case the latent heat of evaporation is not simply the binding energy of the charged particle, but that we have to add to this the electrostatic energy due to the mutual repulsion of the escaping particle and the residual nucleus. This repulsion will moreover have the effect of speeding up the particles after their escape from the nucleus, and the mean kinetic energy of the charged particles will thus be larger than that of the neutrons by an energy amount corresponding to this repulsion. We should, therefore, expect that the most probable energy of the emitted particles would be approximately equal to the sum of the temperature energy and the electrostatic repulsion, and that the probability for the emission of charged particles with still larger energies would, as in the case of neutrons, decrease exponentially according to a Maxwellian distribution. This preference for nuclear processes, where the escaping charged particle takes only a part of the available energy, leaving the residual nucleus in an excited state, is in fact one of the most striking features of a great number of reactions in which protons or α-particles are emitted from the compound system.

So far we have mainly been concerned with nuclear processes initiated by impacts of neutrons. Similar considerations concerning the formation of an intermediate state will, however, apply for collisions between charged particles and nuclei; but in this case it must be taken into account that the repulsive electric forces acting between the positively charged nuclei may often for small kinetic energies of the incident particle prevent or make less probable the contact necessary for the establishment of the compound nucleus. The combined action of this electrostatic repulsion of nuclear particles at great distances and their strong attraction at small distances can in fact be simply described by saying that the nucleus is surrounded by a so-called "potential barrier" which the incident charged particles have to pass in order to come in contact with the nucleus. As is well known from the explanation of the laws governing the spontaneous α-ray disintegration of radioactive nuclei, a charged particle may in quantum mechanics have a probability of penetrating through such a potential barrier, even in cases where the particle on classical mechanics, on account of its insufficient energy, would be stopped at the surface of the barrier. This quantum mechanical effect gives also a familiar explanation of the experimental fact that slow protons, when striking not too heavy nuclei, have been found to have a considerable probability of producing nuclear disintegrations, even for energies where classically the particles would be prevented by the electric repulsion from coming in contact with the bombarded nucleus.

Another interesting feature in collisions between charged particles and lighter nuclei is the remarkable resonance effects found for disintegrations caused by impacts of protons and α-particles. As in the case of selective effects of slow neutrons, such resonances must be ascribed to the coincidence of the sum of the energies of the incident particle and the original nucleus with a stationary state of the compound system corresponding to some quantized collective type of motion of all its constituent particles.[5] Especially in case of α-particle impacts, much information concerning the distribution of highly excited levels in lighter nuclei has been derived from such resonance effects. In contrast to the dense distribution of levels found in heavier nuclei, the spacing of the levels in this case is as large as several hundred thousand volts for an excitation considerably higher than ten million volts. This result can, however, be readily understood if one realizes that the lowest excited levels are farther away from each other for light nuclei than for heavier and that therefore the number of possible combinations of these levels in a given energy region is much smaller in the first case than in the second.

Not only the distances between the resonance levels, but also their half value breadths, are in general much larger in lighter nuclei than in heavier, indicating that the lifetime of the compound system is very much shorter in the former case than in the latter. This comes first of all from the circumstance that the resonances in heavy nuclei are found only for very slow particles, where the probability for escape is extremely small, so that the lifetime of the compound system is only limited by the probability of emission of electromagnetic radiation, whereas in lighter nuclei the lifetime is in general entirely determined by the possibility of releasing comparatively fast particles. Quite apart from this, we should, however, expect that the lifetime of a heavy nucleus—even if the nucleus were highly enough excited to emit fast particles—would be much longer than of a light nucleus on account of the lower temperature to be ascribed to a heavy nucleus than to a lighter one for a given excitation energy.

In fact, it would appear that quite simple considerations such as those here outlined enable us to account in a general way for the peculiar features of nuclear reactions initiated by collisions. Likewise it seems possible to explain the characteristic differences between the radiation properties of nuclei and those of atoms by means of similar considerations based also essentially on the extreme facility of energy exchange between the closely packed nuclear particles as compared to the approximately independent binding of each electron in the atom. The closer discussion of such problems will, however, claim more detailed considerations, which lie outside the scope of the present brief report.[6]

PHYSICS TEACHING IN THE SOUTH[1]

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PRESIDENT RICHTMYER of our association in his letter inviting a paper for this program suggested that it might be appropriate, on this the first joint meeting of the national group of physicists and the southeastern section, to discuss some of the peculiar problems of the South with reference to physics and physics teaching.

In suggesting the paper, I suspect, although he did not say so, that the president had in mind a fact, known to all of us, that from the view-point of per capita production the South has contributed and is contributing much less to scientific progress than the country as a whole, especially certain industrial sections. For instance, in a certain statistical[2] study made in 1927 of the geographical distribution as to place of birth of the one thousand starred scientists in "American Men of Science" the South Atlantic states showed a ratio (corrected for population) of one to two as compared with the Middle Atlantic states and one to three as compared with the New England states. It is significant, however, as showing progress that in 1903, twenty-four years earlier, a similar study shows an unfavorable ratio of one to eight of the South Atlantic to the New England states and one to five to

[5] Besides the total energy of the compound system also its spin and other symmetry properties may, as often pointed out, be of importance for the analysis of resonance phenomena. How such considerations can be brought into connection with the general picture of nuclear reactions here presented is discussed in a paper by F. Kalckar, I. R. Oppenheimer and R. Serber to appear shortly in *Physical Review*.

[1] A paper presented before the American Association of Physics Teachers, Chapel Hill, N. C., February 27, 1937. Somewhat condensed.

[6] A more comprehensive account of the development of the ideas here presented will be published shortly in the *Proceedings* of the Copenhagen Academy by Mr. F. Kalckar and the writer.

[2] See *American Journal of Sociology*, March, 1931.