# Neutron Capture and Nuclear Constitution*

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AMONG the properties of atomic nuclei disclosed by the fundamental researches of Lord Rutherford and his followers on artificial nuclear transmutations, one of the most striking is the extraordinary tendency of such nuclei to react with each other as soon as direct contact is established. In fact, almost any type of nuclear reactions consistent with energy conservation seems likely to occur in close nuclear collisions. In collisions between charged particles and nuclei, contact is, of course, often prevented or made less probable by the mutual electric repulsion ; and the typical features of nuclear reactions are therefore perhaps most clearly shown by neutron impacts. Already in his original work on the properties of high-speed neutrons Chadwick recognised their great effectiveness in producing nuclear transmutations[1]. Especially after the discovery of artificial radioactivity by Mme and M. Joliot-Curie, most instructive evidence regarding nuclear reactions has been obtained through the researches of Fermi and his collaborators on radioactivity produced by bombardment with high-speed neutrons as well as with neutrons of thermal velocities[2].

A typical result of the experiments with high-speed neutrons is the great probability that a collision with a nucleus of not too large atomic number will give rise to the ejection of an $\alpha$-ray or a proton, accompanied by the capture of the neutron and the formation of a nucleus of a new element which in general will possess $\beta$-ray radioactivity. The effective nuclear cross-sections for collisions with such effects are in fact of the same order of magnitude as the cross-sections responsible for simple scattering of high-speed neutrons by nuclei, which in turn agree with ordinary estimates of nuclear dimensions. Another typical experimental result is the surprisingly great tendency even for a fast neutron in collision with a heavy atom to attach itself to the nucleus with the emission of $\gamma$-radiation and the formation of a new isotope which may be stable or radioactive according to the circumstances. In fact, for processes of this kind cross-sections are found which although several times smaller are still of the same order of magnitude as nuclear dimensions.

Capture processes of high-speed neutrons of the last mentioned type are especially significant in offering a direct course of information about the mechanism of collision between the neutron and the nucleus. Indeed, the remarkable sharpness of the lines of the characteristic $\gamma$-ray spectra of radioactive elements proves that the lifetime of the excited nuclear states involved in the emission of such spectra is very much longer than the periods, *circa* $10^{-20}$ sec., of these lines themselves. In order that the probability of emission of a similar radiation during a collision between a high-speed neutron and a nucleus shall be large enough to account for the experimental cross-sections for these capture processes, it is therefore clear that the duration of the encounter must be extremely long compared with the time interval, *circa* $10^{-21}$ sec., which the neutron would use in simply passing through a space region of nuclear dimensions.

The phenomena of neutron capture thus force us to assume that a collision between a high-speed neutron and a heavy nucleus will in the first place result in the formation of a compound system of remarkable stability. The possible later breaking up of this intermediate system by the ejection of a material particle, or its passing with emission of radiation to a final stable state, must in fact be considered as separate competing processes which have no immediate connexion with the first stage of the encounter. We have here to do with an essential difference previously not clearly recognised between proper nuclear reactions and ordinary collisions among fast particles and atomic systems, which have been our main source of information about the structure of the atom. In fact, the possibility of counting by means of such collisions the individual atomic particles and of studying their properties is due above all to the openness of the systems concerned, which makes an energy exchange between the separate constituent particles during the encounter very unlikely. In view of the close packing of the particles in nuclei we must be prepared, however, for just such energy changes to play a predominant part in typical nuclear reactions.

If, for example, we consider an encounter between a high-speed neutron and a nucleus, it is obviously not permissible to compare the process to a simple deflection of the path of the neutron in the inner nuclear field, possibly combined with

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a collision with a separate nuclear particle, resulting in the ejection of the latter. On the contrary, we must realise that the excess energy of the incident neutron will be rapidly divided among all the nuclear particles with the result that for some time afterwards no single particle will possess sufficient kinetic energy to leave the nucleus. The possible subsequent liberation of a proton or an α-particle or even the escape of a neutron from the intermediate compound system will therefore imply a complicated process in which the energy happens to be again concentrated on some particle at the surface of the nucleus.

At the moment it is scarcely possible to form a detailed picture of such processes. In fact, we must recognise that we have no justification even for assuming the existence within nuclei of the particles set free in nuclear disintegrations. In particular, the well-known difficulties of attributing within a space region of nuclear dimensions an individual existence to charged particles with so small a rest mass as have electrons and positrons, forces us to consider β-ray disintegration as a process by which an electron is created as an entity in a mechanical sense[3]. In this respect the situation is, of course, essentially different for the heavier particles emitted in nuclear disintegrations, like neutrons, protons and α-rays. Especially the fact that all nuclear masses in the first approximation are integral multiples of a unit nearly equal to the neutron mass, makes it very reasonable to regard particles of such masses as mechanical entities within nuclei. On account of the small difference between the masses of the neutron and the proton compared with the binding energies in nuclei measured by their so-called mass defect, it would, however, seem more hypothetical to assume the existence in nuclei of particles with the same electric and magnetic properties as those possessed by free neutrons and protons. In view of the scarcity of our knowledge of the extraordinary dense state of matter with which we have to do in nuclei, we may rather regard the integral values of unit electric charge possessed by nuclei and their disintegration products as a fundamental aspect of the atomicity of electrification, which cannot be accounted for by present theories of atomic constitution.

Quite apart from the problem of the nature of the nuclear constituents themselves, which is not of direct importance for the present discussion, it is, at any rate, clear that the nuclear models hitherto treated in detail are unsuited to account for the typical properties of nuclei for which, as we have seen, energy exchanges between the individual nuclear particles is a decisive factor. In fact, in these models it is, for the sake of simplicity, assumed that the state of motion of each particle in the nucleus can, in the first approximation, be treated as taking place in a conservative field of force, and can therefore be characterised by quantum numbers in a similar way to the motion of an electron in an ordinary atom. In the atom and in the nucleus we have indeed to do with two extreme cases of mechanical many-body problems for which a procedure of approximation resting on a combination of one-body problems, so effective in the former case, loses any validity in the latter where we, from the very beginning, have to do with essential collective aspects of the interplay between the constituent particles.

In this connexion it is of importance to remember also that the successful quantum mechanical explanation of the simple law combining the lifetime of α-ray products with the energy of the emitted particles, is essentially independent of any special assumption regarding the behaviour of the individual particles in the nucleus. In fact, on account of the extremely long lifetime of these products compared with all proper nuclear periods, the probability of such disintegration depends in the first approximation only upon the electric field outside the nucleus, which constitutes a so-called potential barrier hindering the escape of the α-rays. It is even very doubtful that α-particles exist in nuclei in the manner assumed in present theories of α-ray decay. Indeed, the frequent appearance of α-rays as a result of natural and artificial nuclear disintegrations may rather be explained by the fact that energy is set free by the very formation of α-particles, and that the liberation of such particles might thus involve a smaller degree of concentration of the excess energy than the liberation of protons or neutrons. So far, the study of the α-ray disintegrations and their intimate connexion with the γ-ray spectra, especially cleared up by Gamow, gives us, therefore, information only about the possible values of the energy and to a certain extent of the spin momenta for the stationary states of the nuclear systems concerned.

The circumstance that the nuclear states involved in the last mentioned phenomena are found to represent a discrete distribution of very sharp energy levels might perhaps at first sight seem to contrast with our assumptions of the existence of a semi-stable intermediate state of the compound system formed by neutron collisions within an apparently continuous range of the kinetic energy of the incident neutron. We must realise, 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. The measurements by Aston of the mass differences of isotopes show that this energy is about ten million volts.

This striking difference in the level schemes for low and high excitations of heavy nuclei is, however, just what we would expect according to the view of nuclear reactions here discussed. In contrast to the usual view, where the excitation is attributed to an elevated quantum state of an individual particle in the nucleus, we must in fact assume that the excitation will correspond to some quantised collective type of motion of all the nuclear particles. On account of the rapid increase of the possibilities of combination of the proper frequencies of such motions for increasing values of the total energy of the nucleus, we should therefore expect that the distance between neighbouring levels would become very much smaller for the high excitation concerned in neutron collisions than in the ordinary $\gamma$-ray levels where we have probably to do with states of collective motions of the most simple types. Even for excitations where the levels are very close together the probability of radiative transition will not, however, on this view be very much different from that in the lower $\gamma$-ray states and any material increase in the width of the levels will not arise, until the probability of escape of material particles becomes comparable with the radiation probability.

Now, in experiments on high-speed neutron impacts on heavy nuclei, the effective cross-section for scattering is normally several times larger than the cross-section for capture. Accordingly, we must conclude that in this case the probability of the escape of a neutron from the compound system is greater than the probability of radiative transitions and that the energy levels of the semistable state are therefore somewhat broader than ordinary $\gamma$-ray levels. This circumstance, together with the rapidly decreasing distance between neighbouring levels in the energy region concerned, makes it indeed very likely that such levels will not here be separated at all, as is required for the explanation of the apparently non-selective character of the capture phenomena. For decreasing velocities of the incident neutrons, however, escape of a neutron from the compound system will rapidly become very improbable, corresponding to the decreasing probability of the necessary concentration of the excess energy of the system on a particular neutron. The sharpness of the levels of the intermediate state must therefore be expected to approach that of the $\gamma$-ray levels, as soon as the kinetic energy of the free neutrons becomes small compared with the total excitation energy in this state.

Most interesting support for these considerations is afforded by the remarkable phenomena of selective capture of neutrons of very small velocities. Working with neutrons of temperature velocity obtained by passing neutron beams through thick sheets of substances containing hydrogen, Fermi and his collaborators found, as is well known, values for the effective cross-sections for neutron capture, which vary in a most capricious way from element to element. While for most elements these values were of the same order of magnitude or not much larger than ordinary nuclear cross-sections, values several thousand times larger were found in certain irregularly distributed elements or isotopes. These at first sight most surprising effects must obviously be attributed to the fact that for such slow neutrons the de Broglie wave-length is very large compared with nuclear dimensions and that, therefore, the simple ideas of path and collision, which can be applied at any rate approximately to high-speed neutron impacts, here fail completely.

Instructive attempts have also been made to explain the phenomenon of selective capture as a quantum mechanical resonance phenomenon, due to the close coincidence between the energy of some almost stable stationary states of the neutron within the nucleus and the sum of the energies of the initial state of the nucleus and of the free neutron[4]. These theories, in which the state of motion of the neutron within the nucleus is treated as that of a particle in a conservative field of force, have failed, however, to account for the fact that the cross-section for neutron scattering in all selective absorbing elements investigated is much smaller than the cross-section for capture. It is true that the large probability of reflection of the waves describing the behaviour of the neutron in the nucleus—arising from the fact that its wave-length here is very short compared with the wave-length for the free motion of the neutron—implies that the mean time interval which a neutron may be said to stay in a nucleus is very long compared with the time interval a high-speed neutron on such a model would take in passing through the nucleus. Still, even in the case of complete resonance, the probability of neutron escape is in this way found to be larger than the probability for emission of radiation. From the far more intimate interaction between the neutron and the nucleus, which the explanation of high-speed neutron capture demands, this remarkable absence of selective scattering of very slow neutrons is, however, just what we should expect for small excess energy, on account of the vanishing probability of neutron escape compared with that of radiative transition.

Moreover, experiments of Fermi and others[5] during the last few months have revealed an extreme sensitiveness of the phenomena of selective neutron capture for small variations in the neutron velocity which necessitates a degree of resonance quite incompatible with the above-mentioned nuclear model. In fact, by the filtration of low-speed neutron beams through thin sheets of different selective absorbing elements great modifications in the cross-sections of selective capture were obtained, showing that the resonance is restricted to narrow neutron energy regions which are differently placed for different selective absorbers. By using for comparison the capture of neutrons in light elements resulting in the ejection of $\alpha$-particles, where the selectivity is much less pronounced—and where therefore from general quantum mechanical arguments the probability of capture within the energy region concerned must be expected to be inversely proportional to the neutron velocity—it has even been possible to conclude that the energy region of resonance for certain selective absorbing elements is confined within a fraction of a volt[6].

From this small breadth of the energy levels of the compound system formed by low-speed neutron capture, we arrive by a simple statistical consideration of the occurrence of selective capture among the heavier elements at an estimate of about ten volts for the distance between neighbouring energy levels for the excitation concerned in these phenomena. This is not only in full agreement with the conclusions about the close distribution of energy levels of highly excited nuclei to which we were led through the discussion of the non-selective capture of the high-speed neutrons; but the extreme sharpness of the levels with which we are concerned in the phenomena of selective neutron capture offers also most interesting support for our primary assumption of the long lifetime of the intermediate state in neutron collisions. In fact, the narrowness of the levels of the compound system proves in a striking way the extreme smallness of the probability of radiative transitions in nuclei and leads to an estimate for the duration of an encounter between a high-speed neutron and a nucleus as large as a million times the interval which the neutron would use in simply traversing the nucleus.

The lack of selectivity in high-speed neutron impacts concerns strictly speaking only the probability of neutron capture by the nucleus and the ejection of a material particle from it. The detailed course of these phenomena will, however, depend in general essentially on the level system of the nucleus finally formed. In fact after the collision process this system must be in some stationary state and if the kinetic energy of the incident neutron is not very large the states between which there can be a choice will all be in the region of ordinary discrete $\gamma$-ray levels. If then the kinetic energy of the neutrons impinging on a heavy nucleus is smaller than the lowest excited level of this nucleus, any neutron escaping from the compound system will necessarily possess the same energy as the incident neutron. In the case, however, of neutron impacts with higher energy there is obviously a certain probability that the nucleus may be left in an excited state after the escape of a neutron with a correspondingly smaller energy. Actually, the probability of the process following such a course, which implies a smaller concentration of the excess energy of the compound system on the escaping neutron, may often be considerably greater than the probability of neutron escape without excitation. There seems, too, to be experimental evidence for the occurrence of nuclear excitation in neutron collisions, namely in the observation of energy loss of high-speed neutrons traversing substances of high atomic weight[7], where a direct transfer of translational energy between the neutrons and the nuclei would be expected to be negligibly small.

As was mentioned earlier, collisions between high-speed neutrons and the nuclei of elements of small atomic number will in most cases result in the ejection of an $\alpha$-ray or a proton. We may conclude here also from the great cross-sections for collision of such effects, that the encounter leads in the first place to the formation of a semi-stable compound system with a continuous range of energy levels. Even though the lifetime of this system may be very much shorter than that of the $\gamma$-ray states of heavy nuclei, we must still realise that the subsequent escape of $\alpha$-rays or protons necessitates a separate concentration process for the excess energy and that in particular we cannot draw any decisive conclusion from these phenomena about the presence of such particles in nuclei under normal conditions. For example, the great probability of emission of $\alpha$-rays compared with neutron escape from the compound system must, as already indicated, rather be explained by the comparatively small degree of energy concentration involved in the former process. As regards the emission of charged particles we must of course also take into account the repulsion from the rest of the nucleus and in particular the greater difficulty experienced by a charged than by an uncharged particle with the same final kinetic energy in passing the potential barrier round the nucleus.

As has often been pointed out, the last circumstance offers a simple explanation not only of the rapid fall in the output of $\alpha$-particles and protons as a result of high-speed neutron impacts for increasing nuclear charge, but also of the decrease with increasing neutron energy of the ratio between the probabilities of ejection of these two differently charged kinds of particles. The probability of the nucleus being left after the ejection of such particles in the normal or in an excited state depends in each case on the distribution of the energy levels of the final system—which are in general more separated for light than for heavy nuclei—and also on the balance between, on one hand, the greater facility of faster particles than of slower ones in penetrating the potential barrier and, on the other hand, the greater demands for energy concentration in the former than in the latter case. Similar considerations will apply for the finer details of the ordinary α-ray disintegrations like the weak groups of long range α-particles and the fine structure of the stronger α-ray lines.

In the case also of nuclear transmutation caused by the impact of charged particles as well as for the nuclear disintegration produced by γ-rays, the formation of an intermediate semi-stable compound system seems decisive for the explanation of the great variety of the phenomena. Besides typical non-selective effects like the ejection of neutrons and protons by fast α-rays, we meet, as is well known, with pronounced resonance effects for slower α-ray impacts, as well as in the capture phenomena of artificially accelerated protons in light nuclei. On account of the very much shorter lifetime of the intermediate state in such cases the degree of resonance here obtained is, however, much smaller than for selective neutron capture by heavy nuclei. In this connexion it is perhaps not out of place to note that expressions like α-ray levels or proton levels, such as are used in the ordinary discussion of these effects, based on the attribution of the excitation to a single nuclear particle, lose all meaning on the view of nuclear excitation adopted here. In fact, the essential feature of nuclear reactions, whether incited by collision or by radiation, may be said to be a free competition between all the different possible processes of liberation of material particles and of radiative transitions, which can take place from the semi-stable intermediate state of the compound system.

A detailed discussion from this point of view of the available empirical evidence regarding spontaneous and induced nuclear transmutations will be published shortly[8] in collaboration with Mr. F. Kalckar, who has given me most valuable assistance in tracing the consequences of the general argument here developed. There we shall also discuss the limitation of this argument in the case of very light nuclei like the deuteron, where the distinction between the mechanism of the storing of the energy in the nucleus and the mechanism of the liberation of particles, so pronounced for the reactions of heavy nuclei, gradually loses its significance. Here, however, I should still like briefly to indicate what modifications in the preceding considerations are to be *expected* even for heavy nuclei should the energy of the intermediate system too far exceed that of its normal state. Even if we could experiment with neutrons or protons of energies of more than a hundred million volts, we should still expect that the excess energy of such particles, when they penetrate into a nucleus of not too small mass, would in the first place be divided among the nuclear particles with the result that a liberation of any of these would necessitate a subsequent energy concentration. Instead of the ordinary course of nuclear reactions we may, however, in such cases expect that in general not one but several charged or uncharged particles will eventually leave the nucleus as a result of the encounter. For still more violent impacts, with particles of energies of about a thousand million volts, we must even be prepared for the collision to lead to an explosion of the whole nucleus. Not only are such energies, of course, at present far beyond the reach of experiments, but it does not need to be stressed that such effects would scarcely bring us any nearer to the solution of the much discussed problem of releasing the nuclear energy for practical purposes. Indeed, the more our knowledge of nuclear reactions advances the remoter this goal seems to become.

In concluding this address, I should just like to point out that even if the problem of nuclear constitution does lack the special simplicity in a mechanical respect characteristic of the structure of the atom which has so much facilitated the disentanglement of the relationships of the elements as regards their ordinary physical and chemical properties, it presents, nevertheless, as I have tried to show, peculiar facilities for a comprehensive interpretation of the characteristic properties of nuclei in allowing a division of nuclear reactions into well separated stages to an extent which has no simple parallel in the mechanical behaviour of atoms.

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[1] J. Chadwick, *Proc. Roy. Soc.*, A, **142**, 1 (1933).

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[3] Cf. N. Bohr, Faraday Lecture, *J. Chem. Soc.*, 349 (1932), and W. Heisenberg, "Zeeman Verhandelingen", p. 108.

[4] Fermi, and others, *Proc. Roy. Soc.*, A, **149**, 522 (1935). Perrin and Elsasser, *J. Phys.*, **6**, 195 (1935). Béthe, *Phys. Rev.*, **47**, 747 (1935).

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