**Zeitschrift:** Helvetica Physica Acta
**Band:** 23 (1950)
**Heft:** I-II

**Artikel:** Compound nucleus and nuclear resonances
**Autor:** Weisskopf, Victor F.
**DOI:** https://doi.org/10.5169/seals-112104

# Compound nucleus and nuclear resonances

by **Victor F. Weisskopf.**

Massachusetts Institute of Technology (Cambridge, Mass.).

(7. X. 1949.)

One of the most striking phenomena in nuclear physics is the occurence of resonances in nuclear reactions. If an atomic nucleus $X$ is bombarded with particles $a$, it is sometimes observed that the ensuing nuclear reaction takes place with appreciable probability only if the energy of the particle is in the neighborhood of certain definite energy values. These energy values are referred to as resonance energies and the extension of the region of appreciable cross-sections around the resonance is called the "width" of the resonance. Resonances are usually found only at relatively low energies of the bombarding particle. The widths of the resonances increase in general with increasing energies. At higher energies the widths may reach the order of the distances between resonances and then no resonances can be observed. The sharpest and strongest resonances are found with heavy nuclei in slow neutron reactions of the $(n - \gamma)$-type (neutron capture reactions) but the phenomenon of resonance is by no means restricted to neutrons.

It is attempted in this note to give a simple qualitative explanation of the occurrence of resonances and of their widths.

We describe the nuclear reaction as proceeding in two successive steps along the lines of Bohr's theory of the compound nucleus. First the formation of a compound nucleus by the bombarding particle and the target nucleus, and second, the decay of the compound nucleus into the final nucleus and the secondary particle. The occurence of resonances can be interpreted in the following way: The compound nucleus can exist only in quantum states $s$ of definite energy $E_s$. Let $\varepsilon$ be the energy of the bombarding particle and $B$ the binding energy of this particle to the target nucleus. The excitation energy of the compound nucleus is then equal to

$$E = \varepsilon + B \tag{1}$$

Thus a compound nucleus can be formed only if $\varepsilon = \varepsilon_s$ where $\varepsilon_s + B = E_s$. The states of the compound nucleus have a finite lifetime $\tau_s$, since they decay during the second part of the nuclear reaction. According to the HEISENBERG uncertainly relation the energy $E_s$ is not sharply defined. The level is therefore broad and its width $\Gamma_s$ is connected with the lifetime by

$$\Gamma_s = \hbar/\tau_s \tag{2}$$

The existence of quantum states in the compound nucleus requires an explanation. One might expect that the spectrum of the compound nucleus is *continuous* if the excitation energy $E$ is higher than $B$. Then the system is excited sufficiently to emit a particle (namely the bombarding particle) and its spectrum should correspond to the spectrum of an atom above the ionization energy, which is continuous. The excitation energy of the compound nucleus created by the bombarding particle is always higher than $B$ (see equation (1)) so that we should expect a continuous spectrum and no resonances.

In what follows we will try to explain the main features of resonance reactions by taking into account only the most important general properties of nuclei.

We make use of the following assumptions regarding the structure of the nucleus:

1. The nucleus has a well defined surface, which is a sphere of radius $R$. The nuclear forces do not act between the particle $a$ and the nucleus if the distance between $a$ and the center of the nucleus is larger than $R$.

2. If the particle $a$ penetrates the nuclear surface it moves with an average kinetic energy $\varepsilon_{in}$ which is much higher than its energy $\varepsilon$ outside. In fact, $\varepsilon_{in} \cong \varepsilon + 20$ MeV. Here 20 MeV is the order of magnitude of the kinetic energy of internuclear motion.

3. The particle $a$ is subject to very strong interactions inside the nucleus so that it interchanges its energy rapidly with the other nucleus. Its motion within the nucleus will be very complicated.

The assumptions 1. and 2. have the following consequence: If a particle enters or leaves the nucleus, it must penetrate a surface at which its wave number changes suddenly from a low value $k$ outside to a high value $K$ inside, or vice versa. Such sudden change of wave number is connected with a reflexion, so that this surface is only partially penetrable for the particle. The penetrability $P$ can be easily calculated for an uncharged particle. (The passage of charged particles is hindered by the Coulomb barrier which increases the reflexion effect). Elementary wave mechanics shows that the ratio $P$ of the penetrating particles to the incident ones from a region in which the wave number is $k$ to a region in which it is $K$ (or vice versa) is given by

$$P = \frac{4\,k\,K}{(k+K)^2}\,. \tag{3}$$

Thus the nuclear surface offers an obstacle to any particle (even uncharged ones) in form of a reflexion which is almost total if $k \ll K$.

We now turn to the description of the stationary states of a nuclear system of $A$ nucleons. It may be a stable nucleus or a compound nucleus created in some nuclear reaction. It is expected that this system exhibits a spectrum of discrete quantum levels, at least for excitation energies less than the energy $B$. Because of the large number of constituents and the complicated interaction we expect many levels, much more than one would get in a one-body problem of the same dimensions and with a potential energy of the order of the average potential in the nucleus.

It is perhaps of some interest to discuss here the physical significance of the level distance $D$ and its connection with some properties of the motion of the nuclear constituents within the nucleus. This motion cannot, in general, be described by a classical picture of moving particles. However, according to the correspondence principle, the highly excited states lend themselves more readily to a classical description. Actually one can build linear combinations of wave functions of a number of neighboring stationary states such that they correspond to a relatively well defined grouping of particles in space with given velocities, within the limits of accuracy set by the uncertainly principle. The movement of these particles (or better, of the maxima in the square of the wave function) corresponds to a good approximation to the movement calculated by classical mechanics. We are here interested in only one feature, the period $T$ of the motion. $T$ is the time after which the initial grouping of particles re-occurs. We find that the time $T$ is intimately connected with the level distance $D$ of the states used in the linear combination. Let us assume for a moment that the energies $E_n$ of these states (say their number is $N$) are equally spaced: $E_n = E_0 + n\Delta$, we then can write for the linear combination of the $N$ states, whose space dependence is given by $\varphi_n$:

$$\psi = \sum_{n=1}^{N} a_n \varphi_n \exp(-i E_n t/\hbar) = \exp(-i E_0 t/\hbar) \sum_{n=1}^{N} a_n \varphi_n \exp(-i n \Delta t/\hbar).$$

It is evident that $\left|\psi\left(t + \frac{2\pi\hbar}{\Delta}\right)\right| = |\psi(t)|$, so that the wave function $\psi$ describes the same configuration at $t$ and at $t + \frac{2\pi\hbar}{\Delta}$. Thus the period of the motion is

$$T = \frac{2\pi\hbar}{D}$$

where $D$ is the level distance. This conclusion holds only if the levels are equally spaced, which is approximately the case in simple systems at high excitations.

In complicated systems, as atomic nuclei, these considerations lose some of their accuracy but they still remain qualitatively valid. We no longer find approximately equidistant level spacing but we can consider the average level spacing $\overline{D}$ as an indication of the period of the internuclear motion. The resulting values for the period are large, much larger for example than the ones of a one-body problem in a potential well of nuclear size. This is due to the interaction between nucleons which makes the motion much more involved so that the time interval between the re-occurrences of the same configuration becomes large.

We now consider the excitation energies of the nuclear system which are higher than the binding energy $B$ of one of the constituents. At these excitations the nucleus is able to emit a particle, and the motion is no longer periodic. The emission probability is strongly reduced, however, because of the reflexion which the particle suffers when trying to get out through the nuclear surface. Especially at excitation energies only a little above $B$ the reflection will be almost complete, since the wave number $k$ outside is very small. As a consequence of this characteristic reflection the motion above $B$ is not essentially different from the one below $B$. The reflexions lead to a nearly periodic motion which in turn gives rise to an energy quantization and to the existence of discrete, almost stationary states. Thus, the series of discrete energy values continues even above $B$, although the states whose energy is higher than $B$ are not strictly stationary, because of the possibility of splitting into two parts, the particle $a$ and the residual nucleus.

This description lends itself readily to a quantitative estimate of the level width. Let us consider a level $s$ above the binding energy $B$ from which an emission of a particle $a$ is possible. The energy should be insufficient, however, to emit any other particle. We also neglect, for the moment, any radiative transitions to lower levels with the emission of a light quantum $h\nu$. We call the level width $\Gamma_a$, since it is due to the emission of $a$. It can be determined by the following consideration: We have discussed the relation between the level distance $D$ and the period $T$ of the motion. Let us apply the concept of period to the re-occurrence of a very special configuration. We know that the level $s$ can be created by a particle $a$ entering into the residual nucleus. We single out the configuration, which is realized when the particle $a$ has just entered into the nucleus, and we ask, after what time the particle would reappear again at the nuclear surface with the same momentum with which it has entered, ready to leave in the same way by which it came in. Such a question can be answered only in a very approximate way: the time $T$ will be of the order of the period of motion and we expect again the relation $T \sim 2\pi\hbar/D$ to hold.

The reoccurrence of this configuration does not necessarily mean that the particle $a$ will actually leave the compound nucleus. The nuclear surface is equivalent to a strong and sudden change of potential and the particle may be reflected at this surface and start the motion inwards into the nucleus over again. This repetition of the motion is essential for the existence of well defined compound states. If the particle $a$ would have left the nucleus after the time $2\pi\hbar/D$, the lifetime $\tau$ of the state would have been of the order of $T$, and the width $\Gamma_a = \hbar/\tau$, would be of the order $D$. The states of the compound nucleus are well defined only if $\Gamma_a \ll D$. Thus the lifetime $\tau$ must be large compared to $T$; a well defined state does not decay after the particle $a$ has returned once to the surface. Evidently the lifetime $\tau$ is given by $\tau \approx T/P_a$, where $P_a$ is the penetrability of the surface for the particle $a$. Thus the width $\Gamma_a$ becomes

$$\Gamma_a \simeq P_a \frac{D}{2\pi}. \tag{5}$$

We may express this relation with the following words: The particle reaches the nuclear surface $\frac{D}{2\pi\hbar}$ times per second and tries to escape. $P_a$ is the chance of a successful escape, hence the emission probability per unit time is the product of these two magnitudes.

If the particle $a$ is a neutron of zero angular moment, we may use expression (3) for $P_a$ and get for $k \ll K$:

$$\Gamma_a \approx \frac{2\,k}{K}\,\frac{D}{\pi}\,. \tag{6}$$

This is a simple derivation of the well known relation between particle width and level distance[1]). A recent compilation by WIGNER[2]) of measured particle widths has confirmed this rule. WIGNER finds that the neutron widths can be represented by an expression $\Gamma_a = C\,k\,D$, where $C$ is a constant which varies very little from nucleus to nucleus. Although the actual values of $\Gamma_a$ vary between 100 KeV and $10^{-4}$ eV, more than 90 percent of the constants $C$ do not differ more than a factor 5. A reasonable average for $C$ is $C = 0.45 \times 10^{-13}$ cm, which, according to (6), gives rise to a value $K = 1.0 \times 10^{+13}$ cm$^{-1}$. This is the wave number which corresponds to an energy of 20 MeV, in good agreement with our present ideas about the average kinetic energies within nuclei. The measured proton widths give rise to a similar constant after reducing them to equivalent neutron widths by correcting for the effect of the Coulomb barrier.

Formula (5) shows that the particle width cannot be larger than $D/2\,\pi$, since $P_a$ never can be larger than unity. This limit can be understood in the picture which we have used here: The lifetime of a level must be at least equal to the period if its decay can take place only by the re-emission of the entering particle.

If the incident particle has a low energy, the widths of the resonances are very small. This characteristic property of the compound nucleus is due to two factors:

a) The strong interaction between the nucleons, and

b) The small penetrability (even for neutrons) of the nuclear surface. The first factor causes a long period of the nuclear motion, which is found in form of small values of $D$. This alone, however, does not suffice to explain the occurrence of sharp resonances. Only because of factor b) the lifetime of a compound state is much *longer* than the period which makes the width smaller than the level distance, and hence establishes the possibility of resonances.

---

[1]) H. A. BETHE, Phys. Rev. **47**, 747 (1935); Rev. Mod. Phys. **9**, 71 (1937); N. BOHR and J. A. WHEELER, Phys. Rev. **56**, 426 (1939); H. FESHBACH, D. C. PEASLEE and V. F. WEISSKOPF, Phys. Rev. **71**, 145 (1947).

[2]) E. WIGNER, Am. J. of Phys., **17**, 99 (1949).

In this discussion we have neglected the radiative transitions to lower states and we have considered the emission of a particle as the only way in which the compound nucleus can decay. Actually the total width $\Gamma_s$ of a state consists of the sum of the particle width $\Gamma_a^s$ and the "radiation width" $\Gamma_{\text{rad}}^s$. Hence even the quantum states with an excitation energy below $B$ are not strictly stationary and have a width equal to the radiation width. The width of levels whose energy is barely above $B$ is mostly due to radiative transitions.

It is necessary to specify the type of levels whose average distance $D$ can be interpreted as the reciprocal of the period of motion. The correspondence principle as used in the interpretation of $D$ is applicable only to a series of states which fulfill the following condition: all physical magnitudes which are integrals of motion must have the same value, with the exception of the energy itself. Thus the distance $D$ must be taken between levels of equal $J$ (quantum number of the total angular momentum of the nucleus). It is generally assumed that there are no other integrals in the motion of nucleons within the nucleus because of the strong interaction. If the character of nuclear forces admits more integrals the meaning of $D$ must be altered. We indicate a few examples.

If there is no coupling between spin and orbital motion in a nucleus, $D$ is the distance between levels of equal $L$ and $S$. If one were allowed to consider a nucleus as a system of independent nucleons moving in a common potential, the energy of each nucleon would be an integral, so that $D$ would be the distance between the states of one single nucleon only.

In any case, $D$ is just the distance between those states which can be formed by an incoming particle with a definite angular momentum and spin. If there were no interaction between particles, only the states could be formed in which the incoming particle itself is excited. If there is no spin orbit coupling, only states which have the quantum numbers $L$ and $S$ can be formed, where $L$ and $S$ are those orbital or spin momenta resp., which occur from the combination of the orbital and spin momentum vectors of the particle and the target nucleus.

It is of interest to consider a magnitude which is appropriately called the "path length" $S$ of a nucleon in a given state. We know the time $T = 2\pi\hbar/D$ which the incident nucleon takes to return to the nuclear surface ready to leave (which means that the rest of the nucleons find themselves in a state corresponding to the original target nucleus). We also know the average velocity $v = \hbar K/m$ of the nucleon within the nucleus. The path length is given by $S = vT = 2\pi\hbar^2 K/Dm$. This length is quite considerable. If we insert a level distance of 25 eV as found in the capture of slow neutrons by heavy nuclei, we obtain $S \approx 10^{-6}$ cm which is about $10^6$ larger than nuclear dimensions. This fact is an illustration of how complicated is the nuclear motion and how many times the neutron is deflected back and forth before it reaches the surface and before the other nucleons are correctly arranged to form the residual nucleus. It is perhaps significant that this path lenght is much shorter for low lying nuclear states. If $D$ is put equal to 1 MeV, as it is found near the ground states, we obtain $S \approx 2 \times 10^{-11}$, a value which is only ten times larger than the nuclear diameter. The motion in the low lying states is very much simpler and much nearer to the motion of an independent particle in a potential well. It is probably due to the fact that the Pauli principle prevents the scattering of one nucleon by another if the energy is not sufficient to lift one particle into an unoccupied state.

Our considerations may have some significance in connection with the recently discovered regularities which are usually referred to as "magic numbers"[3]). These effects point to a pronounced shell structure in the ground states of nuclei which is understandable if one considers the independent nucleon model as a good first approximation. In contrast to this, the experience with nuclear reactions points to a very strong interaction between nucleons. In view of the above considerations it appears that the lowest states of the nuclei are perhaps much better approximated by an independent particle model whereas the highly excited states of the compound nucleus which are created in a nuclear reaction should exhibit a very different behavior.

The analogy with an electron gas in metals is perhaps not too far fetched. Here we are able to explain a great number of phenomena by assuming independently moving electrons, especially the existence of shells (Brillouin zones). In spite of this, the interaction between the electrons is very strong: the cross-section for the Rutherford scattering by $90^0$ of two electrons is so large that the corresponding mean free path would be less than the distance between two atoms. This scattering is of no consequence in the lowest states of the electron gas, since the two electrons can only exchange their momenta. All other states into which they could be scattered are occupied. The situation changes completely when an electron enters the metal from the outside. It then has an energy well above the

[3]) See f. c. Maria G. Mayer, Phys. Rev. **74,** 235 (1948).

upper limit of the Fermi distribution, and is slowed down within a few atomic distances by Rutherford scattering on other electrons. Here the independent particle model breaks down and the behavior of the electron is determined by the strong interaction. Hence it is perhaps not too surprising to find that some properties of the lowest states of nuclei can be explained by the independent particle model, whereas the effects of a neutron entering a nucleus are typical for strong interaction.

We now suppose that the energy of the state $s$ is high enough that the state $s$ can decay in more than one way. For example, it can emit another particle $b$, or it can emit the particle $a$ in more than one way, namely with different energies by leaving the residual nucleus in different excited states. Then the total width $\Gamma^{(s)}$ of the level can be divided into partial widths corresponding to the different modes of decay:

$$\Gamma^{(s)} = \sum_{\alpha} \Gamma_{\alpha}^{(s)} + \Gamma_{\mathrm{rad}}^{(s)}. \tag{7}$$

Here the index $\alpha$ refers to some specific mode of decay and $\Gamma_{\mathrm{rad}}^{s}$ corresponds to the decay by radiative transition to a lower level. $\Gamma_{\alpha}^{(s)}$ may be defined as the reciprocal lifetime (multiplied with $\hbar$) of the level $s$ if all other modes of decay, except $\alpha$, are closed by some artifice. We then expect the partial width $\Gamma_{\alpha}^{(s)}$ to be given again by $\Gamma_{\alpha}^{(s)} = P_{\alpha} \cdot D/2\pi$ where $P_{\alpha}$ is the penetrability of the nuclear surface in the decay $\alpha$.

So far our picture has enabled us to understand the existence of quasi stationary states in the compound nucleus and the relation (5) between the particle width and the level distance. A closer analysis of our picture will be helpful for the understanding of the validity of Bohr's assumption regarding the compound nucleus, especially the assumption that the decay of the compound nucleus is independent of the mode of its formation. Let us consider a nuclear reaction in which the compound nucleus is formed in one of its resonance levels of well defined energy. The fact that the width of the level is small compared to the level distance is equivalent in our description to the fact that the lifetime of this level is long compared to the period of the motion. The same motion is repeated many times before the compound state decays. Hence, the mode of decay cannot depend on the way the state has been created.

The situation changes, however, if the energy of the incident particle is raised. The width of the compound state increases. Not only every single particle width $\Gamma_{\alpha}$ increases with higher particle energy since the penetration $P_\alpha$ becomes larger. Also more modes of decay are possible which increases the number of terms in expression (7). There will be an excitation energy of the compound nucleus above which the width of the levels is larger than the average distance $D$. No resonance can be expected in that region. The situation $\Gamma > D$ can be described in our picture as follows: There are many channels through which the compound nucleus can decay. The sum of all these probabilities is so large that its lifetime is shorter than the period. Thus, if $\Gamma > D$, the motion of the compound nucleus is far from periodic; it has no chance even to complete one single cycle of its motion.

The validity of the Bohr assumption in this case appears questionable: Since the compound nucleus cannot complete the cycle of its motion, it cannot assume all possible combinations compatible with its energy. It may happen that the properties which the compound nucleus assumes, depend on the way it was formed. Let us illustrate the situation with an example. A compound state is created by $\alpha$-particle bombardment of the nucleus $(A, Z)$, where $A$ is its mass number and $Z$ its charge. We measure the yields of the $(\alpha - p)$ and $(\alpha - n)$ reactions. We then create the *same* compound nucleus in the same state of excitation by irradiation of the nucleus $(A + 4, Z + 2)$ with $\gamma$-rays, and we compare the ratio of the yields of the $(\gamma - p)$ and $(\gamma - n)$ reactions with the ratio of the corresponding $a$-reactions. If the excitation energy of the compound nucleus is in the resonance region, we would expect the two ratios $\frac{(\alpha, p)}{(\alpha, n)}$ and $\frac{(\gamma - p)}{(\gamma - n)}$ to be equal, since the lifetime of the compound state comprises so many periods of its motion, that the effects of the mode of creation are completely wiped out. It runs many times through all arrangements compatible with the energy before it decays. If the excitation energy is above the resonance region, the compound nucleus has not time enough to go through all the motions which it could perform if it did not decay. Then, whether it reaches first an arrangement in which the emission of a proton is more likely to occur or an arrangement in which the neutron is favored, may depend on the way it was formed.

The assumptions of validity of the Bohr hypothesis in the non-resonance region is much less obvious than in the resonance region. If it is borne out by the experiments in the non-resonance region, we must conclude that even within the small part of the motion which takes place during the lifetime of the compound state, all modes of decay have had the same chance as they had if the compound nucleus would go through its complete motion. This corresponds to an assumption of some kind of statistical disorder or lack of correlation between the modes of decay in the motion; an assumption which need not always be fulfilled. WÄFFLER and HIRZEL[3]) have recently investigated the ratio of $(\gamma - p)$ to $(\gamma - n)$ reactions and have found values for this ratio which are much larger than one would expect on the basis of the independent competition between these two processes. In the light of the foregoing considerations such anomalies could be considered quite generally as cases in which the lifetime of the compound nucleus was too short to establish independent competition. The special arrangement of nucleons created by $\gamma$-rays may lead more likely to proton emission than to neutron emission. If there would be time enough for this arrangement to develop further through mutual exchange of energy among the constituents, a state would have been reached in which the ratio of proton and neutron emission had the expected value. The lifetime was too short, however. It should be remarked that this does not constitute an explanation of the anomalies found by HIRZEL and WÄFFLER[5]); it is only an attempt to understand the possibility of deviations from the Bohr picture of independent competition between different modes of decay.

There is another kind of reaction in which one may expect deviations from the Bohr picture: If a nucleus is above the resonance region, one should expect a tendency of the compound nucleus to re-emit the incident nucleon with a higher energy than the one which is predicted by independent competition. The effects of independent competition are usually expressed in form of an evaporation model from which it follows that the expected re-emission energies are much lower than the incident energy. They are supposed to be of the order of the nuclear temperature $\Theta$. The lifetime of the compound state may not be long enough to allow the incident neutron to exchange all its energy with the other nucleons before it finds a channel to leave the compound nucleus with a higher energy than the one with which it would be emitted from the equilibrium state. Hence the evaporation model may be inadequate in some cases to describe the re-emission of the incident nucleon. Especially if the incident particle is a neutron which is not kept within the nucleus by any Coulomb barrier, it may find its way out of the compound system before "thermal" equilibrium is established. One

[4]) H. WÄFFLER and O. HIRZEL, H. P. A. XXI, 200 (1948).

[5]) Attempts of an explanation are found in L. J. SCHIFF, Phys. Rev. **73**, 1311 (1948), and E. D. COURANT, Phys. Rev. **74**, 1226 (1948).

would imagine that this happens at energies at which the reflexion effect of the surface is no longer very effective and at which the neutron has many channels available to leave the compound system. Eq. (3) shows that $P$ becomes $1/2$ for $\varepsilon \sim 1$ MeV, so that we may expect the deviations to occur, for neutron energies larger than perhaps 5 or 10 MeV. This phenomenon is less likely to happen with protons of similar energy since their re-emission is hindered by the Coulomb barrier.

The failure to attain a "thermal" equilibrium leads to an abnormally small ($n$-2 $n$) cross-section. The evaporation model predicts that almost all re-emissions of the incident neutron take place with low energy $\varepsilon'$ (about nuclear temperature: $\varepsilon' \sim \Theta$). Thus the residual nucleus is highly excited and will emit a second neutron if the incident energy $\varepsilon$ is high enough, namely $\varepsilon > B + \Theta$. Here $B$ is the binding energy of one neutron and also the threshold energy of the ($n$ — 2 $n$) reaction. Thus according to the evaporation theory the ($n$-2 $n$) cross-section ought to be of the order of the target area $\pi R^2$ of the nucleus for neutrons if $\varepsilon > B+\Theta$. (At still higher energies the ($n$ — 3 $n$) process sets in and reduces the ($n$-2 $n$) cross-section). If, however, the neutron has no time to exchange its energy completely with the nucleus, the energy of re-emission will be higher and the excitation of the residual nucleus correspondingly lower, and no second neutron can be emitted. Hence the ($n$ — 2 $n$) cross-section would be less than $\pi R^2$ even if $E > B + \Theta$. Some recent observations tend to confirm this hypothesis[6]).

In all other reactions, as $(p, n)$ $(p, 2n)$, $(\alpha, n)$ $(\alpha, 2n)$ etc., one should expect that the model of independent competition to give correct results. The emitted neutrons should be of low energy and their energy distribution should correspond approximately to a Maxwell distribution as given by the evaporation model. It gives rise to a characteristic behavior of the cross-section for the emission of two neutrons: The cross-section should rise quickly above the threshold of the $2n$-reaction (within an energy interval of the order of the temperature) at the expense of the cross-section for the emission of a single neutron. This phenomenon has been observed by several authors[7]).

The character of the nuclear reactions changes completely at very high energies of the incident particles. This change takes place be-

---

[6]) Unpublished observations by OGLE, PHILLIPS and TASCHEK at the Los Alamos Scientific Laboratories.

[7]) BRADT and TENDHAM, Phys. Rev. **72**, 1117 (1947); KELLY and SEGRE, Phys. Rev. **72**, 746 (1947). G. M. TEMMER, Phys, Rev. **76**, 424 (1949).

cause the cross-section for interaction between the nucleons becomes so small that the "mean free path" of a nucleon in nuclear matter is of the order of a nuclear radius. In order to estimate this mean free path we use the results of recent experiments which have shown that the neutron-proton cross-section is approximately given by $\sigma \sim (8/E) \times 10^{-24}$ cm$^2$ for $E > 10$ MeV where $E$ is the relative kinetic energy in MeV and about a third as much between equal nucleons. This cross-section gives rise to a mean free path for a nucleon in nuclear matter of $l \sim 4 \times 10^{-15}\ \varepsilon$ cm if $\varepsilon$ is its kinetic energy in MeV, and this value becomes of the order of nuclear dimensions if $\varepsilon > 50$ MeV.

If the energy of the incident nucleon is above this limit, there is a finite probability that it passes through the nucleus without any energy loss. If it does exchange energy with the nucleus it mostly interacts with one nucleon only to which it transfers a large fraction of its energy. The nucleon which was hit will have a good chance to leave the compound system without further collision. The total effect of the process is an ejection of a very fast nucleon and a residual nucleus left in an excited state because of the violent perturbation. The state of excitation gives rise to effects predicted by the usual evaporation model of a "heated" nucleus; it will boil off one or several nucleons with low speed. Processes of this type have been observed recently in Berkeley after bombarding materials with protons and $\alpha$-particles of several hundred million volts[8]).

We have mentioned in this paper several instances in which the decay of the compound nucleus may not be independent of the mode of its formation. The assumption of an independent decay is valid only in the region in which sharp resonances occur. The sharpness of the resonances is a guarantee that the motion in the compound state is repeated many times before it decays so that the mode of its excitation is irrelevant. Strictly speaking the assumption is not justified in the non-resonance region, since the compound nucleus decays long before having completed its cycle of motion. The decay should therefore depend on where and how the cycle began. The assumption may be approximately valid, however, because of the very complicated nature of the motion within the compound nucleus in which the incoming particle shares its energy with all nucleons evenly after a time which is very short compared to the lifetime. Such quick interchange of energy requires a very short "mean free

---

[8]) Theoretical description and references to experiments can be found in R. Serber, Phys. Rev. **72**, 1114 (1947); M. Goldberger, Phys. Rev. **74**, 1269 (1948).

path" of a nucleon in nuclear matter, and we expect, therefore, the assumption to break down for incident energies higher than 50 MeV. The rapid interchange probably also requires some barrier which keeps the entering nucleon within the nucleus during the first energy exchanges. Such barrier is provided for in case of charged particles but may be lacking if the entering nucleon is a fast neutron. When the compound nucleus is formed by high energy $\gamma$-ray excitation, there is experimental evidence against the validity of the assumption. The original picture of a nuclear reaction taking place in two independent stages has been extremely useful to explain a great number of phenomena. We must be prepared to find an increasing number of exceptions, however, as observations are extended into the regions of higher energy.