I would like to thank all of you for inviting me here and I am very grateful to the Japanese physicists for inviting me and my wife to come to Japan. This is probably the most interesting trip we have ever made.

Today I would like to talk about the present situation in low energy nuclear physics. The situation is not too good, as we have seen before early this afternoon. There are many, many new experimental materials, but the theory does not catch up with the experiment. So I would like to just give you a survey of what I think the most important point of interest in low energy physics, and also mention the most important points where we have reached a better understanding, where we are still searching for it. Low energy physics changes very much, and I am afraid that what was written eight years ago in the book by Blatt and myself there is not much which is still correct, and we will have to write a new book pretty soon.

Now I would like to divide the topics into four parts. (i) Nuclear Forces. (ii) Nuclear matter. (iii) Deformed nuclei. (iv) Reactions. There are certainly many other questions, but I would like to discuss these four questions, because they seem to me to contain the most important problems. I have not included $\beta$-decay, because I think we now understand this field pretty well, apart from the fundamental question of the nature of the interaction. Due to the discovery of the parity violation, this field has been pretty much cleared up and, once the fundamental interaction is assumed, anything else seem to follow from the calculation and the experiments seem to be in very good agreement with the theory. The fundamental questions connected with $\beta$-decay are rather more part of high energy physics.

(i) **Nuclear forces**

I understand low energy nuclear physics to be the theory of the properties of the nucleus, i.e. the theory of the system of the protons and neutrons which interact with nuclear forces.
In low energy nuclear physics we are not too much interested in what the nature of the nuclear forces is, i.e. in the meson aspect, but we must know the properties of the nuclear forces. Here, there was great progress recently: We found that the nuclear forces can be represented by a potential, as long as the relative energy is not too high, say less than 200 Mev. But in nuclear physics we are not interested in energies higher than that, because within the nucleus we only have low relative energies.

Much experimental material is accumulated regarding this potential. First of all we can now say that this potential exists, which was questionable many years ago. That is, we know that it is charge independent, but it depends on the distance, isotopic spin and the ordinary spin in a way which has not yet been cleared up. However, the following points are evident: First of all, there exists a repulsive core which is very important for the existence of nuclear matter. The dependence on $r$, the distance, consists essentially of a repulsive core and an attractive tail. We do not know much about the exact shape, except at very large distances.

The dependence on $r$ and $\sigma$ is also not too well known, but very roughly speaking, we know that they are approximately Serber forces; that means that they act approximately only in even relative angular momenta and not in odd ones. The spin dependence is rather weak. I do not want to go in detail but would like to emphasize two things. First we do not know the exact form of the spin dependence; we know the nuclear force contains a spin dependent central force, a tensor force, (that is of course trivial because of the quadrupole moment of deuteron). But does it contain $(l\cdot s)$ forces? We do not know. In the Western world people say "yes", and in Japan "no".

Miyazawa  How about you?
Fukuda    He is of course a Western physicist.
Weisskopf No, I am international.

I do not know. I have only one little reason to believe that this exists. I would like to mention this later. I think this is still an open question, and it would be very interesting to know more about it, and for this I think we have to wait for experiments and more accurate analyses. I personally think that the result of Otsuki, Watari and Tamagaki is correct, but the question is whether it is true. By "correct" I mean that the present experimental material up to 150 Mev can be explained without spin-orbit force. But, of course, that does not exclude the existence of such a force which can be observed only at higher energy.

The next question I would like to mention is the question of the many-body forces. It is usually assumed that the nuclear forces act only between pairs of particles. In other words, it is assumed that the potential between two nucleons is independent of the third nucleon, even if the
third nucleon is rather near by. This is an assumption which has been made only because it makes the calculations so much simpler. It is obvious that this cannot be exactly true. Every meson theory of nuclear forces gives such an effect. So far I do not think there has ever been found any experimental evidence for three-body forces. They have not been disproved either, but it seems that calculations can be made without it and good results can be obtained. Nevertheless, here we have a very fundamental question, and it is somewhat astonishing that one can really neglect three-body effects, since in nuclear matter the distance between the particles are very small and the meson clouds touch each other. Therefore one would think that a third meson cloud would change the force. This is a very interesting experimental and theoretical question. For example, the investigation of $H^3$, $He^3$ and the $p-d$ and $p-n$ scattering, can perhaps shed light on this, but only if one has a very good theory of these processes. Therefore the investigation of this problem presents more a theoretical difficulty than an experimental one. I think perhaps some calculating machines should be used, for example, to calculate the energies of the nuclei $H^3$ and $He^3$, accurately with the forces as we know from the previous discussions, in order to be sure that there is no three-body forces. Of course it might even be that the three-body forces comes in more complicated nuclei than this. So here is an open problem which is of fundamental interest, and I think it is rather strange that so far one has not yet discovered any effect connected with many-body forces.

Tamura Do you think that we know the properties of the two-body forces very well to the extent that we can already start the detailed calculation of the three-body problem?

Weisskopf I do not know. Maybe not. Maybe one does not know two-body force very well. But we now have made rather detailed studies of it, and it is now time to apply to three-body problems. Certainly, that is also a problem which is connected with the knowledge of the two-body force.

Fukuda Do you believe the result coming from the static meson theory, that the three-body force is quite negligible in the nuclear matter so long as the $S$-wave parts are neglected?

Weisskopf The static theory of nuclear forces is right only at large distances, but this part comes about from short distances where we have no meson theory. I have to make the assumption here that we have no meson theory. If we had a meson theory this chapter would have been much simpler.

(ii) Nuclear matter

Now let me go over to point two. Here I think large progress has
been made in the last five years; we understand a little more how a force of the kind mentioned in (i) can give rise to the existence of what we know to be the properties of the nuclear matter. The main problem was, as you know, that nuclear matter behaves as if the nucleons are free particles, although there is interaction between them. This was a great problem which has substantially been solved by the theories of Brückner and many others. We now know that the interaction is a relatively weak force and is just big enough to bind the neutrons and protons together, but does not change their motion from the one of free particles; hence the free particle motion is a good approximation. I do not want to give here a detailed analysis of these complicated theories but I would like just to mention one point. The essential reason that free particles is a good approximation comes from the Pauli principle which makes it difficult for particles in the nuclear matter to scatter into other directions because all states are occupied. The main point is that the attractive part of the nuclear forces is actually not very strong in contrast to what one often says. The nuclear forces are really weak forces. Weak in a certain sense, if one compares them with the chemical forces. The deuteron exists only in the state $l=0$, and $l=1$ is already a dissociated state. However, the chemical forces in the molecule are much stronger, since the molecules can be in many rotational states. That is the reason why in the nuclear matter nucleons move like free particles whereas atoms in crystals are fixed. I would like to say that there still remain quite a number of mathematical problems connected with this theory, but the fundamental ideas will very probably turn out to be correct.

From the fact that the free particle picture is a good approximation, we get the shell model. Perhaps I should not call it the shell model; I should call it an independent particle model. What does this independent particle imply? It implies that if one considers one particular nucleon, then one can say that the action of all the other nucleons on this nucleon can be expressed as a potential, which depends only on the coordinate of this particular nucleon. That means that one can average the potential of all the other particles. This is of course only an approximation, and I would like to divide the exact interaction between two nucleons into two parts: One part which can be incorporated into this average and the rest which cannot.

$$V = V_{\text{collective}} + V_{\text{individual}},$$  \(1\)

and we will later talk about how one can perhaps separate this. But here I would like to indicate that the most part of $V$ is contained in $V_{\text{collective}}$ and the smaller part one may still consider as individual interactions. Most of the potential can be expressed by the independent potential well $U(r)$.
which averages this $V_{\text{ext}}$ over all the particles. Now let me say a few words about this potential well. This potential well here has two characteristic properties. First $U(r)$ is usually spherically symmetric but not always. In some nuclei it is deformed, and we will speak about this later. The main point here is that it contains a central part and also a spin-orbit part.

$$U(r) = U_o(r) + (l \cdot s) v(r)$$

(2)

This spin-orbit part is very important, because it characterizes the shell structure and is important for the spectrum of nuclei. The question arises what is the source of this spin-orbit force. Here I come back to the question which we discussed before. One must ask oneself, how can such spin-orbit term come about from our potential between pairs of particles. Here there are two opinions. One is that spin-orbit part can be derived from the tensor force, and the other is that this part can not be derived from the tensor force, and therefore there should be $(l \cdot s)$ term in the fundamental interaction in order to give rise to this well established spin-orbit term in the collective potential of the shell model. I do not think this question is decided. I personally think that the tensor part cannot give rise to the spin-orbit coupling. But my statement is not very strong, because it is based only on the following facts. In the second order Born approximation, the tensor force in the fundamental interaction gives the wrong sign here and much too small an amount. That means that anybody who believes that this tensor force gives rise to the $(l \cdot s)$ term in $U(r)$ must show that exact calculation gives you much more than the Born approximation and turns around the sign. That is a rather improbable situation.

**Yoshida** Recently Terasawa has shown that if one takes into account the pair excitation from closed shells, one can really get spin-orbit interaction in the shell model from the two-body tensor forces, with correct sign and right order of magnitude.

**Weisskopf** I would be very pleased if this is true. Maybe I am wrong. I have tried this one time ago. One can easily make mistakes and also miss some terms. Is this published already?

**Yoshida** Yes. In the latest issue of the Progress of Theoretical Physics (Prog. Theor. Phys. 22(1950), 150; ibid. 23 (1960), 87).

**Weisskopf** Now I would like to talk about the surface of the nuclear matter. All the calculations that have shown that the free particle is a good approximation assumed that the nucleus has an infinite dimension, which made the calculation tremendously easier. One has no boundary condition; one knows the form of the wave function, i.e. they must be plane waves and one can make use of the high density of the nuclear
matter, because the high density is an important fact to make the free particle a good approximation. High density makes the Pauli principle very important. Now it is clear that when you come to the edge of the nucleus, the density goes down, and the whole situation becomes more complicated. Many attempts have been made to take this into account, but I do not think there is any clear solution which explains how nuclear matter behaves at the boundary. Therefore I would like to see the problem of half infinite nuclear matter solved. (Fig. 1) Here for $x$ going to infinity we have nuclear matter, for $x$ going to minus infinity we have vacuum. This is a very simple one-dimensional problem, and I would like to know how the boundary looks; i.e. how the density depends on $x$, in this very general case and how are the correlations. We know for $x \to \infty$, in the center, that there are very weak correlations between the particles, since the free particles are very good approximation. When we go into the surface, what happens with the correlation? There are two effects there in opposite directions. In one respect the Pauli principle will be less important here because of the low density that will increase the correlation. On the other hand, the correlations generally decrease for low density. So what will we win out? It will probably be stronger, but we have no quantitative calculation. There is one numerical calculation by Brueckner and collaborators about a finite nucleus, but when you give a problem to the machine, you do not understand it any more. Maybe the machine does. But you do not know what is really going on. Therefore I think the half space problem of nuclear matter should be solved so that one can see the solution and understand it. That is a very difficult problem, but I think it is a very important problem also because of the following reason, and here I speak about a new problem. We know that the potential $U(x)$ is a real potential when the nucleus is in its ground state. If, however, we have a particle in an excited state, and additional particle
above Fermi energy, then the collective potential for this particle can be expressed by a complex potential. In this case we have

$$U(r) = U_n(r) + iW(r).$$

This imaginary part $W(r)$ can in principle also be calculated by the method of Brueckner, and has also been calculated by a number of people; by Oda and Harada here. We have also made a similar calculation as they, and it turns out that the imaginary potential is especially strong just here in the surface (Fig. 2). Now I would like to say that we are not sure that this is correct, because neither we in Cambridge nor you here know how to treat the surface, and both of us have made very, very bad approximations. It is probably true, and if it is true it shows how important it is to understand the surface, because the imaginary potential is especially strong here at the surface; that means that all the important nuclear reactions will take place here, and not in the centre. This again just emphasizes the fact that an understanding of this region is most desirable. As long as we only know what is going on inside the nucleus, we do not know very much.

**Tamura** From what experiment can one get the knowledge of the radial dependence of $W(r)$?

**Weisskopf** It is very hard to determine these functions simply from the analysis of experiments; e.g. the analysis of elastic scattering experiments. It is not too good a method. The experimental situation is this. There are certain people who maintain that they get a better agreement with the theory if you assume a maximum of $W(r)$ at the surface. However, these analyses are not very exact. For example, one does not know whether the maximum would be inside or outside of the half-fall-off radius. The calculation which we made, and the calculation which was made here,
show that the maximum is pretty far outside; in fact our calculation gives it in farther outside for low energy particles. If a neutron, for example, comes in with energy of 3—4 Mev, we get a maximum even further out than the half-fall point. The experiments cannot yet decide this.

_Tamura_ Previously the Saxon type radial dependence of \( W(r) \) was thought also to give fairly good agreement with experiment.

_Weisskopf_ Yes. For the elastic scattering there is very little difference. It is very important for the theory of reactions, whether the maximum is inside or outside. However, so far the elastic scattering experiment was the only place where you can get some information. Therefore the experimental method has not been too good.

The way that we have calculated \( W(r) \), I must say, was a very bad one because we have calculated as if we had an infinite nuclear matter for each density, and obtained \( W(r) \) as a function of the density of nuclear matter, and plotted it in Fig. 2 as a function of \( r \) as the density goes down. That is, of course, very inexact because the situation here is quite different from that in infinite nuclear matter. This again shows that the problem of the surface is not yet solved at all.

(iii) Deformed nuclei

Now let me go over to deformed nuclei. Here very great progress has been made in last five years, mainly through the work of Bohr and Mottelson. Nuclear spectroscopy has become a completely different science when Bohr and Mottelson discovered the fact that deformed nuclei give rise to rotational spectra. The fundamental ideas as to what is deformed, and what causes the deformation have had gone through a lot of changes, and quite a number of problems are still unsolved. But let me shortly say in what way, I think, one understands the situation now.

Here I have to come back to the previous division of the nuclear forces between two particles into the part which can be expressed by an average potential in nuclear matter, and another part which still must be considered as individual particle interaction.

Let me do this a little more mathematically. We can expand the two-body potential \( V(r_{12}) \) (we neglect about its spin dependence) in spherical harmonics as

\[
V(r_{12}) = \sum_{l=m} a_{lm}(r_1, r_2) Y^{*}_{lm}(\theta_1, \varphi_1) Y_{lm}(\theta_2, \varphi_2).
\]

There is a connection between this sum here and the division in (1). In fact, if one makes the assumption that \( U(a) \) is either spherically symmetric or elongated, but has no further detailed structure, then the sum of (4) over \( l=0, 1 \) and 2 gives rise to \( V_{\text{tot}} \), and the sum over \( l=3, 4, \ldots \) gives rise to \( V_{\text{tot}} \). This can be seen as follows: A spherically symmetric
field means averaging over $Y$'s except for $l=0$. If one also allows for an elliptical deformation, then one also takes $l=2$ into account. The $l=1$ function is not really important, because it is only a displacement of the center of mass. We will for a moment forget about $V_{\text{indiv}}$ and only look at $V_{\text{coll}}$. In some ways, but not very exactly, one can call $V_{\text{coll}}$ "long range", while $V_{\text{indiv}}$ "short range". This is not really very accurate, but evidently the short range features are in the higher $l$'s and the long range features are in the lower $l$'s.

I would like now to explain in very simple terms, that when we assume that only $V_{\text{coll}}$ is different from zero then we would certainly expect a deformed nucleus, in a nucleus with a not-closed shell. In other words $V_{\text{coll}}$ alone gives rise to deformation with an open shell. Why?

Let us take the simplest case, i.e. let us take a shell with given $j$. This is a simplification, because we know that the nuclear shell contains not only one $j$, but also several $j$'s. We know that this shell is $(2j+1)$-fold degenerated. Let us put $n$ particles in this shell, $n$ being less than $2j+1$, and ask ourselves what will be the lowest state.

Let us assume that $n=2$ as the simplest case. Then it is clear that the lowest state is the one where the two particles are in substates which give rise to the strongest deformation. Actually the two particles are in $m=l$ state. Why? Because the wave function of this state has the shape of Fig. 3 and so if the nucleus is deformed in the same fashion, then the energy will be lowered. Whenever $n<(2j+1)$, the particles will go into those states, which give rise to the largest deformation, so that the kinetic energy becomes as low as possible.

In fact, however, this is not so. We know that the nuclei are not always deformed even if they have open shells: they are deformed only when $n$ is large. The reason for this is that $V_{\text{indiv}}$ acts against deformation. Why?

One can also understand this very simply. $V_{\text{indiv}}$ is an interaction which is short-ranged, because relatively high $l$'s are involved there. Therefore the $V_{\text{indiv}}$ would like to have a very strong overlap of the wave functions. Therefore the $V_{\text{indiv}}$ likes to form states in which all particles are grouped in pairs of $j=0$. $V_{\text{indiv}}$ forms the states of so-called seniority zero. They are spherically symmetric; that opposes the deformation, and thus we have here two opposite elements: $V_{\text{coll}}$ likes to get deformation, because it gives the lowest kinetic energy. $V_{\text{indiv}}$, however, gets lowest energy for spherically symmetric states. Which one is stronger? The effect of $V_{\text{coll}}$ will be proportional to $n^2$, because of the fact that the
kinetic energy goes down with the elongation; the deformation is proportional to \( n \), the energy decreases in proportion to \( n^2 \). On the other hand \( V_{\text{indiv}} \) or the pairing energy, of course, is only proportional to \( n \) because the number of pairs which one can form is just proportional to \( n \). Each pair will give a certain energy decrease, which is called the pairing energy, and that is just proportional to the number of pairs that one can form.

Then you will see that for small \( n \), \( V_{\text{indiv}} \) wins, and for large \( n \), \( V_{\text{coll}} \) wins. So you will expect that, if you start from closed shell and add up particles, first you will get spherically symmetric nuclei until you come to certain characteristic \( n = n^* \), and for \( n^* < n < N - n^* \), where \( N \) is the total number of places in this shell, you get the deformed nuclei. This is just what the experimental discovery by Sharff-Goldhaber and Wenser was shown, namely that if you are filling a shell, then up to certain \( n = n^* \) you get vibrational spectra, and for bigger \( n \) you get rotational spectra. The vibrational spectra appear if spherical nuclei vibrate around the spherically symmetric equilibrium position. The frequency of this vibrational motion, \( \omega \), goes down with increased \( n \), because the nearer we come to \( n^* \), the less the restoring force simply because the restoring force is an \( n \) term minus an \( n^2 \) term. Then finally you come to \( n > n^* \) side, and you get deformation. The theoretical treatment of this problem of vibration was quite successful, and one could calculate this part very well, which I will show in a seminar in Kyoto.

There are still many theoretical problems in the rotational spectra, which are not solved yet; let me just mention the main problem which is not quite understood yet, although some progress has been made. That is the problem of the moment of inertia. The question is: "Can one predict theoretically the amount of deformation and is the moment of inertia correctly calculated?" Here we meet certain difficulties. In the middle of the shell where \( n \) is large, you will get very large deformations. Then one should be able to neglect \( V_{\text{indiv}} \) completely; that should mean that one would have to do with particles that move like free particles in the collective field. Now there is a rule that free particles moving in a deformed field give rise to a moment of inertia which is the same as the moment of inertia which you will get simply by the rigid rotation of the mass distribution. If \( n \) is much larger than \( n^* \), we can neglect \( V_{\text{indiv}} \), and the moment of inertia \( \mathcal{J} \) is equal to \( \mathcal{J}_{\text{rig}} \).

The experiments, however, have shown, as you know, that \( \mathcal{J} \approx (1/3 \sim 1/5) \mathcal{J}_{\text{rig}} \). It is true that the consideration of the interaction, \( V_{\text{indiv}} \), cannot be completely neglected. If one considers the interaction, it reduces the moment of inertia and one obtains results in the neighbourhood of the experimental one. But there is still some problem whether one gets
the correct value, since $V_{\text{indiv}}$ is certainly only a small perturbation and one must be able to understand why a relatively small perturbation gives such a large change in the moment of inertia. I think some studies here are necessary.

Altogether I would say that, as far as the deformed nuclei are concerned, the situation is relatively good. One has, I think, understood the essential points. One knows qualitatively what the phenomena are, but quantitatively there are quite a number of problems. The theory of this field is especially interesting, because it has strange similarities with the theory of superconductivity. This similarity is purely formal and, at least to my mind, the physical reason why these two things should be connected is not obvious. But somehow similar mathematical formalisms are used, and that is why theorists are quite attracted by this field.

Let me also mention another problem here. One usually assumes that the whole vibration and deformation concerns only the particles which are in the open shell. The question arises: "Do the closed shells which are below the open shell also participate in the deformation?" This is still a problem. The probable answer is this. In the vibration region, there are only a few particles in the open shell, and the closed shells are pretty inert. That means that the vibration is made only by the open shell. But in the case where $n > n^*$, i.e. for large deformations, these deformations are so big that also the closed shells below are broken up and deformed. Then, of course, the mechanism becomes more complicated and this has not been investigated too well.

In the early period of the Bohr-Mottelson model, one always has assumed that the whole nucleus is deformed. Now one thinks rather that, especially for small deformations, only the open shells participate.

Tamura How do you think about the calculation of Mottelson and Nilsson?

Weisskopf Nilsson's and Gottfried's calculations are actually, in my mind, applicable only to large deformations, and there, just as Mottelson and Nilsson have shown, the lower closed shells are broken up. But for smaller deformations Nilsson's calculation probably does not make much sense, and then what are deformed might only be the open shells.

(iv) Nuclear reactions

We now proceed to the fourth part; the theory of nuclear reactions. There the situation is rather sad. The theory of reactions was in the old days strongly influenced by the compound nucleus idea; namely the division of the reaction into two parts; formation of the compound nucleus and the decay of it. Today our knowledge of the properties of nuclear matter, the individual particle motion, has, of course, made this picture rather
questionable because the idea of the compound nucleus was based upon
the theory that, if a particle enters into the nucleus, it interacts very
strongly with other particles inside the nucleus. We have just learnt,
however, from the analysis of nuclear matter that the particle does not
interact strongly. So there is a conflict of the compound nucleus vs.
independent particle model.

However, the situation perhaps is not quite so bad, because the theory
of nuclear matter has at least given us means of understanding the first
part of nuclear reactions, namely the interaction between the incident
particle and the target. This can be described by the optical model.

The nuclear reaction can be described as

$$a + X = b + Y.$$  \hspace{1cm} (5)

As long as one is interested in what happens to $a$, and not in what
will be the $b$, one can describe the nuclear reaction with the optical model.
The optical model contains the following two phenomena; scattering and
absorption.

The scattering is the re-emission of the particle without change of
the quantum state of the target, and absorption contains everything else,
i.e., is the real reaction. The optical model can describe these two alter­
natives. One assumes that the incident particle is subject to a potential
which can be written as a sum of a real part and an imaginary part:

$$V(r) = U(r) + iW(r),$$  \hspace{1cm} (6)

and we get scattering plus absorption. The trouble is that we do not
know what is the absorption. It might be inelastic scattering, it might be
emission of other particles. It might be compound nucleus formation; it
might also be direct reaction, or surface reaction. So anything where the
energy is transferred to the nucleus is the absorption. The energy region
in which one really knows something about what happens is the very low
energy region, and I would like to explain this.

If you have a reaction of the kind

$$a + X = C$$  \hspace{1cm} (7)

with energy $\varepsilon$, you can divide the energy region into two characteristic
parts. At very low energies, the system $C$ (We would not call this a
compound nucleus, but a quantum mechanical system composed of $a$ and
$X$.) has certain spectrum. We know that if the energy is very low, we
find resonances. But as we go up with the energy of the reactions, the
widths of the resonances becomes larger until it goes over into a continuum.
We find a division into resonance region and continuous region.

In the resonance region we know a little more about what the absorp-
tion is. In the resonance region, we have elastic scattering, but the absorption can only take place in the resonances themselves. The resonances are quantum states of this system $C$. Therefore the resonances are necessarily compound states. By compound states I mean the state of a quantum system whose properties are independent on the way that it is produced; just as the definition of the compound state in the sense of Niels Bohr, let's say, because the quantum state has well defined properties. If we hit a resonance, then the particle really has interacted with all other particles, because it has formed one definite quantum state. In this quantum state the motion of all the particles are well defined. If we formed the same quantum state by another way, then we must have exactly the same properties, because it is a quantum state. However, if we come into the non-resonance region, this does not hold any more, because there the width is large and with one energy we excite many quantum states. Then it is very important with what phase we excite this. Therefore the compound state will depend very much on how it is made. In order to get a better understanding we must use some simple model of the interaction between incoming particle and nucleus.

We have two extreme models. One is based upon the idea of compound nucleus formation; the energy is distributed statistically over the whole nucleus, and this leads subsequently to evaporation. We have seen that this kinds of compound nucleus formation make really sense only in the resonance region.

One can also take an opposite view of the compound nucleus. One can say that there is a very little interaction; the independent particle model. If a particle gets into the nucleus it interacts only with one other particle and then gets out. This view is what one calls the direct interaction: The incoming particle interacts with only one other particle. This model has the advantage that it can be calculated, as has been done by Butler, Austern and McManus and also by many other people who did calculations of direct interactions.

The method of direct interaction is only an approximation. In the resonance region, this method leads to the same results as the compound nucleus method, as one can see in the following way: In this region the energy is very low, and when the incoming particle (a) hits another particle (b), then the situation is as seen in Fig. 4. The incoming particle (a) has lost energy, (b) has obtained energy, and both do not have enough energy to escape, ex-
cept in the rather improbable case in which (a) goes down all the way and (b) all the way goes up. So in general, these two particles are caught, in the nucleus, where they spend a long time, and collide with other particles, thus exchanging their energy. This is what amounts to a formation of a compound state. So the direct interaction can only occur at higher energies.

At present, we can calculate only two extreme cases: The case of formation of a compound nucleus and the case of direct interaction. The truth probably lies in-between, because we expect to find reactions of “different order.” I call the direct interaction a reaction of the first order, where the particle hits only one particle, before the reaction is accomplished. A second order reaction would be the one in which the particle hits one particle and then another and so on. From this point of view the formation of a compound nucleus is really a reaction of infinite order. What the theory can handle so far is either the infinite order or the first order.

Let me perhaps at the end illustrate the situation by means of the following kind of “Gedanken-Experiment.”

Let us have a nucleus, and an incoming particle, which does not have an exact energy. It is described by a wave packet as it was discussed some years ago in an article by Friedman and myself. The wave packet has finite length in time, a pulse with length $\Delta t$. This $\Delta t$, of course, corresponds to $\Delta \epsilon$, the width of energy. Here $\Delta \epsilon$ should be large compared to $D$, the level distances of the compound states, but should be small compared to the spacings of the one particle resonances. If the reaction is of the type

$$a + X = b + Y,$$

then one can ask whether $b$ will come out right away, or $b$ will come out later, or what is the time dependence of the secondary reaction.

If we are in the resonance region, one can solve this problem exactly, and one finds out that if the pulse shape of the incoming beam is given by the curve (a) of Fig. 5, then that of the outgoing beam is given by

![Fig. 5.](https://academic.oup.com/ptps/article-abstract/doi/10.1143/PTPS.11.52/1932522/67941)
the curve (b) of the same figure; i.e. the outgoing beam is composed of a part that has the same shape as the incoming beam and another part that has a very long tail. The first part is what we call the shape elastic scattering and the latter is the compound elastic scattering.

Physically what happens is this. The optical potential gives rise to an immediate scattering. The absorption forms the compound nucleus and the compound nucleus has a long life so that the particles come out very slowly and very late. That means one has a reaction of zero order, that is the scattering which occurs immediately, and a reaction of infinite order which takes a very long time.

Now the question arises what happens if the energy of the incoming particle is above the resonance region.

If we have reactions of the first and second order, the secondary particle will come out immediately, or almost immediately. If we have mainly reactions of very high order, then it would come out very late, and we have a long, long tail. I believe that in fact we have a mixture of all kinds of orders. That means that we get something like the pulses as shown in Fig. 6, in which \( n \) signifies the order of the reaction. You first get the curve \( n=1 \) and then if further you wait, you get curves with higher \( n \)'s.

Physically speaking, the particle gets in and reacts with one particle. That is the first order reactions. This one particle has a chance to get out, but it has also a chance to hit the second particle and this might get out. That is the second order reaction, and so on. We do not know what order is the important one. For example, it might be that the particle reacts with the nucleons in the open shell, and not in the closed shells. That would limit the order of reaction.

There are quite a number of experiments, and some of them were told here to us this afternoon, where the evaporation formula were quite well fulfilled. That might mean many things. It might mean that really the higher orders are important. But it might also mean that some of the lower orders essentially give the same result as the evaporation. So from experiments, even if the evaporation formula is fulfilled, we cannot conclude too much. More evidence one can get from the following thing.
The distribution of the outgoing particles is given in the compound nucleus theory by
\[ P(\varepsilon)\,d\varepsilon = \text{const.} \, \varepsilon w(\varepsilon_0 - \varepsilon) \sigma(\varepsilon)\,d\varepsilon. \] (9)

This is the evaporation formula. If the reaction is mostly a higher order reaction, then this formula should be correct and this \( w \) should be the level density of the residual nucleus. And all the reactions which lead to the same residual nucleus should give the same level density. There are experiments in which different reactions lead to the same residual nucleus. Unfortunately, one finds different level densities depending on what reactions are observed. This shows that we are not really dealing with a higher order reaction but with something in-between. In other words, if the reaction is
\[ a + X = b + Y \] (10)
and
\[ c + Z = b + Y, \] (11)
then the function determined by (9) should always be the same. But in many experiments this is not so. That means that the order of the reactions is not infinite. Somehow the reactions excite different parts of the residual nucleus in different experiments. Hence it is not the real compound nucleus that is formed, but it is a reaction of lower order.

I would like to end by saying how very little we know about reactions. Our knowledge of the first part of a reaction is better because it is based upon the optical model which seems to be a very good description of experiments. But the second part of the reaction is very difficult to describe and many problems are unsolved.

I have covered only small parts of nuclear physics, just parts which I myself am interested in these days. Even in those parts there is so much to be cleared up. I hope that the theorists and experimentalists in Japan will do much of this work. They have done so much in many other parts of physics, and I am confident that they will also solve all these problems.

Tomonaga From the experimental knowledge of the function \( w \) in (9), i.e., the level density of the residual nucleus, would not it be possible to estimate the number of particles which participated in the reaction?

Weisskopf It could be a way of clarifying this problem. One still has to have some theory in finding a relation between \( w \) and the order of the reaction.

Tamura Izumo and others at the Tokyo University of Education considered that only a fraction of the nucleons in the target is interacted. They claimed that in this way they could explain the experiments by
Matsuda et al., which found several peaks, with distances of the order of a few hundred kev, in the excitation curves of some \((p, p')\) reactions of medium heavy nuclei. I personally think, however, that it is difficult to justify this sort of approach.

In connection with this, it seems to me, at least the lower order reactions in your sense is concerned, that the main part of the reaction might go through in a way as would be described by the Monte Carlo Method.

\textit{Weisskopf} It could be. However, I want to draw your attention again to the fact that even in this case the main part of the reaction will occur at the surface, and that we do not know anything about the surface.