Nishina Memorial Lecture

Niels Bohr and the Development of Concepts in Nuclear Physics

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It is a great priviledge for me to be able to join with you in this celebration of Niels Bohr, scientific revolutionary, and fore-sighted thinker on questions bearing on science and on the human condition as well as being our common teacher. This is indeed an occasion on which scientists in both Japan and in Denmark can feel pride and inspiration. I think especially of the early decades of this century when Nishina participated so effectively in the work at Niels Bohr's institute and then returned to Japan to set in motion the development of modern physics in Japan that has produced so many marvelous results. I wish to thank very warmly the Science Council of Japan, the Japanese Physical Society, and the Nishina Foundation for their kindness in providing this opportunity.

In preparing for this occasion, I quickly realized that any attempt to report systematically on Niels Bohr's many very different contributions to modern science is more than I am competent to do and would inevitably be a program too rich and diverse to be compressed into a single lecture; I therefore decided to confine my report to a discussion of Niels Bohr's profound contributions to the understanding of atomic nuclei and even here, as you will see, I have been forced to drastically abbreviate some parts in order to properly describe the general background of the development and to include a little of the subsequent impact and evolution of the ideas initiated by Bohr.

Let us begin at the beginning: Niels Bohr was eleven years old when Becquerel discovered the first hint of the existence of atomic nuclei in the occurrence of natural radioactivity, a kind of faintly glowing ashes left from the violent nuclear phenomena that created the heavy elements from which our solid earth and living bodies are made. Fifteen years later Rutherford used the natural radioactivity as a marvelous probe which established the profound distinction between the open, planetary structure of the atomic electrons surrounding the small, dense, enigmatic atomic nucleus in the center. This discovery made possible Bohr's analysis of the dynamics of the electrons in the atom which lead to the discovery of quantum mechanics. However, the understanding of properties of atomic nuclei in terms of a dynamics of nuclear constituents had to wait for more than 20 years, until after Chadwick's discovery of the neutron (1932). At last one could begin a rational theory of the structure of atomic nuclei.

Immediately after the discovery of the neutron, it was Heisenberg who took the first step in developing a theory of nuclear structure by recognizing that

(i) a nucleus of charge $Z|e|$ and mass AM can be considered as a composite system built out of A protons and (A-Z) neutrons;

(ii) a new force of nature (later called the 'strong' interaction of 'nuclear' force) is required to hold this system together.

From the available evidence on nuclear masses and stability, Heisenberg, Wigner and Majarana were able to derive some basis features of this new force. The fact that the nuclear volume and binding energy are approximately proportional the total number of neutrons and protons (in contrast to atomic binding energies that go as $Z^{7/3}$) implies that the nuclear forces saturate. The magnitude of the nuclear binding energies imply that the nuclear forces are much stronger than the electric forces even when one takes account of the 1/r dependence of the latter and the fact that nuclei are 10^4 times smaller than atoms. A comparion of the binding of the deuteron and ^{4}He nucleus shows that the forces are of short range (a few times 10^{-13} cm) (Wigner 1933).

It was, of course, this last feature that Hideki Yukawa recognized as the crucial point in formulating a fundamental theory of these interactions based on the exchange of massive bosonic quanta. Yukawa's insight was a major turning point in the whole development. For nuclear physics it provided the first insight into the microscopic origin of nuclear cohesion, and at the same time it provided a fundamental scale of length and energy at which one must expect major corrections to the picture of nuclei as build out of neutrons and protons. Especially this last point can be seen as the opening of the great development of elementary particle physics which reveals that the proton itself, when examined on a fine enough scale, has a rich and fascinating composite structure.

But, now I have gotten far ahead of my story and so I must go back to the period around 1932-34 when, at last, it became possible to begin the detailed discussion of the structure of nuclei based on a picture of the nuclei as composite systems built out of neutrons and protons. It is at this juncture that the first nuclear accelerators begin to provide evidence on nuclear reactions produced by protons and deuterons (Cockcroft and Walton 1932, Lawrence and Livingstone 1932). However the energies available in these early machines were only sufficient to produce reactions in the lightest elements.

At this point, Fermi (who had done theoretical work up to this time) realized that the recently discovered neutron afforded a powerful tool for producing reactions in even the heaviest nuclei. The difficulty with neutrons was that they had first to be produced by bombarding Be with natural alpha particles and thus there were not too many of them; in the experiments in Rome the sources produced of order 10^7 neutrons/sec. This disadvantage was however compensated by the fact that the neutron, having no charge, can reach the nuclei of all atoms without having to overcome the repulsive electric potential barrier that surrounds the nucleus. Fermi and his collaborators took up the program of irradiating all the elements of the periodic table with neutrons; they started at the beginning of the periodic table and by March 25, 1934 they had reached ${}_9F$ and observed their first new radioactivity $({}^{19}_{9}F(n\alpha){}^{16}_{7}N(\beta^-){}^{16}O)$. With the heavier elements they soon discovered that in almost every case new radioactive species were produced. It was an enormous expansion of the material available for studying nuclear processes. They showed that in most cases the radioactivity was produced by radiative capture $({}^{A}Z + n \rightarrow {}^{A+1}Z + \gamma)$.

Having found this wealth of new activities the Rome workers began studying the relative efficiency with which the different activities were produced, i.e. establishing relative cross sections for the neutron reactions with different substances. In the course of this work one day Fermi, in an apparently unpremediated act, inserted a piece of paraffin, between the source and the sample (Ag) and immediately observed a marked increase in the rate of activation. The same day he had interpreted the effect as resulting from the slowing down of the neutrons in their collision with hydrogen in the paraffin, the slow neutron apparently having a larger cross section for capture than the fast neutrons (which had energies extending up to about 8 MeV) coming directly from the source.

These developments stimulated theoretical analysis of the interaction of slow neutrons with nuclei and soon papers were published by Beck and Horsley (1935), Bethe (1935), Fermi (1935), and Perrin and Elsasser (1935). All of these authors based their analysis on the interaction of the incident neutron with a nuclear potential that was assumed constant inside the nuclear volume. These investigations provide valuable insight into the prevailing prejudices as well as the tools available for the analysis of the nuclear problem at this time and therefore the analysis is briefly recapitulated in Table I. The description in terms of a single particle potential in these investigations was borrowed directly from the successful use of this description for the scattering of electrons by atoms. We may wonder whether the practitioners had other reasons of theoretical or experimental nature for believing in the appropriateness of this description. Apparently such evidence or arguments was quite lacking, as indicated by a remark in Bethe's paper, "It is not likely that the approximation made in this paper, i.e. taking the nucleus as a rigid body and representing it by a potential field acting on the neutron, is really adequate ... . Anyway, it is the only practicable approximation in many cases ..."

The analysis in Table I implies that the $(n\gamma)$ capture cross sections should depend on the neutron energy as $(E_n)^{-1/2}$ over a considerable range of energies and thus one obtained a direct explanation for the observed increase in activation produced by slowing down

I <u>wave lengths</u>

outside nucleus:

$$E_n \sim kT \sim 0.025 \text{ eV}$$
$$\bar{\lambda}_{out} = \hbar/(2ME)^{1/2} \sim 3\times 10^{-9} \text{ cm}$$

inside nucleus:

$$E_n \sim V_0 \sim 50 \text{ MeV}$$
$$\bar{\lambda}_{in} \sim 0.6\times 10^{-13} \text{ cm}$$

II <u>residence time</u> for neutron in nucleus, t_{in}

a) traversal time, τ_0

$$\tau_0 = \frac{2R}{v_{in}} \sim \frac{10^{-12}\text{cm}}{10^{10}\text{cm/sec}} = 10^{-22} \text{ sec}$$

b) reflection at nuclear surface

$$T_R = 1 - R$$
$$\frac{\bar{\lambda}_{in}}{\bar{\lambda}_{out}} \sim 10^{-4}$$

c) residence time

$$t_{in} = \tau_0 \, (T_R)^{-1} \sim 10^{-18} \text{ sec}$$

III gamma <u>radiation</u>

P = radiation probability/time

$$= \frac{4}{3}\,\frac{1}{\hbar}\left(\frac{E\gamma}{\hbar c}\right)^3 |P_0|^2 \qquad E_\gamma = \gamma\text{-ray energy} \sim 7 \text{ MeV}$$

$$\sim 10^{17} \text{ sec}^{-1} \qquad P_0 = \text{"dipole moment"} \sim eR \sim 10^{-12}\text{cm}\cdot e$$

IV Cross sections

(a) $t_{in} \Rightarrow \Delta E_n \sim \frac{\hbar}{t_{in}} \sim \text{keV}$

thus, cross sections are <u>smooth</u> and <u>universal</u> for $E_n \lesssim$ keV

(b) $\sigma_{n\gamma} \propto t_{in} \propto (E_n)^{-1/2}$

(c) $\frac{\sigma_{n\gamma}}{\sigma_{scat}} = P\cdot t_{in} < 1$

TABLE I Analysis of slow neutron reactions (1935)
Beck + Horsley; Bethe; Elsasser + Perin; Fermi

the neutrons in paraffin. However, almost immediately the theory began to run into difficulties. The capture cross sections of some elements for slow neutrons were found to be unexpectedly large (in some cases as much as 100 times the geometrical cross section of the nucleus) and the elastic scattering cross section in these cases was not exceptionally large.

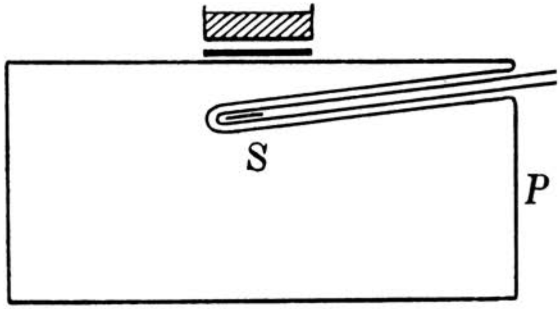

FIGURE 1

Arrangement used by the Rome group for studying the absorption cross sections of slow neutrons (Amaldi 1984). S = neutron source, P = paraffin block, A = absorber, D = detector.

And then came the remarkable discovery of "selective absorption" (Bjerge and Westcott (1935); Moon and Tilman (1935)) which was quite outside the theoretical expectation of a smooth energy dependence of the cross section. The experimental set up for the observation of this effect is the very essence of simplicity and elegance (Fig. 1) and consists of a neutron source (Be + Ra) a paraffin moderator, the material whose absorption is being measured and a detector directly above the absorber. The amount of neutrons removed by the absorber was monitored by the amount of radioactivity produced in the material of the detector. The first measurements with this set-up confirmed, as expected, that the substances with large cross sections for activation also were especially efficient in attenuating the source. But, then it was noticed that the amount of the attenuation depended on the material being used as the monitor in the detector position. In every case it was found that when the detector was the same substance as the absorber, the observed attenuation was the greatest (see Table II).

detector \ abs.	Mn	Br	Rh	Ag	I
Mn	73	92	59	59	98
Br	81	61	79	79	86
Rh	88	96	54	67	97
Ag	86	91	68	45	89
I	79	84	91	70	55

TABLE II Evidence for selective absorbtion
Amaldi and Fermi (1935)

This was the "selective absorption" interpreted in terms of the broad energy distribution of the neutron sources and the occurrence of narrow energy absorption bands characteristic of each substance. By ingenuous arrangements involving the slowing down of the neutrons between absorber and detector it was possible to order the absorption bands of the different substances and even to get measures of the widths of the bands. The observed sharpness of the absorption bands implies that the slow neutrons residence time in the nucleus is an order of magnitude longer than the estimate given in Table I.

It was Niels Bohr who saw first and most clearly that these experimental discoveries concerning the interactions of neutrons with nuclei demanded a radical revision in the basic picture of nuclear dynamics. He recognized that the assumed single particle motion, copied from atomic physics, was being falsified and he suggested in its stead an idealization which focused on the many body features and the strong coupling of all the different degrees of freedom of the nuclear system - the compound nucleus.

There are two dramatic accounts (one by Frisch and one by Wheeler) of a colloquium in Copenhagen that appears to mark a decisive turning point in the development of these ideas. First, as reported by Frisch (1968):

> "According to what was then believed about nuclei a neutron should pass clean through the nucleus with only a small chance of being captured. Hans Bethe in the USA had tried to calculate that chance, and I remember the colloquium in 1935 when some speaker reported on that paper. On that occasion, Bohr kept interrupting and I was beginning to wonder with some irritation why he didn't let the speaker finish. Then in the middle of a sentence, Bohr suddenly stopped and sat down, his face completely dead. We looked at him for several seconds, getting anxious. Had he been taken unwell? But then he got up and said with an apologetic smile, "Now I understand it all", and he outlined the compound nucleus idea."

Wheeler's account appears to refer to the same occasion (Wheeler, 1979):

> "The news hit me at a Copenhagen seminar, set up at short notice to hear what Christian Møller had found out during his Eastertime visit to Rome and Fermi's group. The enormous cross sections that Møller reported for the interception of a slow neutron stood at complete variance to the concept of the nucleus then generally accepted. In that view, the nucleons have the same kind of free run in the nucleus that electrons have in an atom, or planets in the solar system. Møller had only got about a half hour into his seminar account and had only barely outlined the Rome findings when Bohr rushed forward to take the floor from him. Letting the words come as his thoughts developed, Bohr described how the large cross sections led one to think of exactly the opposite idealizations: a mean-free path for the individual nucleons, short in comparison with nuclear dimensions. He compared such a collection of particles with

a liquid drop. He stressed the idea that the system formed by the impact of the neutron, the "compound nucleus", would have no memory of how it was formed. It was already clear before Bohr finished and the seminar was over, that a revolutionary change in outlook was in the making. Others heard his thoughts through the grapevine before he gave his first formal lecture on the subject, before the Copenhagen Academy on January 27th, 1936, with a subsequent written account in Nature."

These recollections give a lively picture of the style of discussion at the Institute in the mid 1930's, but I should warn you that there is rather strong evidence that the two accounts cannot refer to the same occasions and thus it is impossible that both can describe the moment of conception of the compound nucleus. This question has been carefully considered by Peierls (1985), exploiting the extensive letters and unpublished manuscripts in the Niels Bohr Archives, who has concluded that Bohr had in fact been developing his ideas about nuclear dynamics for some time. The two colloquia reported by Frisch and Wheeler are then to be seen as occasions on which Bohr saw some additional significant piece of information fall into place. Significant support for the assumption of a long gestation period for the compound nucleus ideas is contained in several letters quoted by Peierls. In a letter to Gamow (26. Feb. 1936) Bohr writes, "As you will see from the enclosed article which will soon appear in "Nature", this is a development of a thought which I already brought up at the last Copenhagen conference in 1934 immediately after Fermi's first experiment about the capture of fast neutrons, and which I have taken up again after the latest wonderful discoveries about the capture of slow neutron." Similarly Rutherford writes to Max Born (22. Feb. 1936) reporting on Bohr's new ideas, "The main idea is an old one of Bohr's, viz. that it is impossible to consider the movements of the individual particles of the nucleus as in a conservative field, but that it must be regarded as a "mush" of particles of unknown kind, the vibrations of which can in general be deduced on quantum ideas. He consider, as I have always thought likely, that a particle on entering the nucleus remains long enough to share its energy with the other particles".

Let us now turn more directly to the consideration of the new ideas initiated by Bohr's article in "Nature" (1936). The core of Bohr's thinking is the recognition that the densely packed nuclear system being studied in the neutron reactions forces one to place the collective, manybody features of the nuclear dynamics at the center of attention. To illustrate these ideas I do not know of any better figures than those prepared by Niels Bohr in connection with lectures which he gave at this time and which were published in the same issue of "Nature" (as a news item) that contain his famous article. The first (Fig. 2) draws attention to the far reaching consequences for the

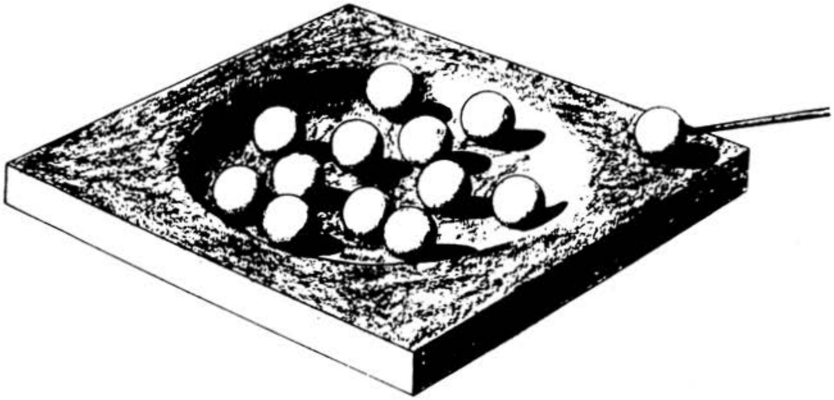

FIGURE 2

course of a nulear reaction of the assumption of a short mean free path for the nucleons. If we imagine the balls removed from the central region of the figure, the ball entering from the right will be accelerated as it enters the central depression, but just this acceleration ensures that after running across to the opposite side the ball will have enough energy to surmount the barrier on that side and run out of the nuclear region. A very different dynamical history results if we restore the balls to the central region. Now, the entering ball (nucleon) will soon collide with one of the balls of the target and, sharing its energy with the struck ball, will no longer be able to leave the confining potential. Being reflected back it will collide and share its remaining energy with still other balls and these struck balls will also collide and ultimately the total energy will be distributed among all the balls in a distribution of the type described by the equilibrium distribution of the kinetic theory of gases. In this situation the only possibility for one of the balls to escape from the central region requires the occurrence of a fluctuation in which almost all of the energy is again concentrated on a single ball which will then be able to surmount the confining potential. The unlikelihood of such an extreme fluctuation implies that the duration of the reaction phase is enormously increased (as compared with the first situation considered with only a static potential acting). This increase of the reaction time makes it possible to explain both the observed large ratio of capture to scattering cross sections for slow neutrons as well as the narrowness of the selective absorption bands. Perhaps even more important, the intermediate stage representing a kind of thermal equilibrium from which the final decay represents a rare fluctuation, ensures that the relative probability of different final states will be governed by statistical laws and is independent of the mode of formation of the compound system.

Fig. 3 shows Bohr's sketch of a schematic nuclear level system. The study of radioactivity had shown that the lowest excited states in heavy nuclei are of order a fraction of 1 MeV, and Bohr assumed that these excitations represent some sort of collective vibration of the whole nucleus. With increasing excitation energy an increasing number of different vibrational modes can be excited and the different possibilities for partitioning the total excitation energy between these different modes leads to an enormous increase in the total number of excited states. (Note the similarity to the mathematical problem of counting the number of ways of partitioning a given integer n into a

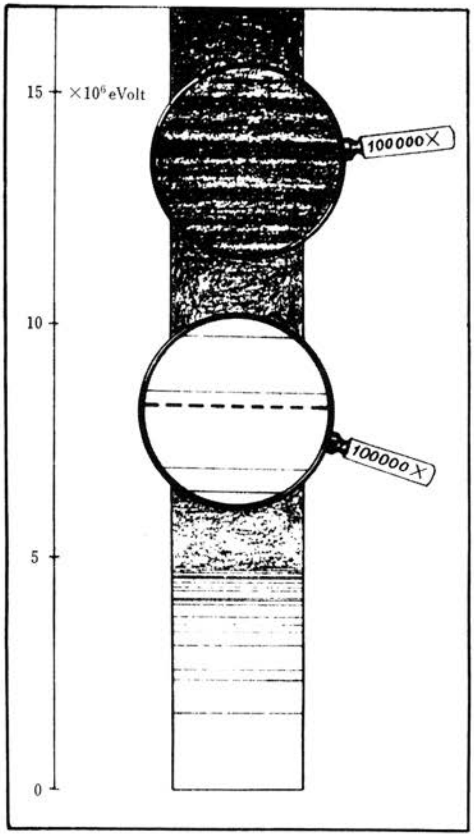

FIGURE 3

sum of smaller integers - a problem that had been solved by Hardy and Ramanujan who found an exponential increase in the number of partitions $(n\sqrt{48})^{-1}\exp\{\pi(2n/3)^{1/2}\}$.) All of these quantum states can be resonantly excited by an incoming neutron thus accounting for the dense spacing and narrowness of the levels observed in the selective absorption phenomena. The dotted line in the magnifying glass at about 10 MeV indicates the neutron separation energy, but the level scheme above and below this line are not significantly different; indeed, the neutron escape probability is much less than the γ-emission probability for levels slightly above this energy as a result of the extreme improbability of the fluctuation required to concentrate all of the excitation energy on a single particle. Only at higher energies will the neutron emission probability contribute appreciable to the width of the individual levels and lead to a broadening and eventually the overlapping of the level (indicated in the upper magnifying glass at about 15 MeV). Bohr contrasts this picture of densely spaced many particle levels in the nucleus with the spectrum of atoms excited in collisions with electrons

FIGURE 4

where the incident electron will at most collide with one of the atomic electrons causing it to change its binding state from one orbit to another; the resulting spectrum contains relatively few, widely spaced, resonances.

The profound reordering of the picture of nuclear dynamics implied by Bohr's ideas was, apparently, rapidly and widely accepted in the nuclear physics community; within months the literature is completely dominated by papers applying, testing, and extending the ideas of the compound nucleus. It would take us much too far to include within the framework of this lecture a discussion of the many significant ideas and discoveries which went into this development; as a very anemic substitute for such a discussion I have attempted in Table III to list some of main landmarks in the expanding development of the subject.

Each of these developments involves many deeply interesting ideas that significantly extended and exploited the general picture that Bohr had sketched. There is much too much to tell about here, so let me take a single example to illustrate the flavour of this development - I take as an example the first steps in the interpretation of the fission process.

The story begins already in 1934; Fermi and his collaborators had in their systematic studies irradiated Th and U with neutrons and had found induced activity. However, the results were difficult to interpret since for these elements (and for them alone) it appeared that many different activities were being produced simultaneously (compound decay curves). Four years later Fermi referred to these experiments which were being interpreted in terms of the production of "transuranic" elements in his Nobel lecture (December, 1938), but the picture was still confusing.

Just a month after Fermi's Nobel lecture, Hahn and Strassmann published the startling news that among the activities produced by neutron irradiation of U there was an isotope chemically indistinguishable from Ba ($Z = 54$). They say in their publication that as chemists they have to call it Ba, but as nuclear chemists a field with close connection to physics they cannot take this step since it would be in conflict with all previous experience in nuclear physics.

1. Resonance formula; Breit and Wigner (1936)

$$\sigma_n (E) = \pi\lambda^2 \frac{\Gamma_\gamma \Gamma_n}{(E-E_0)^2 + (\frac{1}{2}\Gamma_{tot})^2}$$

2. Level density and thermodynamic concepts

   Bethe; Bohr and Kalckar (1936-37)

   entropy α $\ell n\rho$

   temperature: $T^{-1} = \frac{1}{\rho}\frac{d\rho}{de}$

3. Nuclear decay as evaporation

   Weisskopf (1937)

   reciprocity arguments

4. Cross sections for "black" nucleus

   Bethe (1940); Feshbach, Peaslee, and Weisskopf (1947)

5. Semi-empirical mass formula

   Weizsacher (1935)

   Bulk energies (volume, surface, symmetry)

   pairing energy

6. Collective vibration of nucleus

   shape oscillations

   density fluctuations) Bohr and Kalckar (1937)

   electric dipole mode Migdal (1940)

   Baldwin and Klaiber (1947)

   Goldhaber and Teller (1948)

7. Fission: The compound nucleus' finest hour!

   Hahn and Strassmann (1939)

   Meitner and Frisch (1939)

   Bohr and Wheeler (1939)

TABEL III Major developments bearing on compound nucleus (1936-48)

On hearing of Hahn and Strassmann's work, Frisch and Meitner immediately recognized that the experiments were revealing a new type of nuclear reaction, which could be directly understood in terms of Bohr's ideas on the compound nucleus.

Indeed, all nuclei heavier than Zr are exothermic for a reaction that divides the nucleus into two approximately equal fragments. This instability is the result of the Coulomb energy which increases as $Z^2e^2/R \sim Z^2/A^{2/3}$ and thus eventually overwhelms the surface energy ($4\pi R^2 \sim A^{2/3}$) which holds the nucleus united and approximately spherical. For the heaviest nuclei the energy release can be estimated from the known masses and is of order 200 MeV. Thus Frisch and Meitner envisioned a process in which a heavy nucleus, acting like a charged liquid drop, divides itself, going through a sequence of more and more elongated shapes until finally the Coulomb forces take over and drive the two nascent droplets apart.

When Frisch told Bohr about these ideas, Bohr was enthusiastic. As told by Frisch, he had only a brief chance to tell Bohr of their ideas before Bohr was to leave for a trip to the United States:

'When I reached Bohr, he had only a few minutes left; but I had hardly begun to tell him, when he struck his forehead with his hand and exclaimed: Oh, what idiots we all have been! Oh, but this is wonderful! This is just as it must be! Have you and Lise Meitner written a paper about it?'

As is well known, Bohr and Wheeler took up, with great energy and breadth of scope, the problem of elucidating the various aspects of the fussion reactions, building on and extending the concepts of the compound nucleus. Of this very great development I can only remind you of a single little nugget, as told in the words of Leon Rosenfeld, who accompanied Bohr on that famous trip to the USA following immediately after the interview with Frisch which I quoted above. Rosenfeld tells of a morning in Princeton shortly after their arrival:

'Some time in January Placzek, who had just come over from Europe, came to see us as we were sitting at Breakfast at the Faculty Club. The conversation soon turned to fission. Bohr casually remarked: 'It is a relief that we are now rid of those transuranians'. This elicited Placzek's protest: 'The situation is more confused than ever', he said, and he explained to us that

there was a capture resonance at about 10 volts both in uranium and thorium showing, apparently, that transuranians were produced concurrently with fission. Bohr listened carefully; then he suddenly stood up and, without a word, headed towards Fine Hall, where we had our office. Taking a hasty leave of Placzek, I joined Bohr, who was walking silently, lost in a deep meditation which I was careful not to disturb. As soon as he entered the office, he rushed to the blackboard, telling me: 'Now listen: I have it all' And he started - again without uttering a word - drawing graphs on the blackboard. The first graph looked like this (Fig. 5a).

Clearly, the idea was to show, for thorium, the capture cross section, with its resonance at about 10 volts, and the fission cross section starting at a much higher threshold. Then he drew exactly the same graph, mentioning ^{238}U instead of Th, and he wrote the mass number 238 with very large figures - he broke several pieces of chalk in the process. Finally, he drew quite a different picture which he labelled ^{235}U. This was intended to show the fission cross section, with non-vanishing values over the whole energy range (Fig. 5c).

Having drawn the graph, he started developing his argument; obviously, the resonance capture must belong to the abundant uranium isotope, otherwise its peak value would exceed the limit set by wave theory. For the same reason, the fast neutron fission must also be ascribed to the abundant isotope, whose behaviour is thus entirely similar to that of thorium. Consequently, the observed slow-neutron fission must be attributed to the rare isotope ^{235}U: This is a logical necessity. The next step was to explain the similarity between the two even-mass nuclei Th and ^{238}U and the essential difference respecting fissility between the even-mass and the odd-mass uranium isotope'.

The difference results from the well-known pairing effect in the nuclear masses. A neutron added to a system with an odd number of neutrons forms a compound system with an additional neutron pair, and therefore with about 1 MeV more binding energy than when the neutron is added to an already paired system.

In retrospect, we may have the impression that this was fairly obvious conclusion from the facts. However, at the time it was far from obvious, and very few physicists accepted Bohr's explanation. Fermi, in particular, was highly skeptical.

The application, expansion, and deeper understanding of these ideas has undergone an enormous development in the fortyfive years since that time, and it would be quite beyond the scope of this lecture to even attempt an enumeration of all the important ideas that have, through the development, enriched the compound nucleus concept. However, there are two chapters in the post war development that I think I really must include; the reconciling of the compound nucleus with the occurrence of shell structure and as a second point the random matrix models.

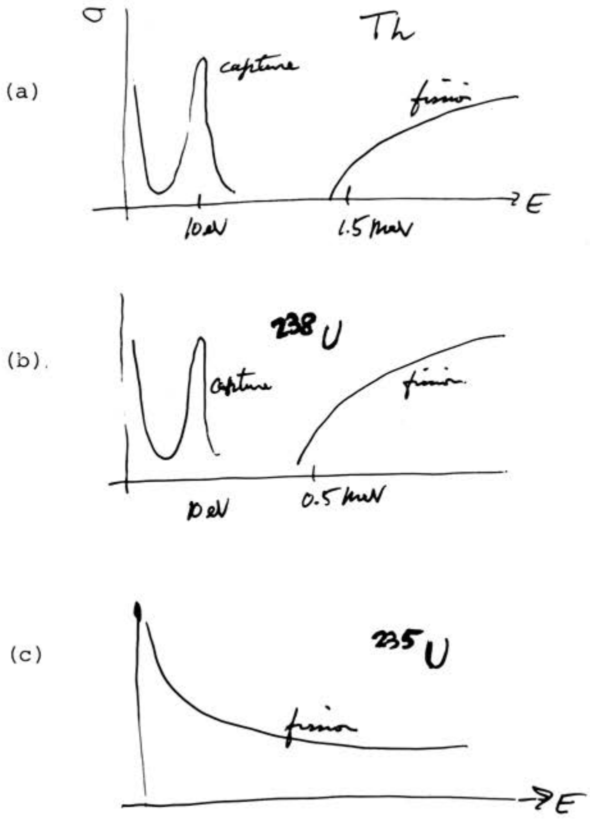

FIGURE 5

If we continue the story chronologically, the next step is the analysis in 1948 of the vastly expanded data on the systematics of nuclear binding energies by Maria Goepert Mayer, showing the unmistakable effects of nuclear shell structure. The correct independent particle model, based on strong spin orbit forces, was found by Mayer and independently by Haxel, Jensen, and Suess about one year later. This development, at first sight, seemed to disastrously undermine the arguments that had been employed to justify the compound nucleus concept - the mean free path of a neutron in the nucleus is long (for low energy neutrons $\lambda_c \sim 14$ fm) - not short, as assumed in arguing for the compound nucleus. But still, the compound nucleus idea had been enormously successful.

The resolution of this paradox is provided by considering the different time scales involved in single particle motion, in scattering, and in compound nucleus formation (see Fig. 6). The strong reflection of slow neutrons at the nuclear surface implies that the

TIME SCALES IN NUCLEAR REACTIONS

(1) traversal time, τ_0

$$\tau_0 = \frac{2R_0}{v_{in}} \sim 10^{-22}$$

(2) collision time, t_{col}

$$t_{col} = \frac{\hbar}{w} \sim 6 \times 10^{-22}$$

w = absorbtion potential

~ 1 MeV

(3) single particle residence time, t_{in}

$$t_{in} = \tau_0 / T$$

T = transmission of nuclear surface

$\sim \left(\frac{\lambda_{out}}{\lambda_{in}}\right)$

$\sim 10^{-4}$ slow neutron

$t_{in} \sim 10^{-18}$ sec

(4) physical pictures

"black nucleus"	:	$t_{col} < \tau_0$
shell structure	:	$t_{col} > \tau_0$
compound nucleus	:	$t_{col} < \tau_{in}$

FIGURE 6

residence time of the neutron is much longer than the traversal time (see also Table I). If the collision time is short compared with this residence time, the compound nucleus will be formed and Bohr's ideas will be applicable. This is not at all in conflict with the occurrence of shell structure and single particle motion which is a major effect under the much weaker condition that the collision time is comparable to or longer than the traversal time.

If we now look back over the development of nuclear physics in the period 1933-52 we see, besides the great discoveries of different types of nuclear reactions and processes, a gradual clarification of the nature of that fascinating new form for matter encountered in nuclei. A deep understanding of the dynamics of this matter could not be built until one had settled on the correct starting point; is one to start from something like the localized highly correlated picture of a solid or from the delocalized orbits of particles quantized in the total volume of the nucleus? The question is, of course, intimately linked to the strength of the nuclear forces (measured in units of the Fermi energy which is a measure of the energy required to localize particles at the equilibrium separation). From this point of view one may feel that from the start there were strong arguments for believing that the forces are rather weak - in the two body system there is only one very weakly bound state for $T = 0$ and no bound state at all for $T = 1$ - and hus unable to produce the localization necessary for a quantum solid. We must, however, remember that in assessing this question today we are exploiting the results of a long development in which the analysis of nuclear matter could be compared with a variety of quantal systems encountered in condensed matter physics and that even with this advantage the answers are not very simple (see, for example, the necessary uncertainty in discussing the deconfinement transitions for quarks and gluons, as well as the question of a possible solid phase in the interior of neutron stars). We are here forcefully reminded that despite the impressive development of the powers of formal analysis, the important many body problems of nature have repeatedly revealed the deepseated limitations of straightforward reductionism. Each rung of the quantum ladder has revealed marvelous structures the interpretation of which has required the invention of appropriate concepts which are almost never discovered as a result of purely formal analysis of the interactions between the constituents.

The recognition of single particle motion in the average nuclear potential provided a basis for developing a very detailed understanding of the nuclear dynamics, an understanding that reveals a fascinating tension between the concepts relating to independent particle motion and those referring to collective features associated with the organized dynamics of many nucleons. The compound nucleus ideas have effected this development in many and far reaching ways but I shall here confine my discussion to a single example, the remarkable development of the statistical theory of quantal spectra.

The experimental impetus for this development is again the neutron resonances which played such a role in the original inspiration of the compound nucleus. It is impossible for me to think about these resonances without a sense of awe at the profound generosity of nature in providing a window in the nuclear spectra at a point where the level densities are about a million times greater than those of the fundamental modes, where the quantal levels are still beautifully sharp in relation to their separation, and where the slow neutrons provide an exquisitly matched tool with which to resolve and measure the detailed properties of each resonance. The effective exploitation of this tool has provided complete spectra comprising hundreds of individually resolved and measured neutron resonances, (Fig. 7) while corresponding developments in charged particle spectroscopy have lead to the measurement of similar spectra for proton resonances. It was Wigner (1955) who initiated thinking about this material in terms of random matrices. The idea is to provide a detailed characterization of the wavefunctions and spectra describing the quantal spectrum of the compound nucleus. The compound nucleus idea implies that the quantal states are complicated mixtures involving all the available degrees of freedom of the many-body-system (the quantal equivalent of ergodic motion in classical mechanics). Wigner suggested that significant features of these quantal spectra might be modeled by considering, for some region of the spectrum, an expansion of the Hamiltonian matrix on an arbitrarily

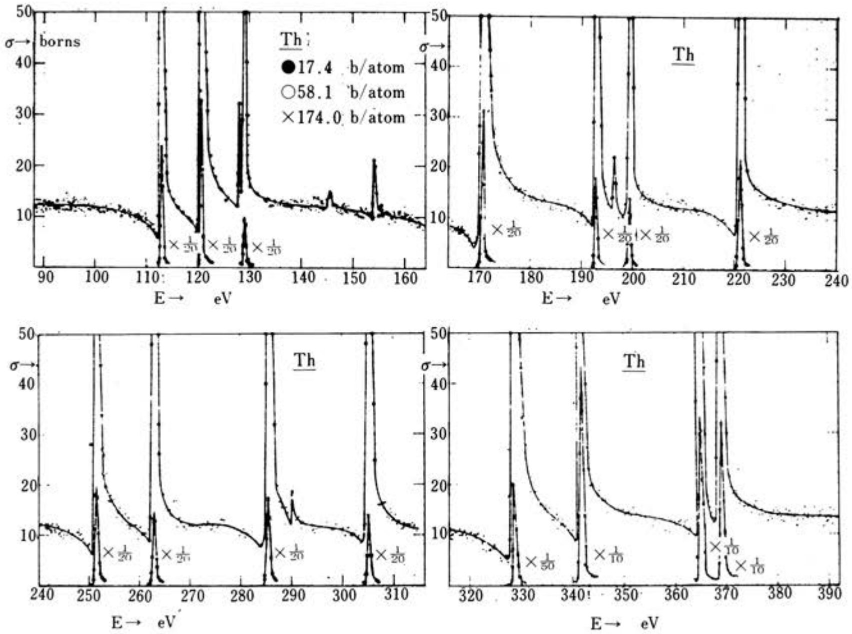

FIGURE 7

chosen finite set of basis states. The strong mixing of different degrees of freedom and the randomness of the compound nucleus is expressed by chosing the matrix elements of the Hamiltonian matrix independently and randomly from an appropriate ensemble. We may then ask whether there are significant features in the eigenvectors and eigenvalues which reflect the strong coupling of the different parts but are otherwise universal in the sense of being the same for almost all of the matrices generated by such a process. It turns out that the answer to this question is yes; indeed, as shown by Thomas and Porter, Mehta, Dyson, and French and co-workers, the fluctuations in level widths and spacings are just such universal properties (see Table IV and the review article by Brody et al. (1981). The extensive evidence from nuclear resonances referred to above, has in recent years been

1. object of study:

   $N \times N$ real orthogonal matrix, H

   constrained average and dispension of eigenvalues

   otherwise, maximize "entropy" = chose

   "most typical" matrix

2. joint probability of eigenvalues E_1 -- E_N

$$P(E_1 \text{ -- } E_N) = (\text{norm}) \prod_{\alpha<\beta} |E_\alpha - E_\beta| \exp\{-C\sum_1^N E_\alpha^2\}$$

C - constant related to level spacing

note (Dyson, 1962) complete analogy to partition function for classical electron gas in 1-d with interaction $V_{12} \sim \ell n|x_1 - x_2|$ and harmonic confining potential

$$Z(x_1 \text{ -- } x_N) = \exp\{-\frac{e^2}{a^2 T}\Sigma\, x_i^2 + \frac{e^2}{T}\Sigma\, \text{Ln}\,|x_C - x_i|\}$$

3. electrostatic analogy "explains" almost crystaline order of the eigenvalues

   a) nearest neighbors

$$P(E) \approx \frac{\pi}{2D^2} \quad E \exp\left(-\frac{\pi}{4}\left(\frac{E}{D}\right)^2\right)$$

Wigner distribution

   b) number of eigenvalues in interval L

$$P_L(n) \approx (2\pi\rho)^{-1/2} \exp\left(-\frac{1}{2\sigma^2}\left(n - \frac{L}{D}\right)^2\right)$$

$$\sigma^2 = \frac{2}{\pi^2}\,\ell n\,\frac{L}{D} + 0(1).$$

TABLE IV Microscopic structure of Compound Nucleus = Random Matrix shown to agree in striking detail with the prediction concerning these fluctuations based on random matrices (see Fig. 8) and thus to confirm the applicability of this characterization of quantal states of the compound nucleus in the regions to which it has been applied. (These ideas have also played an important role in the interpretation of experiments on laser excitation of polyatomic molecules (Stenholm; Fields) and have been invoked in the discussion of electronic properties of small metalic particles (Kubo, Gorkov and Eliashberg).)

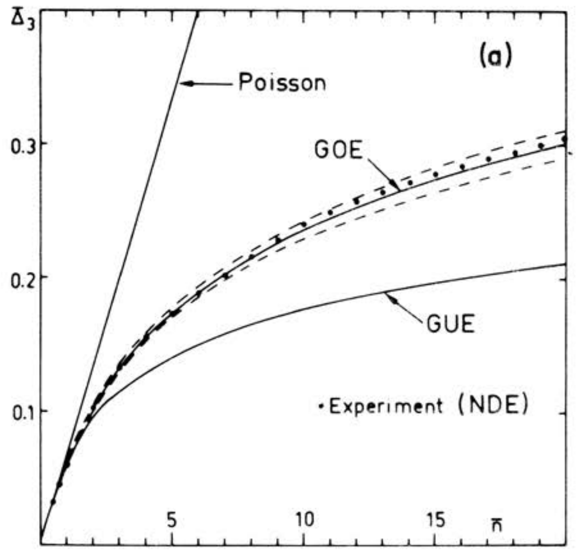

FIGURE 8

While the original formulation of this model was based on random matrices, current developments have made it possible to relate these characteristic features of quantal chaotic motion to more physical models (first to a model of electron motion in a disordered medium (Efetov 1983)) and quite recently to direct semi-classical quantization of the classical chaotic motion based on the (unstable) periodic orbits (Berry 1985).

The current questions are concerned with issues such as: how can one characterize the transition between the low energy spectrum with its many conserved quantum numbers (classically multiply periodic motion) and the compound nucleus region, exhibiting quantal chaos? and how to characterize the limitations on the random matrix model that are associated with the existence of a finite relaxation time for the nuclear configurations? In attempting to understand questions such as these nuclear physicists are joining with workers in many other areas of physics in attempting to understand more deeply the significance of classical chaos in quantal spectra and, at least for the nuclear physicists, Niels Bohr's idea of the compound nucleus provides the crucial point of entry.

Address at the Niels Bohr Centenary Lecture (November 9, 1985)

Ryogo Kubo
President, the Nishina Memorial Foundation

I am not quite sure if the name of Niels Bohr appears in physics textbooks for Japanese high schools, but I am sure that everyone knows his name if he has ever been interested in modern science. Niels Bohr was born one hundred years ago in Copenhagen, Denmark. To commemorate this, there have been meetings and symposia in various countries in the world. At the Niels Bohr Institute in Copenhgaen, there have been several symposia in last few months, and the highlight was the Niels Bohr Centenary Symposium held through October 4 to 7 with attendance of over three hundred scientists from all over the world. Fortunately I was able to participate this symposium, which was very successful with important review lectures on physics, chemistry, and biology of the present day to commemorate the great man who paved the way to these modern sciences.

The Centenary Lecture Meeting today is not covering so wide fields of sciences as that symposium in Copenhagen, but we are very happy that Professor Mottelson kindly accepted our invitation to give a memorial lecture on Niels Bohr and the modern physics. I imagine that one focus of the lecture would be Bohr and nuclear physics, on which Niels Bohr spent most of the latter half of his life to study.

I think there is no much need to introduce the speaker today, but let me make a brief introduction. Professor Mottelson was born in Chicago, obtained PhD at Harvard, and came to Copenhagen in 1950. He has remained there most of the time since then. His cooperation with Professor Aage Bohr, the fourth son of Niels Bohr, started in 1951 and has been continued to the present. In 1975, both Professor Aage Bohr and Professor Mottelson shared the Nobel Prize with Rainwater for their remarkable achievements on the structure of nuclei. The subject of the work is the relationship between the individual motion and the collective motion in atomic nuclei. This problem in general is a central one not only in nuclear theory but also in other fields of physics of the present day. In fact, the idea of collective motion in the assembly of protons and neutrons was initiated by Niels Bohr as the famous liquid drop model of nuclei. The idea of competitive existence of individual and collective modes is an excellent example of the complementarity which Niels Bohr stressed throughout his life. In this sense also, the subject of Professor Mottelson's lecture is most appropriate for commemoration of Niels Bohr.

Some people maintain that the scientific achievement is only the important matter and it is immaterial who did this or that. It is true that science as an objective existence does not belong to any individual. However, scientific work is done by individuals and its evolution cannot be separated from the life of the man who did it. Scientific revolution always is ignited by some individuals and the way it evolves greatly depends on who did it. Even if there was no Einstein, the relativity might have been discovered by someone before 1915. Even if there was no Niels Bohr, the quantum theory of hydrogen atom might have been formed by someone before 1920. Indeed, there were A. Haas and J. W. Nicolson who thought something about the hydrogen atom, but Niels Bohr did it in an extremely unique way. The breakthrough Bohr achieved was not only the theory of an hydrogen atom but it was the guide which illuminated the way to the new horizon through the year of struggle to the birth of quantum mechanics. Mankind never forget this history. Copenhagen Geist penetrated the new physics and it gave birth of the new science of the new era. The Niels Bohr Institute became the center of international cooperation. Young ambitious scientists gathered here from all over the world. From Japan, which had experienced only a half century since she opened the door to the west, came Takamine, Nishina, Hori, Kimura, Sugiura, Ariyama and some others. These scientists played very important roles after they came back to Japan to create active atmosphere of research in Japan.

Among these Japanese scientists who were in Copenhagen at that time, Dr. Nishina had most deep relations with Niels Bohr and the Institute. Dr. Nishina studied electrical engineering at Tokyo University and entered the Institute of Physical and Chemical Research after graduation. He went to Europe in 1921 and stayed at Copenhagen from 1923 to 1928 to work with Niels Bohr. He did much of experimental studies as well as theory. The most well-known of his work is the derivation of the Klein-Nishina formula for scattering of gamma rays by electron using Dirac's relativistic quantum theory. Dr. Nishina was liked very much by Bohr's family. Children used to call him Onkel Nishina. After coming back to Japan, Dr. Nishina started the work on nuclear and cosmic ray physics at the Institute of Physical and Chemical Research. He also invited young theoreticians such as Tomonaga. His laboratory soon became the center of Japan for the study of modern physics. At that time most of the imperial universities were slow to change, so that the efforts of Nishina was really important for the development of modern physics in Japan. The effect was great indeed. In 1935, there was Yukawa who put forward the revolutionary idea of mesons. In several laboratories including Nishina's laboratory and that in Osaka University, experimental studies on nuclear physics started very actively. So we expected that the day was approaching when the Japanese physics might catch up the level of Europe. It is very sad to reflect the disaster of the Second World War which completely crushed down our hope. Nevertheless, after fourty years since the war, we must not forget the fact that we owe a great deal to the valuable efforts done in 1930's by these predecessors. In this sense also we realize deeply with great appreciation how much we owe today's Japan to Niels Bohr. After the war, during the past few decades there have been a great number of our colleagues who went to Copenhagen to study at the Niels Bohr Institute. They are now the leaders at various universities and institutions.

Thus, there are great number of Bohr's pupils, grandpupils, and grand grandpupils in Japan. Niels Bohr was always very warm and kind to Japanese scientists. He came to Japan only once in 1937. The memory of the visit was talked about repeatedly in Bohr's family. Unfortunately I have had no chance to meet him, but once had a chance to see Mrs. Niels Bohr who told me about those Japanese scientists at Copenhagen and her visit to Japan. In the hall outside of this auditorium there are exhibitions of photographs of Niels Bohr which show us something about Bohr and Japan. If you have not seen them, I hope you pay a look after the lecture.

The Nishina Memorial Foundation was established to commemorate Dr. Nishina and so it has kept a close relationship with Niels Bohr Institute. Some years ago when Professor Tomonaga was the President, he invited Professor Aage Bohr to Japan. Also Professor Tomonaga and his associates did much efforts to support the activity of the Institute through a financial grant from the EXPO Foundation. At the present moment, two young scientists are studying at the Niels Bohr Institute by the grants given by the Nishina Memorial Foundation.

Some time ago, the idea of doing something to commemorate Niels Bohr centenary here in Japan came naturally to the minds of those who have ever studied at Copenhagen. The Nishina Memorial Foundation decided to take up this idea and this Lecture is one of the outcome. Since there have been several such meetings here and there in the world, we worried very much if this can ever be realized. So, we are very grateful to Professor Mottelson for his kind acceptance of our invitation. The Science Council of Japan and the Physical Society of Japan have agreed to cosponsor this Niels Bohr Centenary Lecture Meeting, which I think very appropriate to express our everlasting esteem and gratitude to the great father of modern science, Niels Bohr.

Thank you for your attention.