N. Bohr's model of compound nuclei and parity violation[1)]

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In June, 1937 Professor Bohr delivered a lecture in Moscow at the Institute of Physical Problems of the Academy of Sciences of the USSR. I was in the audience at that lecture. Bohr discussed the consequences arising from his research of 1936, so I shall speak of events that took place fifty years ago. At the time the first studies of the neutron-nucleus interaction had been carried out and the results were not understood. Bohr explained them in his lecture. It was known that slow neutrons penetrated atomic nuclei with great ease. It appeared that the reverse should happen as well—the neutrons should leave the nuclei just as easily. This does not take place, however: after penetrating the nucleus a slow neutron usually remains there and in most cases gamma-rays are emitted in its place. Bohr's explanation took me completely by surprise. There were no complex theoretical deductions, nor formulae of any sort. Instead there was a model, much like a toy, which Bohr demonstrated with evident pleasure. He placed a shallow wooden plate on the table and put in some steel balls. The plate represented a nucleus, with steel balls standing for its protons and neutrons. Another steel ball was rolled down an inclined trough into the plate—a neutron penetrated the nucleus.

Unfortunately I do not have a photograph of that model; the sketch that appears in Fig. 1, borrowed from Bohr's 1937 paper,[1] is somewhat different, although it illustrates the point just as well. If there were no other balls in the plate the rolling ball would simply hop over the opposite edge. Having penetrated the nucleus, the neutron would leave it just as easily. With other balls in the plate it is a different story. Having rolled down into the depression the rolling ball collides with some other ball, then another. Hitting one another the balls begin to move, but usually none of them acquires sufficient kinetic energy to hop over the edge. A neutron that penetrates the nucleus easily cannot leave because it gives up its energy to many particles. This is merely an illustration, of course, but it is backed up by an elegant theory developed by Bohr—the so-called compound nucleus theory.

The compound nucleus theory lies at the heart of our understanding of most nuclear reactions. Certainly Bohr was far from abandoning quantum theory, and indeed he immediately noted some of its consequences. Since a very complex motion of many particles takes place within the nucleus, there should be many quantum states, the so-called resonances, excited by neutrons. The more excited the nucleus, the greater the density of these energy states. As a slow neutron impacts on the nucleus a binding energy reaching 6–8 MeV is released. Bohr demonstrated that this amount ensured that the resonances differed little in energy, and this explained yet another experimental fact: the selective absorption of neutrons. In Fig. 2 we have a typical neutron spectrum of a single nucleus. Clearly the resonant peaks are narrow; this is one of the consequences of Bohr's theory. Certainly such a spectrum could not be obtained in 1937. The evolution of experimental technique proceeds apace to this day. I will speak of current experimental possibilities of studying very weak resonances using polarized neutrons.

Another result of quantum theory is that every resonance is characterized by spin and parity (even or odd).

Certain rules connect the spin and parity of the neutron-absorbing nucleus with the quantum characteristics of the resonance. The only rule relevant to our discussion is that a slow neutron usually excites a nuclear state of the same parity as the original nuclear state. This is so because the excitation is usually due to s-wave neutrons. There exists, however, a very low probability of a slow neutron exciting a resonance different in parity from the original state. Such resonances are very weakly manifested, they absorb very few slow neutrons. Here p-wave neutrons are involved, and their share in the slow neutron beam is insignificant. Without examining in detail the quantum characteristics of neutron waves let us simply note that resonances of different parity are excited—some more, some less. The question which we should like to consider is whether these nuclear states have a well-defined parity or are there cases when odd and even parity are to some extent simultaneously present. And would the latter constitute what is called spatial parity violation? What does that mean? It seems the explanation need not involve a discussion of the wavefunction's symmetry

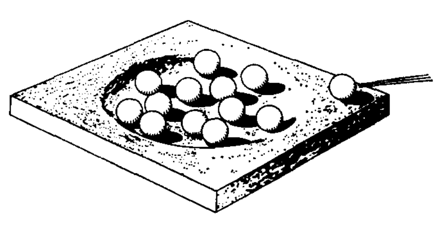

FIG. 1.

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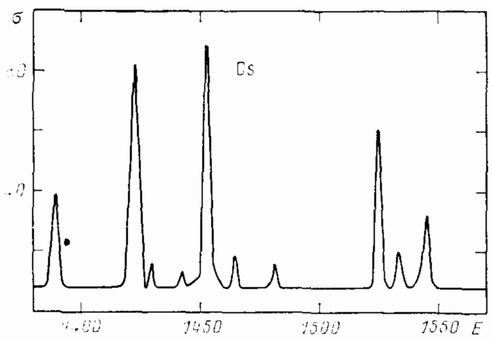

FIG. 2. (E in eV).

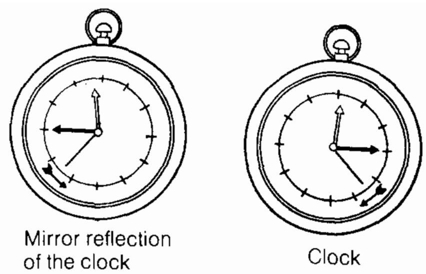

FIG. 3.

properties that determine the parity. Instead let us proceed by examples. Consider the face of a clock. Not only do we see, we know in which direction the second hand is rotating. We know this about the minute and hour hands as well, although their motion is too slow to be immediately perceptible to the eye. But should we look at a mirror reflection of the clock's face we see an amazing thing: the second hand is rotating in the opposite, rather than the customary direction. And so do the minute and hour hands (Fig. 3).

At the same time, a clock whose hands rotate as in the mirror reflection, i.e., counter-clockwise, would serve just as well, although it would be unfamiliar and inconvenient to use. Indeed, it is quite obvious that the clock mechanism cannot depend on the direction of rotation. Should some differences arise they would constitute a violation of parity. In mechanical processes parity is conserved, however. Of course this begs the question: why do we differentiate the clockwise rotation from the counter-clockwise? Why are they not the same for us? Evidently this ability is biologically important, for it makes getting one's bearings in the outside world that much easier. To what do we owe this ability? Perhaps some of our perception processes do not conserve parity? The explanation apparently lies elsewhere. Much is asymmetrical in a living organism, it is not identical to its mirror reflection. Thus it should not be surprising that the two directions of rotation should not appear identical.

Many natural phenomena involve rotation in one or another direction. Thus, for instance, many molecular structures possess a definite asymmetry which affects their optical properties. When polarized light passes through a medium containing such molecules, the plane of polarization is rotated in a determined direction. We say that there exist levorotatory and dextrorotatory molecules. For some reason proteins, the building blocks of living matter, are always levorotatory molecules. Consequently, a marked element of asymmetry is present in the essential make-up of living organisms. Levorotatory and dextrorotatory molecules of the same substance are mirror images of each other, equivalent in all other respects. If, for example, one type of molecule absorbed polarized light more strongly than the other, this would constitute parity violation. But this is not observed.

The question arises, can something similar be observed in the neutron–nucleus interaction? The question is nontrivial, for the neutron possesses an internal angular momentum—spin. Classically speaking it is in a state of rotation. Accordingly, if a nucleus is bombarded by polarized neutrons whose spin is aligned either parallel or antiparallel to their velocity, the nucleus will "see" them rotating clockwise or anticlockwise, as shown in Fig. 4. This is commonly referred to as the two different values of neutron helicity. Is it possible that the neutron capture probability of a nucleus depends on the neutron's helicity? In Fig. 4 the case of a neutron passing through the nucleus is shown on top, the case of a neutron being absorbed is on the bottom. Can there exist such a diffference in absorption probabilities? The theory would appear to rule this out. Indeed, the neutron–nucleus interaction belongs to the class of strong interactions in which parity is conserved. Therefore if the nucleus itself has no preferred direction of rotation, i.e., if the nuclear spin is randomly oriented, the neutron's helicity should make no difference. Yet there remains one apparently insignificant, at first sight negligible addition to our picture. In nature strong interactions are complemented by weak interactions, in which spatial parity is not conserved. An example of weak interaction is the nonelectromagnetic interaction of a nucleus and an electron.

Weak interactions coexist with strong ones, but they are weaker by a factor of about ten million. Thus the spatial parity conservation law which governs strong neutron-nucleus interactions, should be obeyed to very high precision. If parity violation effects are proportional to the contribution of weak interactions they should comprise a millionth fraction of measured quantities. This appears practically undetectable in an experiment. But in physics such statements should be made with great caution. What can be neglected in some circumstances may unexpectedly prove important in others. Precisely this happened in the case of absorption of

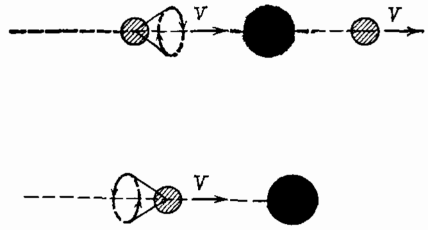

FIG. 4.

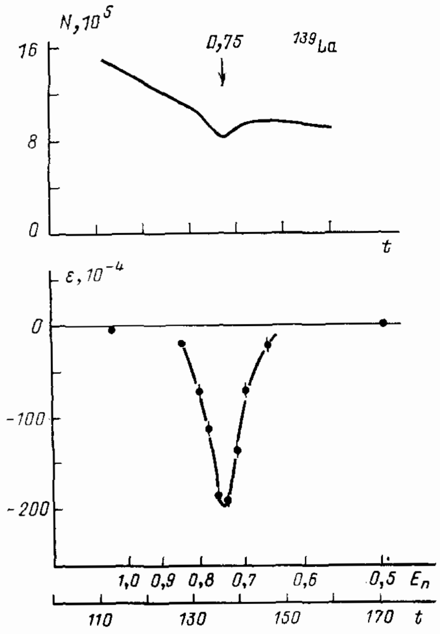

FIG. 5. (E_n in eV).

polarized neutrons, especially resonance neutrons, by nuclei. We have already noted that the main resonances excited by slow neutrons in a given nucleus have the same well-defined parity. Thus, in the lanthanum-139 nucleus, which we will discuss, it is even. But a careful analysis of neutron absorption spectra reveals very weak resonances of the opposite—in our example, odd—parity. Both types of resonances individually should have a definite parity. They are neighbors in the neutron spectrum, however, and this introduces complications. It is precisely the weak interactions that act as a catalyst for the partial mixing of resonances of opposite parity. According to the theory this effect is strongest in p-wave resonances opposite in parity to the main resonances. It turns out that the parity violation effects are then enhanced up to a million times and become significant. In particular, the experiment summarized in Fig. 4 revealed a differential absorption of neutrons polarized parallel and antiparallel to their velocity. The difference was more pronounced in lanthanum-139, which has a very weak resonance of odd partiy corresponding to a neutron energy of 0.75 eV. Fig. 5 presents the neutron absorption spectrum near that energy. Even in a thick lanthanum absorber the resonance appears as a small dip in the spectrum of transmitted neutrons (see Fig. 5, top).

In the lower part of Fig. 5 we have the relative difference in neutron beam intensities of transmitted neutrons for both polarizations. At the resonance the difference in absorption is quite clear: the effective cross-sections differ by 7%. Away from the resonance the difference is practically zero. Consequently, the nucleus does indeed distinguish the helicity, i.e., parity violation is obviously present. These lanthanum results were recently obtained by my colleagues at Dubna.[2)] Analogous, though somewhat weaker effects were observed in several other nuclei. The experiments described here are conceptually simple and hence appear easy to carry out. This is not so. Polarized resonance neutrons are difficult to obtain. Resonances excited by p-wave neutrons are, as a rule, unkown and hardly studied. Their intensity is very low, so measurements of neutron absorption in such resonances requires very sophisticated apparatus and, of course, great experimental skill.

The study of parity violations in neutron-nucleus interaction has a long history.[2)] They were first discovered in experiments performed about 20 years ago in Moscow at the Institute of Theoretical and Experimental Physics. The idea that parity violation effects may be much stronger than the relative contribution of weak interactions was of crucial importance. It proved to be correct and permitted their discovery. Nonetheless the observed effects were very small, only 10^{-4} of the measured quantities. Theoretical and experimental investigations of this topic were pursued in many places using different methods: Moscow, Grenoble, Dubna, Gatchina (Leningrad region), Novosibirsk. In the end they led to an understanding of the conditions in which the parity violation effect of the neutron–nucleus interaction should be most pronounced, and to the experiments the results of which I have discussed.

I began my lecture with the story of a simple model that illustrated Bohr's theory of compound nuclei. Parity violation effects which we have considered here are also a property of compound nuclei—and a consequence and further evolution of Bohr's model.

[1)]This article is based on a lecture delivered on July 3, 1985 at the 35th Conference of Nobel Laureates (12th conference in physics) in Lindau, FRG. The text has been somewhat revised for print.

[2)]See V. P. Alfimenkov's review.[2]

[1]N. Bohr, Prevrashcheniya atomnykh yader (Transformations of Atomic Nuclei) in: *Izbrannye nauchnye trudy* (*Selected Scientific Works*), Nauka, Moscow, 1971, v. II, p. 239. Also, see Usp. Fiz. Nauk **18**, 338 (1937).

[2]V. P. Alfimenkov, Usp. Fiz. Nauk **144**, 361 (1984) [Sov. Phys. Usp. **27**, 797 (1984)].

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