A Theory of Orbital Neutrons

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As an alternative to present theories of the capture of slow neutrons by atoms, it is suggested that such capture is not primarily a phenomenon affecting the interior of the nucleus, but rather that, owing to the interaction between the spin of the nucleus and the spin of the neutron, there is a field outside the nucleus in which neutrons can be held in quantized "orbits." The fall from one of these orbits into the center of the nucleus is regarded as a second phenomenon not immediately related to the first. The probability of capture in a particular orbit is assumed to depend (1) upon a relationship between the energy of the approaching neutron and the kinetic energy in this orbit, and (2) upon the presence in the same neighborhood of occupied electronic orbits. Some consequences are drawn from these assumptions and compared with the results of experiment.

IN the study of slow neutrons, begun by Fermi and his associates, and since continued in many laboratories, it has been found that many elements absorb these slow neutrons to a remarkable extent. The absorption of fast electrons indicates the same small nuclear cross section that is obtained by other experimental methods, but with slow neutrons the effective cross section is frequently many times, and in one case over ten thousand times, as great. This fact does not necessarily imply that there is associated with the nucleus any physical entity which has these large dimensions. If we extend Rayleigh's theory of the absorption of sound and of light to the absorption of material particles, the absorber, no matter how small, should be capable of capturing the particle over an area of approximately λ^2, where λ is the de Broglie wave-length of the oncoming particle. However, this theory, while it gives an estimate of the maximum possible absorption, does not aid in predicting the actual absorption. It may be more naïve, but also may be more useful, to assume that, associated with the atom, there is some definable entity which has dimensions of the order of magnitude of the cross sections deduced from the absorption coefficients of these slow neutrons.

At first these absorption coefficients were supposed to vary inversely with the velocity of the neutron. Now, however, it is known that the absorption is no simple function of the energy of the neutron and that frequently an element absorbs selectively in one or more energy ranges. In the case of lithium and boron the absorption has so far shown no maximum and seems to be nearly proportional to the inverse velocity. To the group exemplified by lithium and boron we must add hydrogen, which absorbs neutrons to produce deuterium far more effectively when the neutrons pass through paraffin at the temperature of liquid air.[1]

An explanation of the selective absorption has recently been presented by Bohr,[2] and by Breit and Wigner.[3] This explanation rests upon two main assumptions. The first assumption is that there is a series of energy levels in the system nucleus+neutron, rising through the enormous range of approximately ten million electron volts to the dissociation potential, and continuing above this potential. The second assumption is that the nucleus has sufficient complexity so that the different parts of the nucleus+neutron system may possess, for a certain time, an energy greater than that required to disrupt the system, if all the energy were possessed by one neutron. According to this second assumption the more complex nuclei possess a mechanism of absorption which would be lacking in so simple a nucleus as that of hydrogen.

At first sight it would seem unlikely that remote control from a state so distant in energy as the ground state of the system nucleus +neutron could account for the fineness, and the highly specific nature of the absorption phenomena. Nevertheless the mathematical analysis

[1] Moon and Tillman, Proc. Roy. Soc. **A153**, 476 (1936).
[2] Bohr, Nature **137**, 344 (1936).
[3] Breit and Wigner, Phys. Rev. **49**, 519 (1936).

of Breit and Wigner shows that it is possible, without the aid of any unreasonable assumptions, to account for existing experimental facts by a consideration of nuclear energy levels alone. They retain the view of an absorption coefficient inversely proportional to the neutron velocity in the low energy range but superpose additional resonance bands in the range of higher energies. This view seems to be in accord with the main body of experimental facts regarding neutron absorption which has so far been obtained.

Furthermore, at the end of their paper Breit and Wigner attempt to show that no mechanism except the one that they suggest can account for the facts of neutron absorption. Here of course their task is a more difficult one, for it would seem impossible in the present state of our knowledge to predict all the possible interactions between nuclei, electrons and neutrons. Yet the ideas of all mathematical physicists are so nearly in accord on this subject that it might appear superfluous to offer at this time an alternative view of the phenomenon of neutron capture. Nevertheless there are some experiments, especially one of von Halban and Preiswerk, to which later reference will be made, which suggest that the capture of slow neutrons may not be a pure nuclear phenomenon, but may be due rather to phenomena occurring in the atom and molecule at a considerable distance from the nucleus. For this reason a rough sketch of such an alternative explanation will be offered in the present paper.

If we had before us only the experimental results regarding the absorption of slow neutrons without any of the theories which have developed, we would be tempted to regard the absorption as analogous to the absorption of light, where we ordinarily find a number of resonance bands with little absorption at energies which are either very much larger or very much smaller than the resonance energies. According to this analogy the absorption which is peculiar to slow neutrons would be regarded as all of one type, and in the case even of those elements which at present show only an absorption which is approximately inversely proportional to the neutron velocity, we might expect, at lower velocities than have yet been investigated, a maximum of absorption, followed at still lower energies by a diminution of absorption with diminishing velocities. This is in fact the picture of the absorption of slow neutrons which follows from the hypothesis that we are now to consider.

While it is probably not permissible to assume any large field of force operating on the neutron at large distances from the nucleus, we may, however, assume a field near the nucleus which becomes faint but not entirely negligible at interatomic distances. Our hypothesis will be that a neutron may be held in such a field and travel in what we may for brevity call orbits. Knowing little of the nature of the field we can only say with certainty that these orbits must be quantized with respect to angular momentum. If, as suggested by the absorption experiments, the kinetic energy of the neutron in its innermost orbit is of the order of a few volts, and if the angular momentum is $h/2\pi$, then the radius of this first orbit will be of the order of 10^{-10} cm.

It seems natural to assume that the field we are speaking of is due to an interaction between the spin of the nucleus and the spin of the neutron. In the first place we know of no other property of the neutron to which this effect could reasonably be attributed, and in the second place, no elements so far investigated have a large absorption coefficient for slow neutrons except those that have at least one prominent isotope which possesses a spin. Atoms with zero spin such as C^{12} and O^{16} do not show this effect, although a neutron entering these nuclei to produce C^{13} and O^{17}, respectively, would release energy of the order of five million electron volts.

Regarding the probability of the capture of a neutron in one of its orbits, we can make use only of the roughest analogies. We might assume that the probability of the neutron capture is highest, either when the kinetic energy of the approaching neutron is of the same order of magnitude as the kinetic energy of the neutron in its orbit, or when the diameter of the neutron orbit bears some definite ratio to the de Broglie wave-length of the approaching neutron. By either assumption we may expect neutrons of larger energy to be captured in the lower orbits and those of smaller kinetic energy in the higher neutron orbits. This will be our first postulate.

At first sight it is hard to imagine how a

neutron falling into an orbit, or falling from one orbit to a lower orbit, can get rid of its energy. It is not likely that a transition involving an uncharged particle like the neutron could lead directly to the emission of a photon. However, in our picture of neutron orbits, beginning at something like 10^{-10} cm from the nucleus, and proceeding outward, some of these outer orbits will lie in the region of occupied electronic orbits, and here the amount of interaction between neutron and electrons may well be sufficient to permit the energy lost by the neutrons to be given off as light, or soft x-rays. We thus arrive at our second postulate: a neutron has a larger probability of capture into a neutron orbit which is in the neighborhood of occupied electronic orbits. According to this view, capture is due to simultaneous interaction between nucleus, neutron and electrons, resulting in a peculiar kind of molecule.

From these two postulates we are able to draw a conclusion for which there seems already to be good experimental evidence. Since the electronic orbits or shells move toward the nucleus as the atomic number increases, we may expect, in the main, that regions of large selective absorption will occur at relatively high energies only in the case of heavier atoms. It is already evident that while many of the heavy elements have absorption bands far above the thermal range, the three light elements, hydrogen, lithium and boron, are powerful absorbers, but only in the range of very small energies. As far as I am aware this striking fact is not predictable by any other proposed theory of neutron capture.

The problem of neutron scattering is a difficult one. The neutrons that are captured and have lost their excess energy by the emission of a photon can no longer be ejected from the atom, but one would expect in the neighborhood of the absorption bands many reversible collisions between neutron and atom which would result in scattering. In the case of cadmium, which has a high absorption coefficient for neutrons of thermal energy, and which apparently does very little scattering,[4] it may be necessary to assume that the neutron falls into the nucleus almost simultaneously with its capture. This would result in a broadening of the absorbing levels, with an increase in the probability of absorption and a diminution in the probability of scattering.

When the neutron is captured to form a radioactive element of measurable life, there seems at present no direct way of ascertaining whether the neutron falls into the nucleus soon after its capture, or whether it remains in the atomic orbit for a time which may even determine the apparent life of the new element. It is to be noted that the latter assumption would enable us to account for the long life of certain artificially radioactive elements which emit β-rays of great energy, and seem therefore hard to reconcile with Sargent's rules for β-emission. If in any case the probability of falling into the nucleus should happen to be of the same order of magnitude as the probability of decomposition of the resulting nucleus, an interesting type of decay curve would be obtained.

A further consequence of the theory of neutron orbits is that the absorption coefficient of an element, depending, as we have assumed, upon the positions of electrons with respect to the nucleus, should vary with the type of chemical binding. This would be especially true of hydrogen. We should, therefore, expect that hydrogen in paraffin, where the electrons are presumably nearer to the hydrogen than in other hydrogenous substances such as water, would be the most efficient in capturing neutrons of thermal energy.

The only experiments that I know which have a bearing on this question are those of von Halban and Preiswerk.[5] They studied the number of slow neutrons emerging when a neutron source is placed in the center of spheres of different size containing different hydrogenous substances. They found that the number of slow neutrons coming through the surface of the sphere depended not only upon the number of hydrogen atoms lying between source and target, but also upon the particular compound containing these hydrogen atoms. They interpreted their results as due to the difference in the rate at which the neutrons are slowed down by the different types of hydrogen atom. More recent experiments on the slowing of neutrons by very cold paraffin, and the fact that hydrogen pre-

[4] Dunning, Pegram, Fink and Mitchell, Phys. Rev. **48**, 265 (1935).

[5] von Halban and Preiswerk, Nature **136**, 951 (1935).

sumably does not absorb efficiently except when the neutron velocities have become small, makes it seem as likely that their results actually indicate a greater absorption coefficient for paraffin than for the other substances which they studied. There are, however, so many factors involved, the slowing down, the scattering, and the capture of neutrons, that it is highly desirable that new experiments be made to ascertain the actual absorption coefficient of hydrogen in its various compounds. These experiments are crucial for, if the capture of neutrons by hydrogen is determined solely by energy levels in the deuterium nucleus, it could in no way depend upon the particular chemical compound in which the hydrogen is bound.

Note added August 14. In experiments which have just been carried out in this laboratory by W. F. Libby and E. A. Long, two remarkable results have been obtained, first, at 20°K there is a great increase either in the slowing of neutrons, or their absorption, or both, when liquid hydrogen is replaced by paraffin. Second, the slowing of neutrons by cold paraffin continues down to temperatures at which there is no mechanism now known to account for this phenomenon. These experiments indicate very strongly that there are processes involved which concern the molecule as a whole and not merely the nucleus.

NOVEMBER 1, 1936 PHYSICAL REVIEW VOLUME 50

The Magnetic Anisotropy of Copper Sulphate Pentahydrate, $CuSO_4 \cdot 5H_2O$, in Relation to Its Crystal Structure. Part I

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The magnetic anisotropy of the triclinic crystal $CuSO_4 \cdot 5H_2O$ has been measured. The crystal is found to be nearly uniaxial magnetically, i.e., has an axis of approximate magnetic symmetry, the susceptibility along the axis being less than that along perpendicular directions by about 300×10^{-6} c.g.s. e.m.u. per gram molecule at 26°C. The above axis is inclined at 156°, 65°, and 52°, respectively, to the '*a*', '*b*' and '*c*' axes of the crystal. These results are discussed in relation to the known arrangement of the water molecules and oxygens round the Cu^{++} ions and the resulting crystalline electric fields acting on the latter.

1. INTRODUCTION

IN some recent papers Van Vleck and his collaborators[1] have discussed theoretically the magnetic behavior of some of the Tutton salts of the iron group of metals, particularly in relation to the influence of the strong internal electric fields which are acting on the paramagnetic ions in the crystals. The two copper salts $CuSO_4 \cdot K_2SO_4 \cdot 6H_2O$ and $CuSO_4 \cdot (NH_4)_2SO_4 \cdot 6H_2O$ have been studied in detail by Jordahl[2] and by Janes,[3] and they conclude from the magnetic data that the crystalline electric field acting on the Cu^{++} ion in these crystals has monoclinic symmetry. The field can be split up into two parts, one with cubic symmetry, which is found to be very predominant, and the other with rhombic symmetry, which is much feebler; the over-all Stark separations of the energy levels of Cu^{++} produced by these two fields are about 18,000 cm^{-1} and 350 cm^{-1}, respectively. This predominantly cubic symmetry of the field is a natural consequence of the octohedral arrangement[4] of the six water molecules in the crystal round each Cu^{++} ion, the disposition of the SO_4^{--} and the K^+ or NH_4^+ ions, which are at a greater distance from Cu^{++}, probably producing the feeble rhombic field.

The magnetic susceptibility of the triclinic crystal $CuSO_4 \cdot 5H_2O$ has been measured in the *powder state* over an extensive range of temperatures by de Haas and Gorter,[5] and from these susceptibility data, both Jordahl and Janes concluded that in this crystal also, the crystalline

[1] See Van Vleck, *Theory of Electric and Magnetic Susceptibilities*, Oxford (1932), Chapter XI.
[2] Jordahl, Phys. Rev. **45**, 87 (1934).
[3] Janes, Phys. Rev. **48**, 78 (1935).
[4] Regarding the structure of the Tutton salts see Hofmann, Zeits. f. Krist. **78**, 319 (1931).
[5] de Haas and Gorter, Leiden Comm. 210 d (1930).