Neutrons

AS WAVES AND PARTICLES

Indifferent to the charge of a nucleus or its electrons, neutrons can penetrate where charged particles can not. Their use to probe the structure of matter is opening up the promising new field of neutron diffraction.

by ***E. O. Wollan and C. G. Shull***

The arrival at our present stage of understanding of atomic and nuclear structure has been greatly complicated by the fact that one's thought pattern has had to be modified with respect to everyday experience in order to gain a truer understanding of atomic phenomena. An example of this, useful for the present purpose, is the dual characterization which is associated with atomic or nuclear particles in their behavior as particles or as waves. Neutrons are of this nature, and although they are invariably referred to as particles, we know them to have the characteristics of both waves and particles. This fact makes it difficult for one to form a sensible mental picture of a neutron and somewhat in desperation we have been led to visualize it as illustrated in the accompanying caricature. This picture may be quite different from the one that you have in mind or that which might be drawn by someone else, but its chief merit is that it possesses features which describe most of the properties which we know to be associated with neutrons.

To understand better how scientists have arrived at some of the characteristics of the neutron, and at the neutron itself, it might be well to review briefly a little of the history of the development of physical science.

Although many physical laws were discovered by

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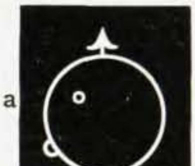
the careful observation of simple everyday events such as swinging chandeliers and falling apples, and the application thereto of what might be called common sense thinking, much of physics as we know it today does not make such common everyday sense. Nevertheless the approach has been that the scientist, by his inquisitiveness, has continued to increase the scope of his daily experiences by carefully observing many things which pass unnoticed by the casual observer, by purposely bringing together matter in its various forms in a great variety of experiments and by then trying to make sense out of his observations.

In classical physics the pattern of thought is essentially consistent with one's everyday experiences. Truly it took imagination to postulate the theory of universal gravitation, but is it not fair to say that this idea came as a logical consequence of efforts to correlate the motion of heavenly and earthly bodies? The wave theory of light was more or less forced on the thought pattern of most scientists as the result of experiments pointing to its wave properties, and the need for an all pervading ether was the need by the scientist for something consistent with his everyday experiences. The great amount of accumulated evidence on the atomic properties of matter and on the wave theory of light left us, at the end of the last century, with a world consisting essentially of four kinds of things. There was energy, there were electromagnetic waves, there were atomic particles, and these particles had electric charges on them. At that time the physicist was allowed free play for his imagination; no one objected if he conjured up pictures of the elements which made up the universe about him.

All this is now changed. We now know that waves don't always behave like waves as we know them in everyday life. The work of Planck, Einstein, Bohr, and Compton convinced us that our notions were too simple. Electromagnetic waves don't always behave like ordinary everyday waves. Waves have a dual character; they behave like waves sometimes and like particles sometimes. The next step came in due course. If waves behave like particles, why shouldn't particles behave like waves? The work of deBroglie, Heisenberg, Schroedinger and Dirac, and the experimental work of Davisson and Germer, and of G. P. Thompson completed this aspect of the picture. Particles do behave like waves. This statement is influenced by everyday thinking. One might say that waves are particles and particles are waves but, more properly, they are different aspects of the same thing or at least different descriptions of it.

It was in 1932 that Chadwick discovered the existence of a neutral particle with a mass about equal to that of a proton and called it the neutron. It was discovered by its essentially particle characteristics. Being uncharged, it was hard to detect by itself because it did not ionize the matter through which it passed. It did, however, bump into atoms on passing through matter and it bumped into protons and they in turn ionized and it was their ionization which led to its discovery. In what follows we will discuss some of the properties of this entity, the neutron, be it particle, wave, or both. We will treat it sometimes as a particle and sometimes as a wave.

As a



Perhaps the most convincing particle aspect of the neutron is the fact that it has mass. This has been determined by a number of experimental techniques and has been evaluated most significantly from studies of the energy release in certain nuclear reactions. Recent determinations give it a mass of 1.008937 mass units in comparison with the proton's mass of 1.008131 mass units.

The neutron spins and has associated with it an angular momentum as would a spinning top. In this respect it is similar to the proton and the electron. Strangely enough, uncharged neutrons possess also a magnetic moment, that is, they behave in many cases like small magnets and the magnetic moments of these particles have been accurately determined. For the neutron $\mu = -1.9103$ and correspondingly for the proton $\mu = +2.7896$, both measured in nuclear Bohr magnetons. The positive and negative signs mean that the direction of spinning and the orientation of the magnets are in the opposite sense in the two cases. The magnetic moment of the electron is very much larger, $\mu = 2$ Bohr magnetons, which is a unit roughly 2,000 times larger than the nuclear Bohr magneton.

Since the mass of a neutron is greater than the mass of a proton by 0.000807 mass unit (equivalent to an energy of 0.75 Mev), it is to be expected that a neutron is an unstable particle and will decay into a proton and a beta particle and, to conserve the spin of the system, a neutrino. The 0.75 Mev corresponding to the mass difference (the neutrino's mass is approximately zero) will appear as kinetic energy of the resulting particles.

Beta decay theory predicts that half of a given number of neutrons will have decayed in about 30 minutes. Neutrons generally spend most of their time wandering around in material, such as the graphite of a pile, and in such a situation they are gobbled up in reactions of various kinds long before they have a chance to decay. But in an intense beam of thermal neutrons from the pile there will be, on the basis of a 30-minute half-life, of the order of 500 neutrons decaying every minute. Experiments designed to measure the neutron's half-life are in progress and preliminary results from this laboratory and from Chalk River give a half-life from experiment in the range from 10 to 30 minutes.

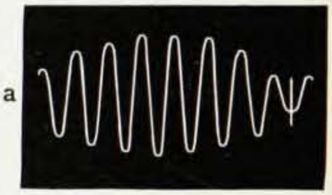
A further characteristic of the neutron which is essentially particle in nature is its directly-measurable mechanical velocity. Early experiments performed at Columbia University with moving mechanical shutters illustrated this and showed the velocity to be commensurate with the expected thermal energy of neutrons which were studied. Newer techniques with electronic shutters have extended the measurable velocity region several hundredfold.

Again, when neutrons are scattered by isolated atomic nuclei they behave very much like particles. If a neutron of a given energy strikes a proton in a glancing collision, the neutron will be scattered off to one side and the proton to the other, just as when two billiard balls collide. The fact that these particles have an angular momentum, as such, plays no role in such collisions. On the billiard ball analogy we may consider that the balls are too slippery to transfer any rotational energy in the collision process. The fact that they are magnets, however, does play a role and this will be brought up later.

The energy transfer between a neutron and a heavier nucleus in an elastic collision process can also be treated as the collision between two balls, in this case of different size. The essentially particle behavior in the scattering of neutrons by nuclei is brought out when one considers the cross section for the scattering process. If the nucleus is placed as the bull's-eye in the center of a one square centimeter target, and neutrons are fired at random at the target, the chances of a bull's-eye hit, per neutron fired, is just given by the area of the bull's-eye and this area is called the cross section for the process. The cross section for the scattering of slow neutrons by most nuclei is given quite closely by the area of the nucleus, where the radius of the nucleus has been determined in some other experiments.

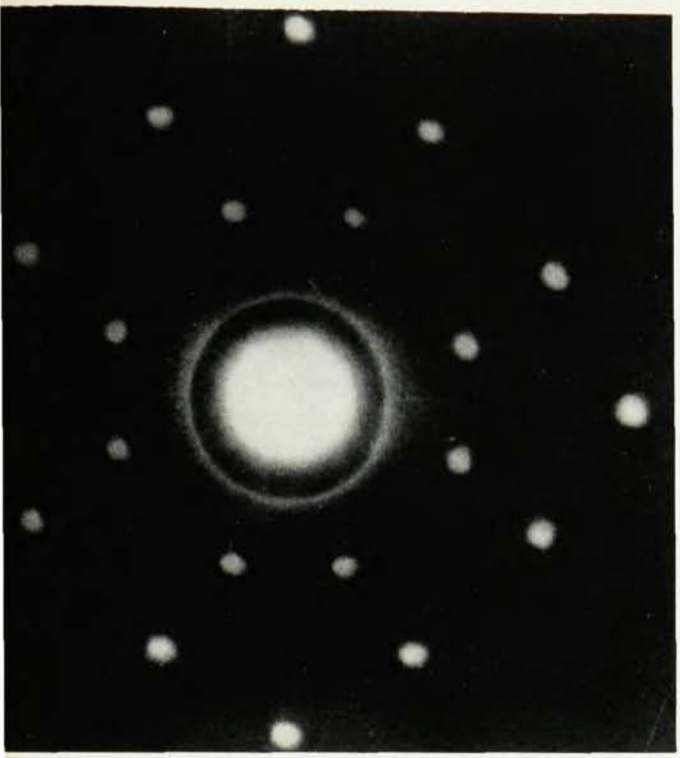
For some nuclei, however, the cross section for scattering of slow neutrons is very much larger than that given by the apparent area of the nucleus, in which case it is necessary to invoke the wave properties of the neutron to explain these large cross sections. On the basis of our caricature, Neut, it is the tail which in this case gets mixed up in the process.

Although many aspects of the neutron's behavior can be described in terms of the particle picture, all the neutron's properties can be described by the wave picture, that is, on the basis of wave mechanics. For the collision problems which have been discussed above, the wave mechanical approach will give the same answer essentially as the particle approach.

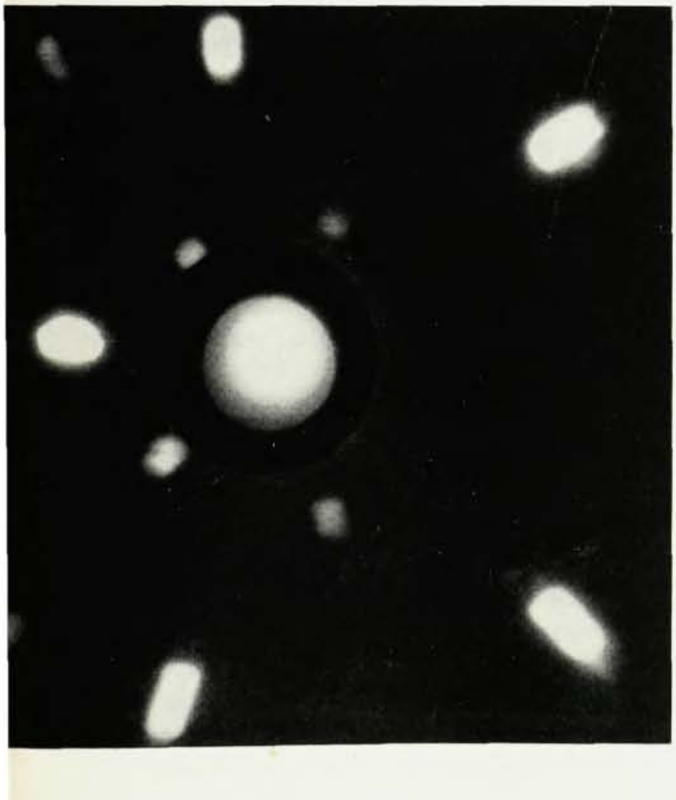
As a 

In many cases involving the interaction of neutrons with matter, for example the diffraction of slow neutrons by crystals, the wave properties stand out so vividly that the dual character of the neutron can almost be forgotten. Many of the equations which describe the diffraction and refraction of x-rays which are, of course, waves, are almost directly applicable to neutrons. The solution of any given theoretical problem involves setting up proper wave equations and selecting the proper wave functions to represent the 'particle' or 'particles' in question.

Where previously, using the particle picture, we considered the collision of a neutron and a proton as a simple transfer of momentum between particles, we have now in addition to consider the change in wavelength of the neutron like the change in wavelength in the Compton scattering of x-ray photons. In view of the relation between the wavelength and velocity of a wave, it is evident that a neutron's



Neutron Laue pattern of rock salt (above) and of lead (below). The lead was five-eighths of an inch thick!



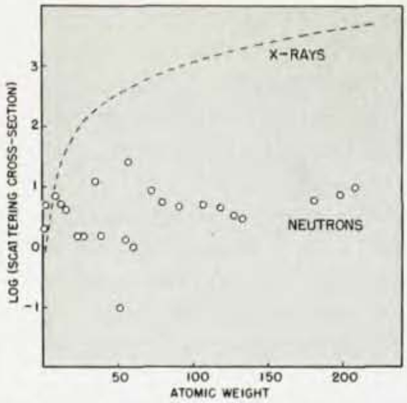
wavelength can be measured in a sort of indirect way by merely determining its velocity. Several types of velocity selectors have been built to produce beams of constant velocity neutrons which are accordingly of definite wavelength and are monochromatic in nature.

A more direct, or what might appear to be a more direct, measurement of the wavelength involves the diffraction of neutrons by crystals in a manner analogous to the diffraction of x-rays. If a beam of thermal neutrons from a chain-reacting pile possessing all velocities or wavelengths in the thermal spectrum is collimated and allowed to fall upon a single crystal, a series of diffracted beams will be observed emanating from the crystal. If all of the diffracted beams are registered on a photographic film, one has a Laue pattern of the diffracting crystal which is similar to those taken with x-rays and which first demonstrated their wave properties. Accompanying illustrations show one such neutron Laue pattern taken with a crystal of rock salt and one with lead. The latter pattern, which was taken by shooting neutrons through a single crystal slab of lead some five-eighths of an inch thick, illustrates the relative transparency of matter to neutrons. X-ray examination of such a crystal would have been confined to a surface layer a few thousandths of an inch in thickness.

Aside from demonstrating the wave properties of the scattered radiation, the diffraction pattern of a substance can be useful in establishing the positional arrangement of the atoms in the substance, that is, its crystal structure. Such studies, which use the wave characteristics of x-rays and electrons, have grown into a science by itself and a tremendous volume of literature has been produced in the past three decades. But they have their limitations and there appear to be many cases where the use of neutrons offers considerable advantage over the use of the other radiations.

Neutron Diffraction Studies

Of paramount importance in crystallographic studies is a knowledge of the relative scattering power of the scattering centers making up the crystal. As mentioned above, neutrons are scattered by atomic nuclei; in passing through or near an atom a neutron is usually completely oblivious to the presence of the electrons in the outer structure of the atom.



Nuclear scattering cross-sections increase in regular fashion for atoms with greater numbers of electrons when x-rays are used. This is not so when neutrons are used.

The nuclear scattering is accomplished by the nuclear force field, about which very little is known, and hence theoretical considerations are not useful in describing relative scattering amplitudes. But many nuclear scattering cross sections have been measured experimentally and we illustrate the general sequence of the experimental values with increasing atomic weight in the neighboring figure. No regular variation exists in these values. The equivalent x-ray scattering cross sections which are also illustrated vary regularly with increasing electron content of heavier atoms. The pronounced differences existing between neutron and x-ray scattering suggest that many problems not amenable to x-ray study may be more effectively attacked with the equivalent neutron technique.

With x-rays, the cross section of hydrogen is so small, compared to the cross sections of most of the elements, that scattering or diffraction effects due to hydrogen in the presence of other atoms are generally not detectable. In the study, for example, of the crystal structure of ice, the effects with x-rays are due almost entirely to the oxygen atoms in the crystal. But with neutrons, if the deuterated form is used, the cross sections for the scattering by deuterium atoms and the oxygen atoms are very nearly equal and a direct analysis of the position of these atoms in the crystal can and has been made.

This aspect of the neutron diffraction technique has as yet not been pushed very far but there is no doubt that much promising work can be done along this line. Structure determinations have been made with thorium deuteride which led to results quite contrary to those expected from indirect inferences from other similar compounds. This example of crystal structure determination by neutron diffraction is interesting because it involves two elements at almost the extreme ends of the periodic table. With x-rays the study of even such compounds as the oxides of the heavy elements is well-nigh impossible and the neutron technique may be expected to give important advances in this aspect of the field.

Neutron scattering by materials containing hydrogen is important for more than crystal and molecular structure. It has a more fundamental significance because it involves the interaction of two fundamental particles, the neutron and the nucleus of the hydrogen atom, the proton. Since matter is built up of neutrons and protons, a knowledge of the forces which bind these particles together must be a part of any theory of nuclear structure.

When a neutron strikes a proton it may be scattered or it may be captured by the proton with the emission of a gamma ray to form a deuteron. The theory of the scattering of neutrons by protons is in a sense the theory of the binding of neutrons and protons together to form deuterium nuclei. It has been found experimentally that the interaction of these two elementary particles is spin-dependent, that is, it depends upon the relative alignment of the nuclear spins. The spins of elementary particles can interact in one of two ways: the spins must either be parallel or antiparallel—they must either point in the same or the opposite direction. These facts, as well as the magnitude of the interaction, have resulted from measurements of the scattering amplitude in crystal diffraction and in total reflection experiments with hydrogen-containing compounds and also in transmission measurements with ortho and parahydrogen.

So far we have considered the interaction of neutrons only with atomic nuclei. The spin and associated magnetic moment of neutrons have been shown to play a role in nuclear interactions, and since electrons also have a spin, magnetic interactions between neutrons and atomic electrons may also be expected. Only in certain special cases, however, are the atoms in a solid found to possess spins or magnetic moments. In most cases the electronic moments existing in all atoms have balanced themselves so that the atom itself has no effective magnetic moment and hence there results no magnetic interaction with an approaching neutron. In ferromagnetic materials such as iron, cobalt, and nickel and in paramagnetic materials such as manganese oxide, the unfilled third shell in the metallic atoms or ions contains electrons with unpaired spins and these are responsible for the magnetic behavior of these materials. In ferromagnetic materials the spins are ordered while in paramagnetic materials they are oriented essentially at random.

The magnetic interaction of neutrons with ions and atoms of this type is comparable and may, in some cases, even be larger than the purely nuclear interactions. Although the magnetic interactions may be visualized as associated with the neutron as a 'particle', scattering effects even from single magnetic atoms will always involve interference effects between waves scattered by the nucleus and those scattered by the magnetic electrons. One of the most significant experiments associated with magnetic scattering of neutrons involves the polarization of neutrons and its application to accurate measurements of the neutron and of the neutron's magnetic moment. Space does not permit going into the details of these experiments; suffice it to say that they are essentially equivalent to experiments involving measurements of magnetic moments of charged particles.

A method of polarizing a beam of neutrons, although not that used in the above mentioned experiments, will be briefly described because it fits so logically into a discussion of the wave properties of neutrons. It involves the total reflection of neutrons from mirrors. The index of refraction for neutrons, as for x-rays, is very nearly unity and the critical angles of reflection are in the neighborhood of 10 to 30 minutes of arc for the commonly used wavelengths of one to several Angstroms. The index is proportional to the scattering amplitude and for most elements which have positive amplitude the index is slightly less than unity, which is a requirement for total reflection from a mirror face.

In the case of a magnetized cobalt mirror the effective amplitude for the scattering by an atom (nuclear plus magnetic interaction) is of one sign when the spins of the neutrons are parallel to the lined-up atomic spins, and it is of opposite sign when the neutron's spins are antiparallel to the atomic spins. Since total reflection only occurs for a positive scattering amplitude, i.e. for index of refraction less than unity, these neutrons aligned in one direction will be totally reflected and hence a beam of 100% polarization is obtained. This experiment is closely analogous to the polarization of light waves by reflection at the proper angle.

There is another aspect of magnetic scattering which promises to be of great help in unraveling problems relating to the structure of magnetic materials. It involves primarily the study of the scattering and diffraction of neutrons by paramagnetic and antiferromagnetic crystals. In some paramagnetic materials the magnetic ions, such as the manganese in manganese sulphate, have their magnetic axes oriented at random with no coupling forces existing between the individual moments. Other paramagnetic substances show a magnetic behavior which suggests that the moments are coupled together presumably by the exchange forces which act between the electron spins of neighboring atoms. Since the scattering of neutrons will depend upon the orientation of the magnetic moments in the crystal lattice, the neutron diffraction pattern permits a direct portrayal of the existing magnetic structure.

For the case of completely uncoupled moments the magnetic scattering effects show up as a diffuse scattering in the pattern with a form factor decrease in intensity with angle of scattering. This form factor is interesting in itself because it permits a determination of the radial distribution function for the specific electrons in the atom which are responsible for the atomic moment. When the atomic moments in the crystal become coupled together, coherence in the magnetic scattering is introduced; and for the two cases of ferromagnetic and antiferromagnetic substances where all of the moments are rigidly aligned, the magnetic scattering is concentrated in the Bragg reflections from the crystal. As is to be expected there are many intermediate cases where the magnetic coupling is only partial, that is, where a short-range magnetic order exists and these effects can be established from the neutron diffraction pattern.

The magnetic scattering effects outlined above appear to be among the most interesting of the neutron diffraction applications and undoubtedly much attention will be directed to problems of this nature. Many years ago x-ray diffraction studies were attempted on such materials without success because the necessary interaction was lacking. Using neutrons as the scattered radiation provides the necessary magnetic interaction and it is to be expected that many interesting magnetic phenomena will be studied by this new technique.