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NEUTRON SCATTERING TO RADIATION CONSTANTS

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NEUTRON SCATTERING. A neutron is said to be scattered when it changes its direction of motion and/or its energy in an encounter with an atomic nucleus. The scattering is called elastic if the energy of the neutron remains constant in the centre-of-mass system, while in inelastic scattering energy is transferred to excite the bombarded nucleus. As measured in the laboratory even in an elastic collision a kinetic energy $E_R = 4mME\cos^2\varphi/(M+m)^2$ is transferred from the incident neutron of mass m and energy E to the bombarded nucleus of mass M which recoils at angle φ with respect to the direction of the incident neutron. For slow neutrons the term inelastic scattering is also applied to the transfer of kinetic energy of the neutron to excitation of a molecule or crystal lattice.

In addition to being scattered a neutron may induce nuclear reactions. The cross-section of a nucleus for all processes, i.e. scattering and reactions, is referred to as the total cross-section. The cross-section for all collisions other than elastic collisions is called the cross-section for inelastic collisions (in contrast to inelastic scattering).

The elastic scattering cross-section exhibits a slow variation with energy upon which there are superimposed rapid variations. The rapid variations are called resonances and are attributed to energy levels in the compound nucleus. The slowly varying background is called potential scattering because it may be approximated by the interaction of the neutron waves with a spherical potential. The potential is about 40 MeV deep and has a radius

$$R \sim (1{\cdot}27A^{1/3} + 0{\cdot}7) \times 10^{-13}\ \text{cm}$$

where A is the atomic weight. Measurements and calculations of the potential scattering cross-section show that it has broad maxima and minima as a function both of A and E. These are called size resonances or giant resonances in contrast to the much narrower compound nucleus resonances. Potential and resonance scattering interfere with each other in such a way that each compound nucleus resonance will show in general a maximum and a minimum although in some cases only a maximum or only a minimum appears.

Inelastic scattering is possible only if the energy of the incident neutron is sufficient to excite the bombarded nucleus to an excited state which subsequently decays with the emission of a γ ray. As the neutron energy is increased, more and more states can be excited. At a neutron energy of several MeV the inelastic scattering cross-section reaches a value of the order of πR^2. At higher energies as (n, 2n) processes become energetically possible the inelastic scattering cross-section decreases again.

The angular distribution of the elastic scattering is isotropic at the lowest neutron energies. At higher energies the angular distributions show rapid variations with energy as the energy is varied through a compound nucleus resonance and they depend on the character of the compound state. When the measurement is carried out with an energy spread large compared to the spacing of resonances, the angular distributions show a large forward peak and smaller peaks at greater angles. These are caused by the diffraction of the neutron wave at the nucleus. Particularly for heavy elements, a narrow peak occurs at the smallest scattering angles which is caused by the interaction of the magnetic moment of the neutron with the electrostatic field of the nucleus.

For slow neutrons which have a wave-length of the order of atomic dimensions additional effects are observed in the elastic scattering such as interactions with the atomic magnetic fields, diffraction by a crystal lattice, and other optical phenomena.

See also: Neutron scattering, magnetic. Potential scattering.

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H. H. BARSCHALL

NEUTRON SCATTERING, CRITICAL MAGNETIC. When slow neutrons are scattered by a ferromagnetic crystal such as iron or magnetite, a large increase in the scattering is observed at temperatures near the Curie point. The phenomenon is known as critical magnetic scattering and results from the large spontaneous fluctuations in the magnetization that occur at these temperatures.

See Index for location of terms not found in this volume

In a ferromagnetic crystal, the average magnetic moment of each domain decreases with temperature and reaches zero at the Curie point. However, at all finite temperatures, the instantaneous magnetic moment varies about the average value due to fluctuating short-range order of the electron spins. These fluctuations become very large as the Curie point is approached and reach a maximum at that point. They give rise to increased magnetic scattering of neutrons in just the same way as the large density fluctuations that occur in a liquid or a dense gas near a critical point cause increased scattering of light. This latter phenomenon, known as critical opalescence, gives scattering up to angles of the order of λ/r where λ is the wave-length of the light and r is the linear dimension over which the fluctuation persists. In the neutron case, similar small angle scattering occurs. In addition, if their wave-length is sufficiently short, neutrons are scattered at angles near the Bragg directions.

A theoretical analysis of critical magnetic scattering has been given by Van Hove in terms of the time-dependent pair correlation of the electron spins. The phenomenon has been demonstrated in iron by Squires, who showed that the total cross-section has a sharp maximum at the Curie point, and by Palevsky and Hughes who, using neutrons with wave-lengths in the range 5–13 Å, showed that the scattering is proportional to wave-length and hence is inelastic. With neutrons of about 1 Å, Wilkinson and Shull observed considerable small angle scattering in the neighbourhood of the Curie point with a pronounced maximum at the Curie point itself. The results of the various experiments indicate that critical scattering occurs at temperatures from about 100° below to about 100° above the Curie point.

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G. L. Squires

NEUTRON SCATTERING, ELECTROSTATIC. Current theories of neutron structure predict and experiments confirm that the neutron, in spite of its vanishing net electric charge, nevertheless interacts with electrostatic fields thus demonstrating that it possesses a non-vanishing charge density. In first approximation the interaction energy is proportional to the Laplacian of the electrostatic potential φ:

$$V(\mathbf{r}) = \varepsilon \nabla^2 \varphi(\mathbf{r}),$$

and hence is of the form of a direct interaction of the neutron with the electrostatic field producing charge density. The strength of the interaction is measured by the second radial moment of the neutron charge density $\varrho(r)$:

$$\varepsilon = \tfrac{1}{6} \int_0^\infty r^2 \, \varrho(r) \, 4\pi r^2 \, \mathrm{d}r.$$

Experimentally, $\varepsilon_{\mathrm{exp}} = -(3{\cdot}4 \pm 0{\cdot}2) \times 10^{-51}$ coulomb-metre^2, the negative sign representing a situation where a layer of negative charge surrounds a region of net positive charge.

Theoretically ε is comprised of two contributions. The first, $\varepsilon_{\mathrm{int}}$ arises from the intrinsic charge separation in the neutron as is anticipated theoretically, at least in part, from the virtual dissociation of the neutron into a negative pi-meson and a proton. The exact magnitude of this contribution is sensitive to structural details of the neutron. The second contribution $\varepsilon_{\mathrm{mag}}$ arises from the fact that the neutron possesses an intrinsic magnetic dipole moment μ_0 which in association with its "Zitterbewegung" gives rise to a relativistic contribution

$$\varepsilon_{\mathrm{mag}} = \mu_0 e/2Mc = -3{\cdot}4 \times 10^{-51} \text{ coulomb-metre}^2$$

where M is the neutron mass. Thus

$$\varepsilon_{\mathrm{int}} = \varepsilon_{\mathrm{exp}} - \varepsilon_{\mathrm{mag}} = (0 \pm 0{\cdot}2) \text{ coulomb-metre}^2.$$

The smallness of $\varepsilon_{\mathrm{int}}$ compared to $\varepsilon_{\mathrm{mag}}$ is entirely unexpected theoretically and has received no satisfactory explanation up to the present time.

Experimentally the electrostatic interaction is observed by measuring the scattering amplitude for slow neutrons from electrons bound in atoms and for this reason is commonly called *the neutron-electron interaction*. The scattering amplitude is determined either by (1) observing the effects of interference between electron and nuclear scattering on either the angular distribution or the variation of total cross-section with energy for neutron scattering from atoms, or (2) measuring the electron contribution to the index of refraction of a material medium for neutrons. It has become conventional to express the strength of the interaction in terms of a "well-depth" V_0 related to ε by $V_0 = -3e\varepsilon(mc^2/e^2)^3$. In this mode of expression:

$$V_{0,\mathrm{exp}} = (4050 \pm 200) \text{ eV},$$
$$V_{0,\mathrm{mag}} = 4080 \text{ eV}.$$

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L. L. Foldy

NEUTRON SCATTERING FACTOR. For an incident neutron wave of amplitude A_0 the scattered wave at distance r from a nucleus is $-A_0 b/r$ where b is the atomic scattering factor for neutrons. Such a simple treatment of the problem applies only to the case of individual nuclei having zero nuclear spin and we have to develop the discussion further for nuclei which have finite spin and for *elements* which consist of several nuclear isotopes.

Considering first of all a single isotope with spin I we may regard the oncoming neutron, which has a spin $\frac{1}{2}$, as able to form either of two temporary compound nuclei, with spins of $I + \frac{1}{2}$, $I - \frac{1}{2}$ respectively, and each of these will have its own scattering factor

b_+, b_-. As a result, the total scattering will be of two types: first, there is coherent scattering which can produce constructive or destructive interference effects with the scattering from other nuclei and, secondly, there will be incoherent background scattering. The effective coherent scattering factor for the nucleus will be

$$\bar{b} = w_+ b_+ + w_- b_- \qquad (1)$$

where w_+, w_- are the effective weights of the two nuclear species. These are equal, respectively, to $(I+1)/(2I+1)$ and $I/(2I+1)$. From the form of the expression for $\bar{b}$ it will be seen that $\bar{b}$ may be very small if $w_+ b_+$, $w_- b_-$ are of the same order of magnitude but of opposite algebraic sign. Such a case occurs in practice for ordinary hydrogen. As a result there is only very little coherent scattering by hydrogen but a large amount of incoherent scattering which gives an isotropic background.

When we consider an element with several isotopes we have to take account of the fact that each isotope will have its own scattering factor, or its own pair of factors if it is an isotope which possesses nuclear spin. As an example, we may remark that the atomic scattering factors for ^{58}Ni, ^{62}Ni are 1·44 and $-0{\cdot}87 \times 10^{-12}$ cm respectively. We therefore extend equation 1 to become

$$\bar{b} = \sum_r (w_r b_r) \qquad (2)$$

where the summation is taken over all isotopes and spin combinations. As before, this represents the effective scattering amplitude of the element for coherent scattering. If, indeed, the different isotopes have markedly different values of b then there will again be a large contribution of incoherent scattering. This is called "isotopic incoherence" in contrast to the contribution from "spin incoherence" mentioned above. The total number of incoherently scattered neutrons from both causes will be proportional to

$$\overline{b_r^2} - (\bar{b}_r)^2$$

where the averages $\overline{b_r^2}$ and $\bar{b}_r$ are taken over the various isotopes and their parallel and antiparallel spin states.

We emphasize two points: (i) we have been considering only the scattering by an isolated atom and we have not considered the various additional effects which arise when the atom is part of a three-dimensional array in a crystal, and (ii) we have only been concerned with nuclear scattering.

See also: Atomic scattering factor. Neutron diffraction. Neutron scattering, magnetic.

G. E. Bacon

NEUTRON SCATTERING, MAGNETIC. Atoms which have a magnetic moment as a result of possessing unpaired electrons will scatter neutrons on account of an interaction between their magnetic moment and that of the neutron. This scattering will be additional to the nuclear scattering which is a characteristic of *all* atoms. Magnetic scattering was first detected experimentally in 1949 from measurements of the total neutron cross-section of paramagnetic compounds such as manganous fluoride, MnF_2, for which it was shown that the scattering was greater than the sum of the component values for its constituent elements. The excess was interpreted as magnetic scattering for the Mn^{++} ion which would be expected to have a magnetic spin quantum number of 5/2 or a magnetic moment of $5\mu_B$. More accurate observations have later been made by studying both the background scattering in neutron diffraction patterns and also the coherent magnetic spectra which, as we shall see later, arise under certain conditions.

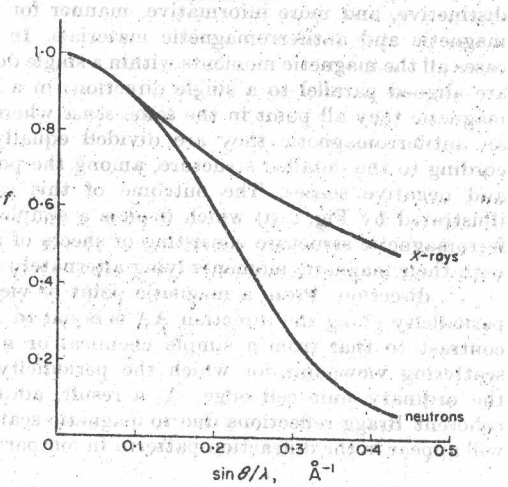

Fig. 1. Variation of the magnetic amplitude form factor of Mn^{++} with $(\sin\theta)/\lambda$, as deduced from experimental measurements of paramagnetic scattering by MnF_2. For comparison the more slowly varying curve for the X-ray scattering by a manganese atom is also shown (from Bacon "Neutron Diffraction").

In a paramagnetic material the magnetic moments are randomly directed in space and, as a result, the magnetically scattered neutrons are distributed in all directions. The distribution is not, however, isotropic and the intensity falls off rather quickly with increasing angle of scattering because an individual atom comprises a scatterer of significant size in relation to the neutron wave-length. The linear dimensions of the orbits of the magnetic electrons are about 1 Å, giving a form-factor type of angular dependence as indicated in Fig. 1. This behaviour is to be contrasted with the *nuclear* scattering of neutrons, which is independent of the angle of scattering because the nucleus is effectively a point scatterer and not an extended source. Equally, it is to be noted that the magnetic form factor (as Fig. 1 shows) falls off more quickly with angle than does the atomic scattering factor for X-rays. This is because the latter depends on *all* the extranuclear electrons whereas the magnetic scattering arises only from electrons in orbits near the surface of the atom.

See Index for location of terms not found in this volume

Quantitatively it can be shown that the differential magnetic scattering cross-section, i.e. the cross-section per unit solid angle, is given by

$$d\sigma_{pm} = \tfrac{2}{3} S(S+1)\left(\frac{e^2\gamma}{mc^2}\right)^2 f^2 \qquad (1)$$

for a paramagnetic atom. Here S is the spin quantum number of the scattering atom, γ is the magnetic moment of the neutron expressed in nuclear magnetons, f is the angular form factor discussed above, e, m are the electronic charge and mass and c is the velocity of light.

The magnetic scattering appears in a much more distinctive and more informative, manner for ferromagnetic and antiferromagnetic materials. In these cases all the magnetic moments within a single domain are aligned parallel to a single direction: in a ferromagnetic they all point in the same *sense* whereas in an antiferromagnetic they are divided equally, according to the detailed structure, among the positive and negative senses. The outcome of this can be illustrated by Fig. 2 (i) which depicts a simple antiferromagnetic structure consisting of sheets of atoms with their magnetic moments lying alternately in the +, — direction. From a magnetic point of view the periodicity along the direction AA is equal to $2a$, in contrast to that from a simple chemical or nuclear scattering viewpoint for which the periodicity is a, the ordinary unit cell edge. As a result, additional coherent Bragg reflections due to magnetic scattering will appear in the diffraction pattern: in our particular

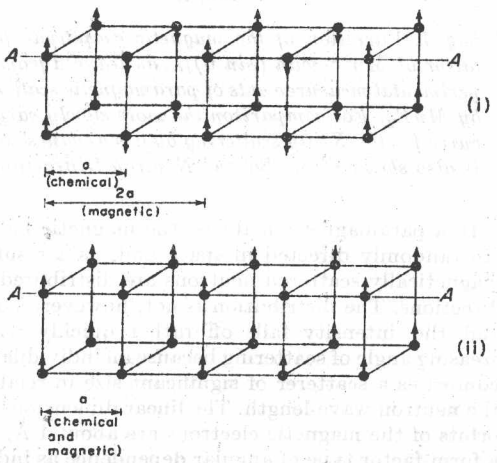

Fig. 2. Simple structures for (i) antiferromagnetic and (ii) ferromagnetic materials, showing the difference between the magnetic and chemical periodicities in the former case.

case of Fig. 2 (i) there will be a reflection which indexes as $(\frac{1}{2}00)$ according to the chemical unit cell. A practical example is provided by the alloy AuMn, for which the manganese atoms occupy positions as in Fig. 2 (i). In Fig. 3 are contrasted the diffraction patterns for this alloy taken at room temperature (where the extra magnetic reflections appear) and at 260°C where the antiferromagnetic alignment has disappeared and the material has become paramagnetic.

If our sample is ferromagnetic we again get coherent reflections due to magnetic scattering but these will appear at the same angles as the ordinary nuclear peaks, because for a ferromagnetic both the chemical and magnetic periodicity will be the same, i.e. equal to

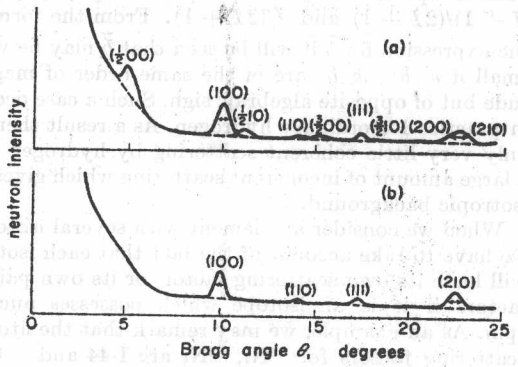

Fig. 3. Typical neutron diffraction patterns for an antiferromagnetic material, AuMn, taken at (a) room temperature, showing the magnetic reflections $(\frac{1}{2}00)$, $(\frac{1}{2}10)$, $(\frac{3}{2}00)$ *and* $(\frac{3}{2}10)$ *and at (b) 260°, in the paramagnetic region where these reflections have disappeared (from Bacon and Street, Proc. Phys. Soc. London, 72, 470 (1958)).*

a along AA in Fig. 2 (ii). In practice it is found possible to disentangle the magnetic and nuclear components of the composite reflections by observing the effects of temperature and magnetic field. Quantitatively it can be shown that the magnetic atoms in a ferro- or antiferromagnetic have a coherent scattering amplitude

$$p = \left(\frac{e^2\gamma}{mc^2}\right) Sf \qquad (2)$$

where the symbols have the same significance as in the expression 1 above for the differential paramagnetic scattering cross-section $d\sigma_{pm}$, which is seen to be close in value to p^2.

In the table are given some typical values of the magnetic scattering amplitude p for a number of atoms and ions. For comparison the nuclear scattering amplitudes b are also shown and it will be seen that b, p are of the same order of magnitude and both are measured in units of 10^{-12} cm. Because of the dependence on the form-factor f, p falls off rapidly as the angle of scattering, 2θ, increases.

The full value of p given by (2) is only attained if the direction of the magnetic moment H in the diffracting sample is perpendicular to the scattering vector specified in Fig. 4, i.e. if H is perpendicular to the normal to the reflecting plane. In general the amplitude will be reduced below this by the factor $\sin\beta$,

Comparison of nuclear and magnetic scattering amplitudes

Atom or ion	Nuclear scattering amplitude b, 10^{-12}cm	Effective spin quantum number, S	Magnetic scattering amplitude p, 10^{-12} cm	
			$\theta = 0°$	$(\sin\theta)/\lambda = 0.25$ Å^{-1}
Cr^{2+}	0·35	2	1·08	0·45
Mn^{2+}	−0·37	5/2	1·35	0·57
Fe (metal	0·96	1·11	0·60	0·35
Fe^{2+}	0·96	2	1·08	0·45
Fe^{3+}	0·96	5/2	1·35	0·57
Co (metal)	0·28	0·87	0·47	0·27
Co^{2+}	0·28	2·2	1·21	0·51
Ni (metal)	1·03	0·3	0·16	0·10
Ni^{2+}	1·03	1·0	0·54	0·23

where β is the angle indicated in Fig. 4. More exactly, it is necessary to consider possible interference between the nuclear and magnetic components of scattered neutrons and it can be shown that there is an effective total differential scattering cross-section

$$d\sigma = b^2 + 2bp\mathbf{q}\cdot\boldsymbol{\lambda} + p^2q^2 \qquad (3)$$

where b is the nuclear scattering amplitude and $\mathbf{q}$ and $\boldsymbol{\lambda}$ are the vectors shown in Fig. 4: as will be seen, $\boldsymbol{\lambda}$ is the polarization vector for the incident neutrons. In

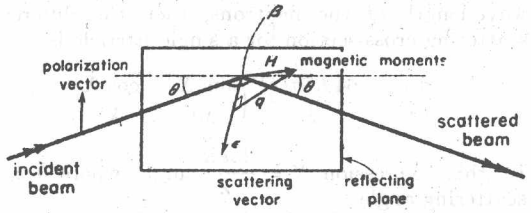

Fig. 4. Magnetic scattering from a crystal plane, indicating the important vectors and angles. The vector $\mathbf{q}$ lies in the plane of ε, H and is perpendicular to ε and of magnitude $\sin\beta$.

practice there are two important cases to distinguish. First, if the incident neutron beam is unpolarized the mean value of $\mathbf{q}\cdot\boldsymbol{\lambda}$ is zero and equation 3 reduces to

$$d\sigma = b^2 + (\sin^2\beta)p^2; \qquad (4)$$

which states that the nuclear and magnetic intensities are additive. Secondly, for a polarized beam having $\boldsymbol{\lambda}$ perpendicular to the plane of the incident and diffracted beams and with a magnetized sample in which the magnetic moments are parallel to this same direction, equation 3 becomes

$$d\sigma = (b \pm p)^2, \qquad (5)$$

the positive or negative sign being taken according to whether the neutron spin direction is parallel or antiparallel to the magnetic moment vector. From the form of equation 5 we see that for polarized neutron beams interference takes place between the nuclear and magnetic components of the scattering.

Most of the applications of the magnetic scattering of neutrons to the study of the solid state depend on the detection and identification of magnetic reflections and their quantitative interpretation in terms of equation 4. The magnetic components, usually distinguished by observation at different temperatures, have to be equated with the expression $(\sin^2\beta)p^2$ for each reflection. This is done by trial and error methods, postulating in turn various reasonable arrangements of magnetic moments and associated spin values. In this way a magnetic structure is found which satisfies the experimental data and this has been achieved for various metals and alloys, e.g. Mn and MnCu, and for magnetite (Fe_3O_4), many ferrites and oxides and halides of the transition elements. The value of the technique has been limited in the past by this essentially indirect trial and error method which has to be applied, with the risk that some other equally plausible magnetic structure may not have been tried and tested. However, this weakness is becoming less important as, with improved neutron techniques and beams of increased intensity, single crystal and single domain samples become available for study.

Studies of a rather different nature by Shull and Wilkinson involving measurements of so-called "ferromagnetic disorder" scattering have yielded important

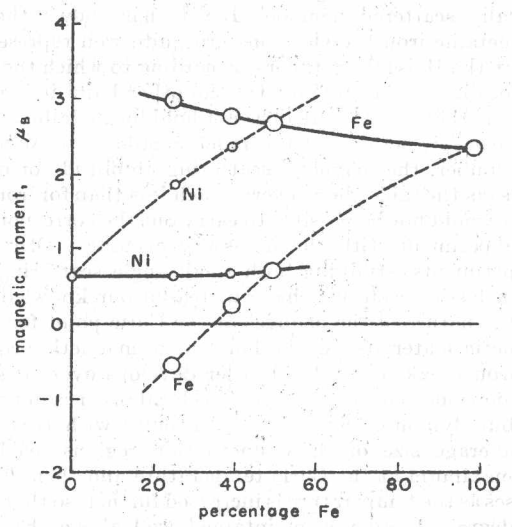

Fig. 5. The atomic magnetic moments found by neutron scattering in the Ni–Fe series of alloys. The solid and dotted lines represent the two possible sets of values [from Shull and Wilkinson, Phys. Rev. 97, 304 (1955)).

information about the variation of magnetic moment with composition for alloys. In many ferromagnetic alloys the structure is "disordered", with the two components distributed at random among the atomic sites. At the same time all the magnetic moments are

See Index for location of terms not found in this volume

aligned parallel and this results in a contribution of diffuse magnetic scattering to the background of the diffraction pattern depending in magnitude on the difference in moment of the two constituents. If measurements of this scattering are combined with magnetic saturation data, which give the average magnetic moment for all the atoms in the alloy, it is possible to deduce (within an ambiguity of sign) the individual moments of the two constituents. Their variation with alloy composition can then be examined, as shown by the results in Fig. 5 for the iron–nickel series.

The majority of magnetic structure studies have dealt with the iron group of transition elements and their compounds. In these it is the unpaired $3d$ electrons in the outermost shell of the ions which give rise to the magnetic moment. Very often the orbital momenta are completely quenched by the crystalline field and the ions behave as though their angular momentum was purely due to spin. On the other hand, the rare earth ions possess magnetic moments due to unpaired electrons in an inner shell and their orbital momenta are fully operative. As a result the magnetic form factors are more complicated than for the iron group elements and it is possible to deduce separate form factors for the spin and orbital moments.

Other studies of magnetic scattering have aimed at improving our detailed picture of the magnetic electrons in a ferromagnet. From observations of inelastically scattered neutrons Lowde has shown that in metallic iron the electrons are quite well represented by the Heisenberg theory, according to which they are localized at fixed sites. On the other hand it is probable that this picture does not hold for metallic nickel; however, because of the much smaller spin quantum number, the magnetic scattering amplitude of nickel is (as the table shows) very much less than for iron and it would not be possible to carry out the corresponding experiment with the necessary accuracy. Other experiments, studying both small angle scattering and inelastic scattering, have increased our knowledge of the nature of the changes at the Curie point for magnetic materials. As the long range magnetic order in iron breaks down local order develops over small regions measuring 10–25 Å. This local order is not static but dynamic and fluctuates rapidly with time. The average size of these fluctuation regions reaches a maximum at the Curie temperature and then decreases as the temperature is increased further, so that some degree of order is maintained well above the Curie temperature.

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G. E. BACON

NEUTRON SCATTERING, SMALL-ANGLE. Small-angle scattering of neutrons refers ordinarily to the scattering of thermal neutrons (wave-length $\sim 0{\cdot}2$–20 Å) by small objects (dimensions ~ 20–2000 Å) into angles of the order of the wave-length divided by the dimensions. Although very similar in nature to small-angle scattering of X rays, it differs chiefly in three important respects. First, because of the generally greater penetrating power of neutrons it is often possible to observe highly multiple scattering. Second, because of the neutron's magnetic moment it may be scattered by small magnetic irregularities, such as domains, in magnetic materials. Lastly, the small-angle scattering of neutrons is determined by the neutron scattering amplitudes, of course, and these are almost exclusively a property of the nuclei in the scatterer, except in the case of magnetic materials.

An accurate calculation of the small-angle scattering can be quite complex when multiple-scattering effects within one particle, interference effects between particles, and absorption are taken into account, but for rough approximation the following formulae are useful:

(1) For the case in which $\varphi = 4\pi\,|\delta|\,R/\lambda < 1$, where δ is the difference between index of refraction for neutrons in the material of the particle and the index of the surrounding medium, R is the radius of the particle (here assumed to be a sphere) and λ is the wave-length of the neutrons, then the differential scattering cross-section for a single particle is:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{64R^6\pi^4\delta^2}{\lambda^4}\left(\frac{\sin X}{X^3} - \frac{\cos X}{X^2}\right)^2.$$

In this expression $X = \dfrac{2\pi R}{\lambda}\sin\theta$, where θ is the scattering angle.

(2) For the other case, in which $\varphi > 1$, the beam may be treated as spread by refraction and, for the case where there are N particles per unit area of beam, the beam may be thought of as spread into a Gaussian of half-width given by

$$\langle\theta^2\rangle = 4N\pi R^2\delta^2 \times \left(\ln\frac{2}{|\delta|} + 1\right).$$

These formulae should not be expected to give precise absolute values, but they do show the variation with particle size, index of refraction, etc.

Magnetic small-angle scattering may be calculated from the magnetic contribution to the index of refraction for neutrons which is $\pm\,|\boldsymbol{\mu}|\,|\mathbf{B}|/E$, where $\boldsymbol{\mu}$ is the neutron magnetic moment, $\mathbf{B}$ is the magnetic induction, and E is the kinetic energy of the neutron. The plus and minus signs correspond to $\boldsymbol{\mu}$ antiparallel to $\mathbf{B}$ and parallel to $\mathbf{B}$ respectively, i.e. there are two indices of refraction as in the case of light in an anisotropic medium. In an unmagnetized ferromagnetic material, the average change between two adjacent domains may be taken roughly as $|\boldsymbol{\mu}|\,|\mathbf{B}|/(2E)$ for the calculation of small-angle scattering. When the ma-

terial is magnetized to saturation the magnetizations of all domains become parallel and small-angle scattering disappears.

See also: Neutron optics. Scattering, small-angle, of photons or particles. X-ray scattering, small-angle.

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G. R. RINGO

NEUTRON SCATTERING, SPIN-WAVE. The scattering of neutrons by atoms can take place in two distinct ways.

1. Isotropic scattering, the atomic nucleus acting as a point scatterer relative to the neutron wave-length.

2. Scattering produced by the interaction of the magnetic moment of the neutron with the spin and orbital magnetic moments of the atom (magnon scattering).

If both type are present, as is usual, the scattering is termed *spin-wave*.

See also: Neutron scattering, magnetic.

NEUTRONS, FAST. Fast neutrons are those whose energy, and hence speed, exceeds some arbitrary limit, whose value depends to some extent on the context.

In reactor theory, fast neutrons are generally reckoned to be those with energy above the fission threshold in U 238, i.e. above 1·2 MeV.

In considering the biological effects of radiation neutrons with energy in excess of 0·1 MeV are reckoned to be 'fast'.

NEUTRONS, FREE. A free neutron is defined as one which is not part of a nucleus. Free neutrons decay to protons by a beta process, with a half-life of about 12 minutes.

NEUTRONS, MIGRATION AREA FOR. The migration area for a neutron is, by definition, the sum of its slowing down area (or Fermi age) and its diffusion area.

The migration area is thus related to the total mean square distance travelled by a neutron, from its time of birth as a fast neutron, through the slowing down and diffusion processes, until it is captured as a thermal neutron.

The migration area of its neutrons determines the critical size of a nuclear reactor.

The square root of the migration area is known as the **migration length**.

NEUTRONS, MODERATION OF. Moderation is the term used in reactor physics to denote the **degradation of neutron energy** by scattering interactions with a *moderator*. In its most important application, it refers to the slowing down of neutrons produced by fission (average energy about 2 MeV) to energies at which, for a given concentration of fissionable material, the ratio of fission reactions to absorption reactions becomes such as to permit a self-sustaining chain reaction. The use of natural uranium (^{238}U and ^{235}U in the ratio 137:1) and fuels of moderate enrichment make it essential to moderate fission neutrons to *thermal* energies, i.e. to the lower limit set by the thermal vibration of moderator atoms (0·025 eV at 20°C). The geometrical arrangement of fuel and moderator is such that the latter provides a medium in which neutrons may slow down through the region of resonance capture in ^{238}U (6–100 eV) with the minimal chance of meeting a ^{238}U atom.

The following is an elementary treatment of slowing down. A neutron of energy E_1 has, after an elastic collision with a moderator atom of atomic weight A, an energy E_2 between E_1 and αE_1, all energies within the range being equally probable. The constant, α, is equal to $(A-1)^2/(A+1)^2$. The exponential nature of the slowing down process is apparent and it can easily be shown that the average *logarithmic* energy loss per collision is

$$\xi = (\log E_1 - \log E_2)_{AV} = 1 + \alpha \log [\alpha/(1-\alpha)].$$

From this it follows that the number of collisions required for slowing down from fission energy E_f to thermal energy E is

$$N = (\log E_f - \log E_t)/\xi$$

and it can also be shown that the *energy spectrum* of slowing down neutrons is

$$F(E)\,\mathrm{d}E \propto \frac{\mathrm{d}(\log E)}{\mathrm{d}E}\,\mathrm{d}E$$

$$\propto \frac{1}{E}\,\mathrm{d}E.$$

The *spatial* distribution of the integrated slowing down flux, $\varphi_1 = \int_{E_t}^{E_f} F(E)\,\mathrm{d}E$, and its *magnitude* relative to the thermal flux φ_2 are given by the solution of the two group diffusion equations.

$$D_1 \nabla^2 \varphi_1 - \Sigma_1 \varphi_1 + k_\infty \Sigma_2 \varphi_2 = 0$$

$$D_2 \nabla^2 \varphi_2 - \Sigma_2 \varphi_2 + \Sigma_1 \varphi_1 = 0$$

where D denotes diffusion coefficient, k_∞ the number of neutrons produced for every absorption, and Σ reaction cross-section per unit volume. $\Sigma_1 \varphi_1$ and $\Sigma_2 \varphi_2$ are respectively the rates of production and absorption of thermal neutrons. Since one in N scatters results in thermalization it can be seen that

$$\Sigma_1 = \Sigma_s/N$$

See Index for location of terms not found in this volume

where Σ_s is the scattering cross-section. The value of D_1 is $(3\Sigma_s(1 - 2/3A))^{-1}$.

Since only the ratios of the coefficients in the diffusion equation need be known, it is convenient to define D_1/Σ_1, which has the dimensions of area, as the *slowing down area*, L_s^2. It can be shown that L_s^2 is one sixth of the mean square 'crow-flight' distance travelled by a neutron from birth to thermalization. In an infinite, critical reactor, $\nabla^2\varphi = 0$ and $k_\infty = 1$, so that $\varphi_1/\varphi_2 = \Sigma_2/\Sigma_1$.

A more rigorous treatment of slowing down gives corrections to the above value of L_s^2 which become important in the case of moderators containing light atoms, e.g. water and heavy water. In practice, it is preferred to measure L_s^2 experimentally and then define Σ_1 as D_1/L_s^2.

It is evident that an efficient moderator will be one which combines a low value of L_s^2 (to give low leakage of slowing down neutrons) with a low absorption cross-section, Σ_a. The former implies a low atomic weight, A (high ξ), and a high scattering cross-section per unit volume. A rough figure of merit is $\xi\,\Sigma_s/\Sigma_a$, which is tabulated below for possible moderators.

Choice of moderator is of course governed also by practical considerations such as cost, stability against corrosion and irradiation damage, and performance as a working fluid.

Moderator	$\xi\Sigma_s / \Sigma_a$	L_s^2
Heavy water	5,600	120
Graphite	190	390
Beryllium oxide	170	150
Beryllium	125	100
Water	60	33

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W. STANNERS

NEUTRONS OF INTERMEDIATE ENERGY. Intermediate neutrons are those whose energy lies within the approximate limits of 10^2 and 10^5 eV. In other words they form the intermediate group between the epithermal and fast groups.

See also: Neutron energy.

K. J. BOBIN

NEUTRON SOURCES AND STANDARDS. The sources of neutrons considered under this description are small compact preparations, weighing from 5 to 50 g with dimensions not greater than 5–10 cm, which emit neutrons at rates between 10^4 and 10^8 neutrons per second. Sources of this size are no longer used to any considerable extent to provide the neutrons used in an experiment. Whenever calibrated sources are needed, however, for determining the efficiencies of detectors, calibrating neutron dosimeters, and similar operations, the small, portable, calibrated neutron source is still useful.

Ra–Be (α, n) *sources.* Possibly more of these sources have been prepared than of any other kind. The reason for this is partly that in the earlier days of investigations of neutrons Ra–Be sources were used to produce the neutrons used in the experiments. In addition they offered a comparatively high yield of neutrons per

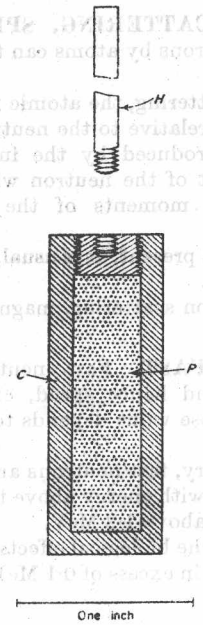

Fig. 1. Cross-section of Ra–Be(α, n) *source. H — removable extension handle, C — metal capsule, P — compressed mixture of powdered beryllium and radium bromide.*

gramme of radium and had a practically constant rate of emission of neutrons with time. Ra–Be (α, n) sources are prepared by stirring finely divided metallic beryllium powder into a solution of a radium salt. The water is evaporated off and the dried mixture compressed into a pellet of a form to fit closely a previously prepared metallic container. Originally the containers were brass and were sealed with lead–tin solder. However, nearly all sources sealed in this way eventually leaked radon, often with disastrous effects upon the laboratory in addition to the impairment of the source. The usual practice now is to seal the pellet in Monel metal, stainless steel, or other corrosion-resistant metal. The closure is made with a high-melting-point solder. However, the possibility of the leakage of radon is one of the disadvantages of most of these sources. A procedure for making compressed, Ra–Be (α, n) sources is described by Anderson and Feld. Because of the

intense gamma rays emitted by all but the smallest Ra–Be sources, a convenient method of attaching a long, removable handle to the container of the source should be provided. Figure 1 is a diagram of a completed Ra–Be source. The yield of neutrons per second, Q, of a Ra–Be source can be estimated approximately by the formula

$$Q = 1{\cdot}7 \times 10^7 \frac{M_{Be}}{M_{Be} + M_{RaBr_2}}$$

where M_{Be} is the mass of the beryllium powder and M_{RaBr_2} is the mass of the radium bromide used in preparing the pellet.

Radon–Be (α, n) *sources.* Occasionally neutron sources have been prepared by introducing radon gas into a glass tube containing fine beryllium powder and flame-sealing the tube. The radon brings with it all the alpha-emitting disintegration products of radium. Therefore a radon–Be source has closely the same properties as a Ra–Be source with the exception of half-life. The short half-life of radon (3·825 days) renders the calibration of the source difficult and limits the useful period to a few days. Significant corrections to all observations must be made for the decay of the radon–Be source. Furthermore these sources must be made near the laboratory where they are to be used to avoid considerable loss of activity in transit. Radon, in useful amounts, can only be obtained from extraction equipment containing several grammes of radium in solution. Such equipment has been available only at a few hospitals using radon preparations for medical treatments. The number of hospitals retaining radon-extraction equipment is steadily decreasing. Consequently it is easy to understand why radon–Be sources are now rarely made.

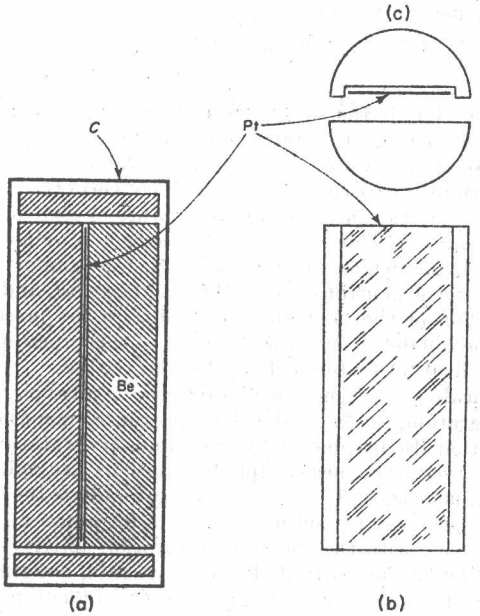

Fig. 2. Diagram of Po–Be(α, n) *sources. (a) cross-section, (b) elevation of a beryllium semicylinder, (c) top view of beryllium semicylinders. C — metal capsule, Pt — platinum foil coated with polonium, Be — beryllium metal.*

Po–Be(α, n) sources. Historically the first method used to generate neutrons, the Po–Be source is still much in use. It is relatively free of gamma radiation, an important feature for nearly all uses. Disadvantages are the short half-life of polonium-210 (138 3 days) and the tendency of polonium to move about within the source by aggregate recoil. Po–Be sources have been made in many forms. One method has been to follow the same general procedure for making Ra–Be sources, stirring finely divided beryllium powder into a solution of polonium. The mixture, after drying, is compressed into a pellet. This is a hazardous operation because of the high volatility of polonium at temperatures above room temperature. Spinks and Graham have devised a scheme for preparing strong Po–Be sources, emitting of the order of 10^6 neutrons per second, which reduces the health hazards of the process materially. The polonium is deposited electrolytically on one side of a platinum foil which is inserted in a slot between two semicylinders of solid beryllium, as indicated in Fig. 2. A neutron source of this design, emitting 3×10^6 neutrons per second, had a gamma-ray activity equivalent to that of 0·3 mg of radium.

Pu–^{13}Be(α, n) sources. Because plutonium forms a natural intermetallic compound with beryllium of the definite formula $PuBe_{13}$, this combination offers a reproducible and stable form of neutron source. Of the isotopes of plutonium, plutonium-239 has been found most useful in neutron sources. It emits alpha particles of 5·1 MeV and has a half-life of $2{\cdot}3 \times 10^4$ years. The gamma rays emitted in the decay of plutonium-239 are low in energy and intensity. Thus they can be classed with Po–Be sources in this respect. Although the neutron yield of $PuBe_{13}$ sources is lower comparatively than that of Ra–Be or Po–Be sources, a cylindrical source about 2 cm in diameter and 3 cm in height will yield about 10^6 neutrons per second. The Los Alamos laboratory of the Atomic Energy Commission is the only laboratory in the United States which has made $PuBe_{13}$ sources to date. When the methods of preparation are better known, and the restrictions on use of plutonium removed, this type of source will become much more common.

Energy spectra of (α, n) *sources.* Figure 3 shows the relative numbers of neutrons as a function of the neutron energy, E_n, for the (α, n) sources described above. The solid curve is for Po–Be, the dotted curve for Ra–Be, and the dashed curve for $PuBe_{13}$. The general course of the curves is much the same. In the graph the curves are normalized to agree at $E_n = 2$ MeV.

Photoneutron sources. Gamma rays incident on nuclei can release neutrons if the energy of the gamma rays exceeds the binding energy of the neutrons in the

See Index for location of terms not found in this volume

nuclei. The (γ, n) thresholds are relatively high in most nuclei, in excess of 6 MeV. However, two nuclides have conveniently low (γ, n) thresholds, deuterium at $2{\cdot}226 \pm 0{\cdot}003$ MeV and beryllium at $1{\cdot}666 \pm 0{\cdot}002$ MeV. A number of radioactive nuclides emit gamma rays with energies in the range 1·8 to 2·8 MeV. They can be used with either deuterium or beryllium

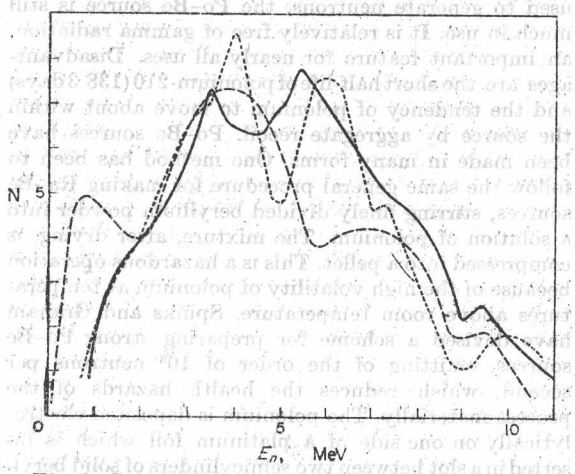

Fig. 3. Curves showing relative distribution of neutron energy E_n from (α, n) neutron sources. Solid curve, Po–Be; dotted curve, Ra–Be; dashed curve, $PuBe_{13}$.

to fabricate photoneutron sources. The usual form for a photoneutron source is a small radioactive pellet mounted in the centre of an otherwise solid sphere or cylinder of the target material when the target is beryllium. For sources using deuterium, the radioactive pellet is mounted centrally in a sealed volume of the gas. Feld has prepared a table giving the half-life, $T_{1/2}$, gamma-ray energies, E, neutron energies, E_n, and comparative neutron yields for a number of typical photoneutron sources. The values in the table are quoted from his résumé.

Some typical photoneutron sources

Components	$T_{1/2}$	E (MeV)	E_n (MeV)	Reletive yield
^{24}Na + Be	14·8 hr	2·76	0·83	130
$^{24}Na + D_2O$	14·8 hr	2·76	0·22	270
^{56}Mn + Be	2·59 hr	1·8, 2·1, 2·7	0·15, 0·30	29
$^{56}Mn + D_2O$	2·59 hr	2·7	0·22	3
^{72}Ga + Be	14·1 hr	1·9, 2·2, 2·5	0·78	50
$^{72}Ga + D_2O$	14·1 hr	2·5	0·13	60
^{88}Y + Be	87 days	1·9, 2·8	0·16	100
$^{88}Y + D_2O$	87 days	2·8	0·31	3
^{116}In + Be	54 min	1·8, 2·1	0·30	8
^{124}Sb + Be	60 days	1·7	0·024	190
^{140}La + Be	40 days	2·5	0·62	3
$^{140}La + D_2O$	40 days	2·5	0·15	8
MsTh + Be	6·7 yr	1·8, 2·6	0·83	35
MsTh + D_2O	6·7 yr	2·6	0·20	95
Ra + Be	1620 yr	1·7, 1·8, 2·0, 2·2, 2·4		30
Ra + D_2O	1620 yr	2·4	0·12	1

Neutron standards. Any well-constructed neutron source having a long half-life can become a neutron standard by an absolute calibration of its rate of emission of neutrons. The high yield and convenient half-life of Ra–Be (α, n) sources have made them a choice in many laboratories for calibration as standards. An absolute calibration may be obtained by placing the source in the centre of a tank containing either pure water or a solution of a neutron-capturing element. The dimensions of the tank are chosen so that very few neutrons escape absorption within its volume. The source strength is then the total rate of capture of neutrons in the tank. The water serves as a moderator to slow all neutrons down to near thermal energies. The convenient methods available for measuring slow neutron densities can be used in the determination of the rate of capture. The source strength Q then in principle is given by

$$Q = K\,4\pi \int_0^\infty A(r) r^2 \,\mathrm{d}r$$

where $A(r)$ is the saturated activity acquired by an activated foil, at distance r from the source, as the result of capture of slow neutrons. K is a constant, determined experimentally, which converts the measured activities into the rate of capture of neutrons in the solution. This simplification neglects a number of corrections which must be applied, for example, for capture of neutrons above thermal energies, and depression of the neutron density due to the presence of the foil detector. An application of this procedure is described by DeJuren, Padgett, and Curtiss.

An alternative method of integration, called physical integration, can be used if the capturing element in the solution also becomes radioactive and serves also as the detector. Manganese sulphate solutions are suitable for this method. The procedure is to irradiate the solution, of a volume sufficient to capture practically all neutrons, with the source to saturation activity. The solution is then stirred. The capture rate, determined from the measurement of the activity of an aliquot of the solution, is then multiplied by the ratio of the total volume of the solution to the volume of the aliquot to give the total capture rate and hence the strength of the source. This method has been used by DeJuren and Chin in the calibration of a standard photoneutron source.

The standard neutron source of the National Bureau of Standards. In 1947 it was suggested that the National Bureau of Standards prepare and calibrate a neutron source to serve as a national standard. A long stable lifetime for the standard was considered of