Neutron Spectrometry

If you count particles as a function of energy, your methods, instruments and purposes can differ greatly depending on whether you are looking for emissions, absorptions or scatterings. Neutron counting started with Chadwick and has become a variegated science.

by Lawrence Cranberg

PROBLEMS OF SPECTROMETRY are by definition those of plotting particles of diverse energies in a two-dimensional array that shows numbers of particles as a function of energy. The prototype was discovered and solved in the 17th century by Isaac Newton when he accomplished the decomposition of white light into a spectrum with a refracting prism. The 19th century brought extension of the problem to electrically charged particles, and it was solved by exploiting the energy and momentum dependence of charged-particle motions in electric and magnetic fields. James Chadwick's discovery of the neutron in 1932 presented the problem in still another form, in which the particles are, like photons, electrically neutral, but, unlike photons, they interact only with the nuclear constituents of matter. It is not surprising, therefore, that the problems of neutron spectrometry exhibit distinctive peculiarities and difficulties. Let us discuss some aspects of the problem as seen from the perspective of recent developments.

As with optical radiation, the problems of neutron spectrometry can be subdivided into those of emission, transmission and scattering. Historically it was the first, of course, that came to the fore since Chadwick's discovery of the neutron can be characterized as a successful attempt to observe a neutron emission spectrum. It is pertinent to review Chadwick's initial observations not only for their historical interest but also because his methods have until recently dominated neutron emission spectrometry. An indication of the present state and difficulties of the subject is that the particular emission spectrum he studied has not yet been fully elaborated although some believe the tools are now at hand for determining the entire spectrum.

Proton-recoil method

Chadwick's initial observations[1] were of neutrons produced by bombarding thick targets of beryllium with alpha particles from polonium, producing the reaction $Be^9(\alpha,n)C^{12*}$. Neutrons are produced in groups n_0, n_1, n_2, (see figure 1) whose energies correspond to the various energetically accessible states of C^{12}. His method of detection was to observe the energies of the nuclear recoils (protons) produced by impingement of the neutrons on matter containing hydrogen or other light nuclei. A proton, recoiling from head-on collision with a neutron, takes up almost all its energy because of the near identity of the masses. Thus a neutron spectrum is transformed into a spectrum of protons that have recoiled in the direction of the impinging neutrons, and the problem of determining a neutron energy spectrum is converted into that of measuring a charged-particle spectrum.

This so-called "proton-recoil" method is gratifyingly simple and straightforward in principle. Unfortunately, it turns out on detailed consideration

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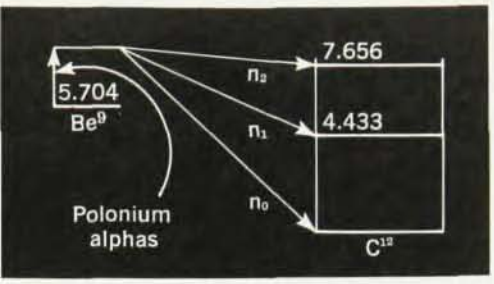
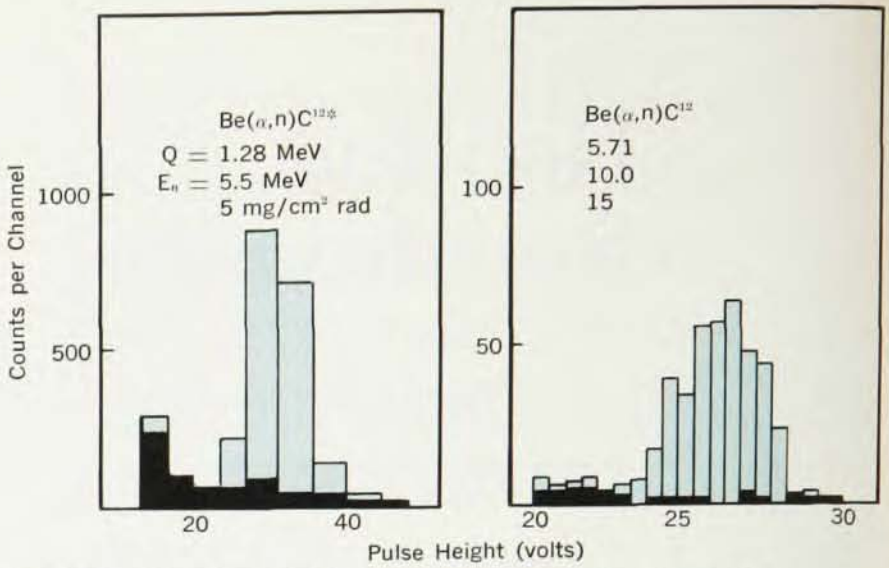


ENERGY LEVELS of states in which the neutron was detected. —FIG. 1



SPECTRA OF PROTON RECOILS ejected from thin hydrogen-containing foils by neutrons of groups n_0 and n_1 that are shown in figure 1. —FIG. 2

that methods based on proton-recoil detection are usually inefficient, tedious, or characterized by poor energy resolution and are essentially inapplicable at all to neutrons whose energy is less than some tens of keV. The difficulties of the proton-recoil method are indicated by figure 2. The data are for the spectrum studied by Chadwick, but these were gathered with "thin" source and target. These are results reported[2] in 1957 with a refined system for electrical detection of proton recoils. Although Chadwick presumably observed proton recoils due primarily to the most energetic neutrons, figure 2 reveals neutron groups n_0 and n_1 corresponding to the residual C^{12} nucleus in its ground and first excited states. As we shall see later, the n_2 group has been observed thus far only with bombarding alpha particles of 14-MeV energy.

Time of flight

The inadequacy of recoil methods for low-energy neutron measurements and even for detection of low-energy neutrons was appreciated very early. John R. Dunning and his colleagues[3] were among the first to use a time-of-flight method for studies of slow neutrons (a few keV and below). In this method one determines transit time of the neutron over a measured flight path. Initial time is fixed by mechanically interrupting a neutron beam, and terminal time is obtained from a neutron detector at the end of the neutron path. To facilitate detection of a slow neutron, the detector embodies material with which the neutron reacts exothermally. Detection of the neutron is accomplished by detecting the ionization produced by the relatively energetic charged-particle or gamma-ray products of the reaction.

Development of neutron research then took a direction quite different, however, from that launched by Chadwick—that is, studies of neutron-emission spectrometry. Indeed, such studies were almost completely passed over for about 20 years. A related subject that experienced intensive development, however, largely by time-of flight methods, was slow-neutron transmission. Such studies offer striking technical simplifications compared, for example, to neutron emission spectrometry. Thus at low neutron energies precise energy measurement could be readily attained with available timing technology, that is, in the range of microseconds. And to determine a nuclear cross section by transmission requires that one measure only a ratio of neutron intensities at a given energy rather than the more difficult absolute numbers of neutrons. At the same time slow neutrons revealed for study distinctive properties of nuclei of great physical and technical importance—in particular the resonance properties of nuclei.

It is pertinent to note, however, that the word "spectroscopy," as often used in the context of slow neutron transmission or absorption studies, may be a misnomer. Slow-neutron "spectroscopists" rarely publish a neutron spectrum. For their work, neutrons with a considerable spread of energies are produced by nuclear reactions in a thick target. Because almost all neutrons produced in nuclear reactions are too fast for slow neutron studies, a neutron slowing-down medium is usually placed close to the neutron source. Rarely, therefore, does the spectrum have any physical interest in itself. In transmission or absorption studies the focus of interest is not on the neutron energy spectrum but rather on a cross section for some neutron-induced process studied as a function of neutron energy. Such data, when obtained with monoenergetic neutrons whose energy is systematically varied, are commonly referred to as "excitation functions." When someone gets excitation functions with neutrons having a continuous energy spectrum and the measurements require sorting out neutrons according to energy the system is essentially an automated monochromator.

"The three spectrometries"

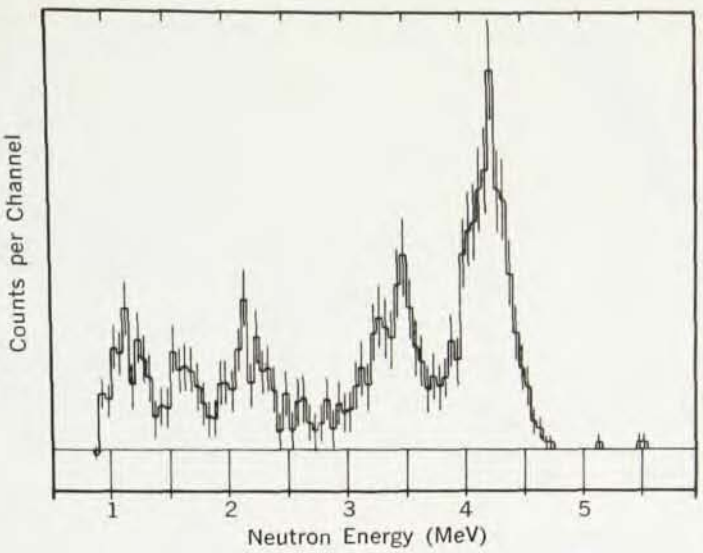
For some years an unspoken and uneasy compromise has, in effect, taken place whereby those who study slow-neutron excitation functions with continuous-energy neutron sources refer to their work as "slow-neutron spectrometry," while those who study the spectra of neutrons produced in nuclear reactions refer to their work as "fast-neutron spectrometry." Although this nomenclature has been assimilated into everyday use and its connotations are

well understood by the cognoscenti, objections on pedagogical grounds persist, and the continuing development of neutron physics threatens further confusion. Thus, in recent years there has developed a new field of study involving monoenergetic slow-neutrons scattering from atoms in solids or fluids. Thereby results a spectrum of neutrons corresponding to inelastic scattering processes in which energy is imparted by the neutron to the system of scattering atoms. This field, evidently, has a strong and proper claim to the designation "slow-neutron spectrometry." Hopefully, those who measure excitation functions of nuclei with slow neutrons will converge on some designation of their activity that will be accurately descriptive and consistent with the usages of others.

In the early 1950's there was a resumption of interest in the spectra of neutrons that are produced in nuclear reactions. It was stimulated, no doubt, by intensified interest in nuclear spectrometry generally, by interest in neutron elastic and inelastic scattering phenomena and by need for refined neutron data for technical purposes. Neutron-emission spectrometry provides very direct information on nuclear reaction energetics and characteristic states of many nuclear species. The spectrum studied by Chadwick, if it had been resolved, would have revealed information about states in the nucleus C^{12} as illustrated in figure 1. Neutron scattering spectrometry furnishes similar nuclear information about the target nucleus itself and affords an invaluable tool for study of nuclear-reaction mechanisms. It is of interest to those involved in design of nuclear reactors and shields. In neutron scattering spectrometry one observes the spectrum of neutrons that results from interaction of monoenergetic neutrons with a sample.

Better instrumentation

Of great importance to renewed neutron spectrometry development in the early fifties were instrumental improvements. Initially the most important seemed to be the photographic emulsion as developed specifically to record ionizing-particle tracks. With such emulsions, proton recoils, originally detected electrically, could be observed visually under powerful microscopes and measured with improved precision and energy resolution. Intensive use of nuclear emulsions produced a substantial body of neutron-emission-spectrometry results in the early fifties despite the laboriousness of the method. It also opened the way to neutron scattering spectrometry.



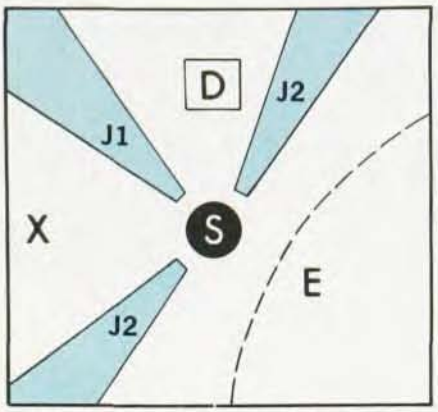
SCATTERING SPECTRUM from 4-MeV neutrons on iron. Emulsion detection reveals elastically and inelastically scattered groups. —FIG. 3

A representative example[4] of a neutron scattering spectrum is shown in figure 3. It is one of the earliest successes in obtaining a spectrum of neutrons produced when monoenergetic neutrons are incident on and scattered from a sample, that is, "a neutron scattering spectrum." In addition to neutrons having essentially the same energy as the incident neutrons, other lower-energy neutron groups are observed, the loss of energy corresponding to the excitation produced in the nuclear target. This spectrum is of special interest because it demonstrated feasibility of neutron scattering measurements in a geometry which proved essential to a major line of development—one with a long distance between scatterer and detector.

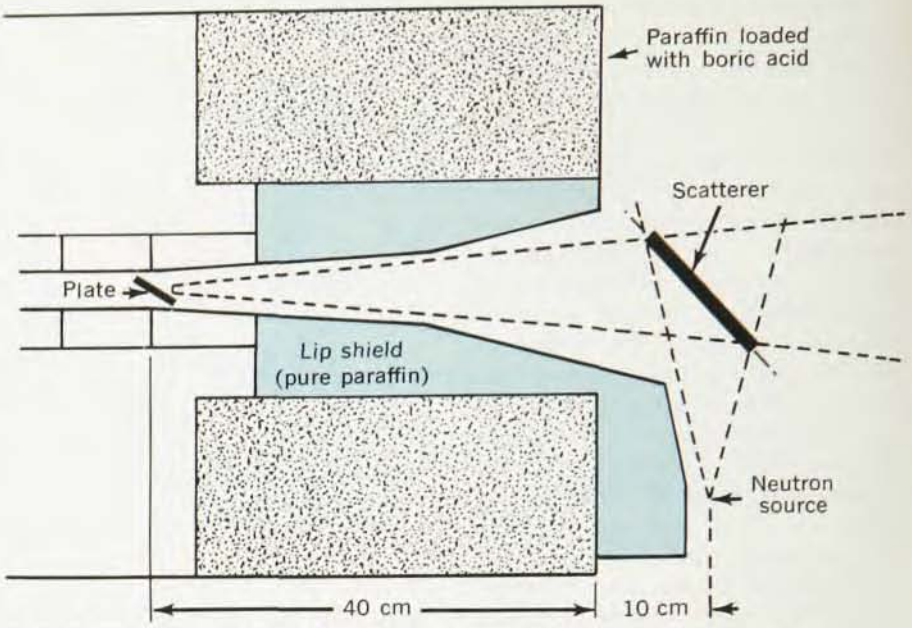
To understand the issues involved here, it may be useful to refer to figure 4. It represents, in general, the problem of observing the effects of radiation of any type from a source X interacting with a specimen S, the results of the interaction being observed with a detector D. It is evident from the figure that essential to detection of the radiations scattered by S is shielding the detector from radiations incident on it directly from the source. This problem arises whenever the source is substantially omnidirectional.

Shielding

To intercept the direct radiation, one must clearly insert stopping material, indicated by J1 in figure 4. To intercept radiation scattered by the environment (symbolized by E in the figure) stopping materials J2 are required. You will recognize that in optical spectrometry, the functions of J1 and J2 are assumed by collimator aperture walls and the slit jaws in front of the detector. In optics a thickness of a tenth of a millimeter of appropriate material suffices. If S is a source of neutrinos, on the other hand, the extreme transparency of matter to neutrinos requires that the jaw thicknesses be of greater than terrestrial dimensions. Where S is a neutron source, neutron interaction cross sections are such that thicknesses of appropriate material of some tens of centimeters are required. With such jaws, however, problems of scattering by the walls of the jaws (which have come to be called collimators) could be formidable and are hard to evaluate. Not until relatively recent work by Alexander Langsdorf[5] did the subject of collimator design begin to yield to analytical considerations. To make optimal the arrangement for a particular neutron energy, angle of observation and neutron detector, much empirical study and adjustment are required. Figure 5 illustrates the ar-



SPECTROMETER PARTS are source, jaws and detector. —FIG. 4



EARLY EMULSION ARRANGEMENT. Empirical study and adjustment leads to a maximum of signal and a minimum of "noise." —FIG. 5

rangement used by investigators who used the emulsion method.

Timing methods

At about the same time that photographic methods came into use, however, it became apparent to a number of physicists that substantial, nearly coinciding improvements in many aspects of technology were setting the stage for a fresh attack on neutron emission spectrometry. They might open the way to systematic studies of neutron scattering spectrometry—a topic prohibitively tedious by photographic methods. These improvements included appearance of good large-aperture photomultipliers, wide-band amplifiers, time-measuring and -sorting equipment and efficient, quick-responding, neutron-sensitive scintillators. These developments enabled one to determine interaction time of a neutron with a detector with a precision of about 1 nanosec, whereas previously the precision of time measurements was of the order of microseconds.

To round out the array of necessary instrumentation it was necessary, however, to develop a means of determining the time at which the neutron is produced with a precision comparable to that with which its arrival could be detected. Two general methods present themselves; they can be designated the "associated-particle" and "pulsed-beam" methods. In the associated-particle method the time of neutron production is determined by detection of a gamma ray or charged particle produced simultaneously with the neutron—a familiar and favorable case being the reaction in which a deuteron bombarding a nucleus of tritium, simultaneously produces a 14-MeV neutron and a 3.5-MeV alpha particle. Observation of the latter fixes the direction and production time of the neutron. In the pulsed-beam method, the bombarding ion beam is directed to the target in intense pulses or bursts of shortest feasible duration and the arrival time of the ion burst at the target determines the production time of the neutron.

The associated-particle method has advantages of technical simplicity, and it produced some of the earliest data[6] on elastic scattering of 14-MeV neutrons. The pulsed-beam method offers the decisive advantage of versatility, however, since it can be applied to *every* process of neutron emission that can be initiated by charged particles and quickly produced useful results in both emission[7] and scattering.[8] It is applicable even when there is no readily detectable particle accompanying the neutron and does not require tailoring to the wide range of energy and reaction products that accompany neutron production. Also, very early in the development of time-of-flight neutron spectrometry, it was noticed that the ordinary cyclotron delivers its output in bursts whose duration is just in the range of a nanosecond or so, thereby matching the capabilities of the new detectors. Thus the pulsing of the cyclotron ion output, which up to that time had been an often annoying characteristic of its performance, found a natural application to neutron spectrometry. Also, in the early fifties an ingenious way to convert a substantial portion of a steady ion beam to intense bursts of nanosecond duration was proposed independently and almost simultaneously[9] by R. C. Mobley and Robert J. Van de Graaff. This, and the application to ions of the principle of velocity modulation earlier applied to electrons in klystron tubes, enhanced the usefulness of dc ion accelerators, which were initially adapted to pulsed-beam studies by simple but inefficient chopping techniques.[7,8] A number of other methods have been proposed and applied to the same purpose. A significant indication of the steadily growing importance of work with pulsed ion beams is that in recent years specifications for new accelerator designs often emphasize ion-pulse intensity and duration from the point of view of application to timing measurements.

Burgeoning research

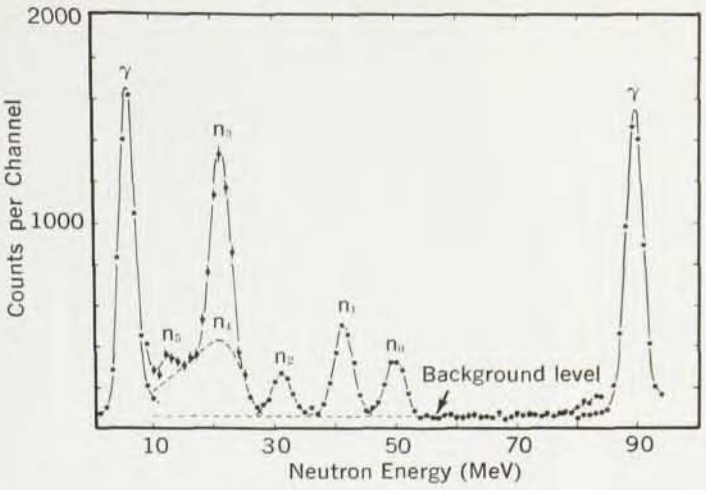
The number of accelerator centers engaged in neutron spectrometric studies by time-of-flight methods is now very large, and the flood of results is readi-

ly visible in data compilations emerging from such places as Brookhaven National Laboratory where these data are of special interest.

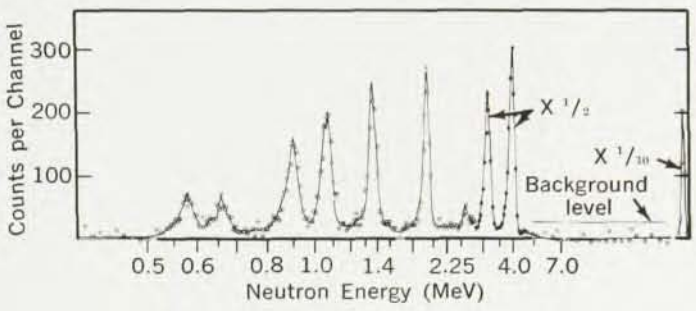
It may be useful to conclude this retrospective survey by citing a pair of results taken with a pulsed cyclotron and an ion-bunched Van de Graaff respectively, which are significant of the progress in the last decade. Figure 6 shows results obtained by a group at the Nobel Institute[10] in Sweden for the spectrum originally investigated by Chadwick, but for an incident particle energy of about 14 MeV. Here we see clearly resolved the three neutron groups which were also excited in Chadwick's case, corresponding to the group state and first two excited states of C^{12}.

Finally, figure 7 shows the spectrum for the scattering of 4-MeV neutrons from ordinary iron.[11] Conditions are essentially the same as those for which the data of figure 3 were taken by the emulsion method. The time-of-flight data were taken in about 20 minutes of running time. They reveal substantially greater detail, including neutron groups corresponding to excited states in a minor isotope of ordinary iron—the isotope of mass 54, which is only about 6% abundant in natural iron. In figure 6 the peak at the extreme right represents events that arrive earliest at the detector and correspond to gamma rays originating in the samples.

Because time-of-flight methods proved so useful first for slow-neutron transmission studies and then for fast-neutron spectrometry, it has often seemed natural to refer to one as the outgrowth of the other. But this, as is evident from what I have said, represents a superficial view that glosses over history as well as significant technical and scientific distinctions. The two areas of study developed among different groups, share almost nothing in the way of technical apparatus or technical problems and in the main are concerned with different aspects of nuclear structure and reaction theory. Indeed, on the technical level, there may be more stimulus to the older field from the newer one than vice versa, and it will be some time before slow neutron monochromators realize the timing capabilities of time-of-flight neutron spectrometers.



TIME-OF-FLIGHT spectrum of neutrons produced by 13.5-MeV alphas falling on a thin beryllium target. Flight path was 2.5 meters. —FIG. 6



4-MeV NEUTRONS ON IRON. Time-of-flight spectrum had an angle of 90 deg, 2-meter flight path and 0.58-nsec channel width. —FIG. 7

The pulsed beam neutron spectrometer can be regarded as a prototype of a very flexible and powerful apparatus applicable to a great many problems not related to neutron physics but involving analysis of time sequences in the nanosecond range. Figure 6 illustrates, for example, techniques for separation of gamma rays from neutrons or charged particles. Similar technology has been adapted to studies of short-lived nuclear or atomic processes and to spectra of velocities of charged particles extending to the velocity of light. No longer is it enough, even at the elementary level, to discuss velocity measurement in the classical terms of electrostatic and magnetic deflection. Histories of events that occur in the nanosecond and subnanosecond realms of experience are now as accessible to the chronicler as are their signatures.

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Figure 2 is from ref. 2, figures 3 and 5 from ref. 4, figure 6 from ref. 10 and figure 7 from ref. 11.

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