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Neutron Capture

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I. Introduction

Neutrons can initiate nuclear reactions even when they have no more energy than is characteristic of the thermal motion of atoms (0.025 eV). In fact, because of the large de Broglie wavelength of these low energy neutrons, the cross section for interaction with nuclei actually increases in inverse proportion to the neutron velocity. This contrasts with the use of charged particles which, because of purely Coulomb repulsion, require quite high energy (of the order of several MeV) before the probability of interaction is high—particularly for heavy nuclei. The neutrons' lack of charge also enables them to travel through large thicknesses of material with little energy loss. Nuclear reactions are therefore correspondingly more numerous if thick targets are used. However, the existence of resonances in neutron cross sections leads to very different behaviour when different target materials are used.

The strength of nuclear forces leads to a release of energy (binding energy, approximately 5 to 10 MeV) when a neutron is captured by a target nucleus. At the moment of formation the product nucleus has an energy of excitation equal to the binding energy plus the neutron energy. Resonances in the neutron cross section show the presence of discrete energy levels at these high excitation energies.

The role of these factors in the development of nuclear reactors and nuclear techniques such as neutron activation, and radioisotope production is well known. To meet the strong demand for measurements of neutron capture, scattering, and fission cross-sections, extensive work has been carried out. Nevertheless, the complexity of the processes involved and the difficulties in building up an adequate framework of theory mean that there is still a great deal to learn from research in this field.

Various kinds of accelerators and reactors provide different types of neutron sources so that work at different centres tends to be complementary. Both separate and joint projects in neutron capture are being carried out in Australia by Universities and the A.A.E.C. (see Table I), thus allowing a thorough study of most aspects of this subject.

TABLE I
NEUTRON CAPTURE PROJECTS

HIFAR Reactor (Lucas Heights)
Continuous thermal beam: 10^{8}–10^{9} neutrons cm^{-2} s^{-1}
Monochromatic beam: 10^{6}–10^{7} neutrons cm^{-2} s^{-1}
1. Thermal-Capture Spectra
2. Thermal-Capture Angular Correlation*

3 MeV Accelerator (Lucas Heights)
Pulsed beam (10 ns, 1 MHz) : 10^{9}–10^{10} neutrons s^{-1}(Peak)
Continuous high energy beam : 10^{12} neutrons s^{-1}
3. keV Resonance Studies
4. Direct-Capture Search*
5. keV Averaging (Capture Systematics)
6. Capture Cross-Sections (Nucleogenesis)*

30 MeV Betatron (Melb. University, School of Physics)
Pulsed beam (20 ns, 50 Hz) : 5×10^{15} neutrons s^{-1}(Peak)
7. Cobalt Resonance Parameters
8. Photonuclear Threshold Neutrons (Inverse Capture)

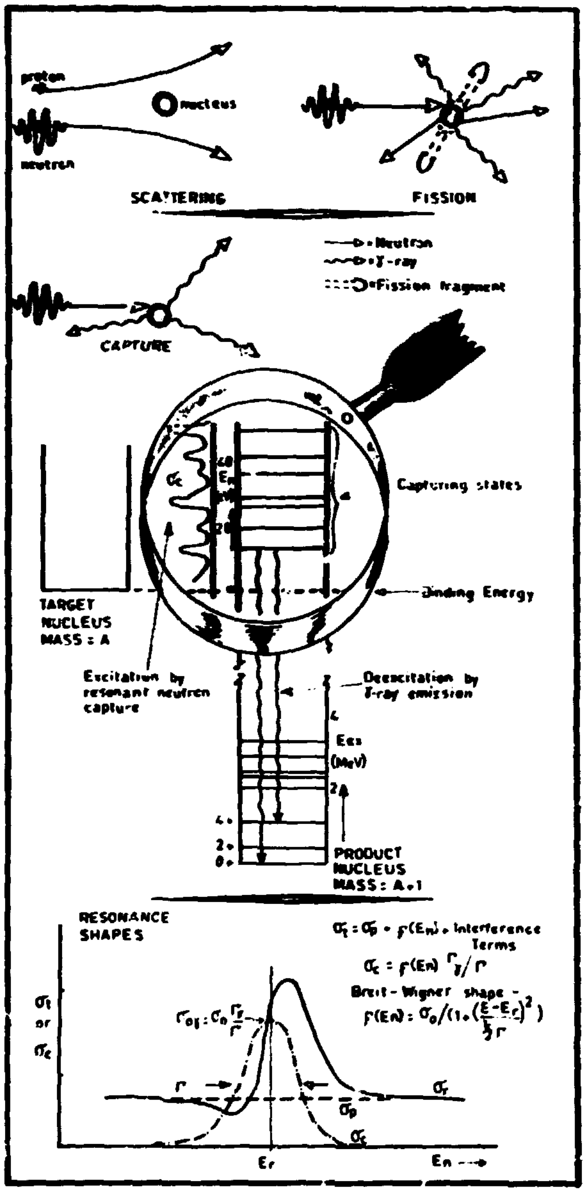
*Experiments by University personnel supported by the Australian Institute of Nuclear Science and Engineering for joint use of facilities.

II. Neutron Resonances

The properties of the resonant states may be described empirically in terms of a set of parameters which allow accurate calculation of the cross section at any energy. The values of the parameters for different target nuclei provide important data on nuclear structure, particularly for conditions under which the excitation energy is thoroughly distributed throughout the nucleus.

Resonance Parameters

A minimum of five parameters is required to describe one resonance fully. These may be determined by a combination of measurements of total scattering and capture cross-sections, but a great



deal of careful analysis is required to do this for many resonances. In this work the capture cross-section may be treated as a single variable or alternatively as the sum of a large number of independent variables each of which describes the probability of nuclear de-excitation by emission of a specific energy gamma ray. Provided sufficiently detailed measurements can be made of the gamma-ray energies it is sometimes possible to determine in one experiment:

(a) the isotope which is responsible for each resonance;

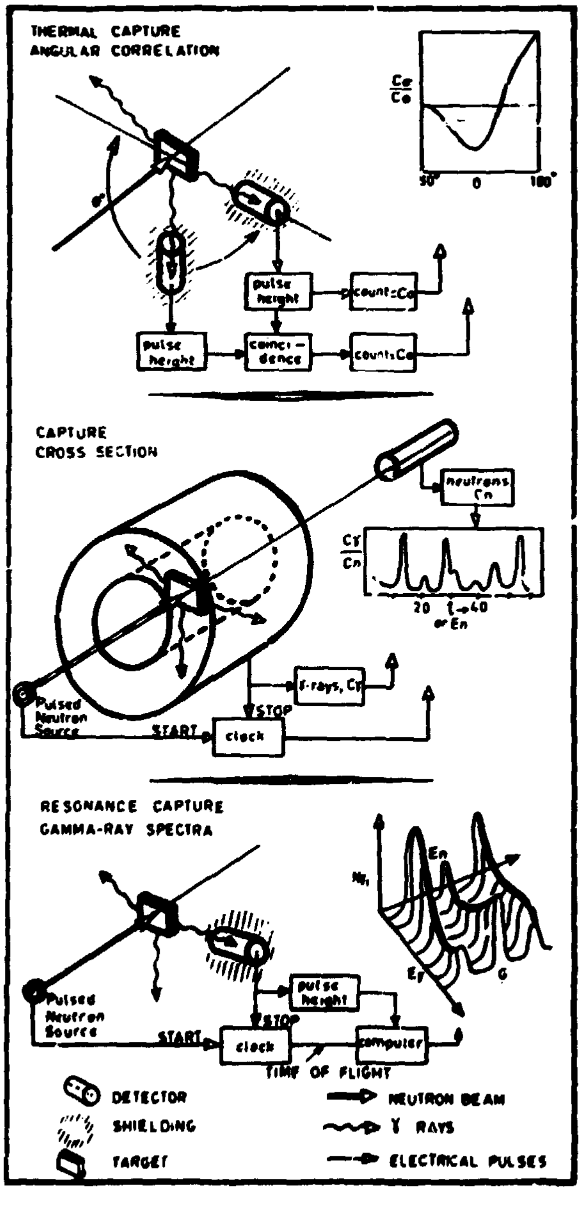
(b) the neutron angular momentum associated with each resonance;

(c) values of partial radiation widths.

Some of the parameters are found to be constant from resonance to resonance, while others show a broad—almost random—distribution. The mean values of the distributions vary systematically with target mass number and show the influence of shell structure of nuclei.

Applications

At times a particular resonance has a vital significance. For example, in cadmium a resonance occurs very close to thermal neutron energies so that the thermal capture cross-section is very high; thus cadmium is a very efficient neutron absorber and frequently used in nuclear reactors. A number of other materials such as cobalt, manganese, tungsten, and gold have very strong resonances at low neutron energies. These can be used to measure the intensity of particular energy neutrons provided the resonance parameters are known accurately enough. Uncertainties in the radiation width of the first cobalt resonance at 132 eV, however, have caused difficulties in this kind of application. An experiment to clarify this situation is being carried out at Melbourne University using the 30 MeV Betatron, while



the results of reactor experiments at Lucas Heights have also been used to obtain a value of the cobalt radiation width.

III. Nuclear Spectroscopy

The high excitation energy produced by neutron capture leads to decay by gamma-ray emission to lower energy levels and eventually to the ground state of the product nucleus. The gamma-ray spectrum may be quite complex and, provided sufficiently detailed measurements are made, a great deal of nuclear structure information may be obtained.

Thermal Capture

The intense beams available from a reactor and the high capture cross-sections for thermal neutrons make possible the measurement of gamma-ray spectra, coincidence, angular correlation, or polarization. The quantity of target material required may vary from milligrammes to kilogrammes depending on the cross-section and the experiment, but very often it is possible to use separated isotopes.

The results are usually summarized in energy-level diagrams in which level positions and quantum numbers are shown. These diagrams form the basic nuclear data which must be fitted by any theoretical model of nuclear structure. The information from neutron capture is usually complementary to that from charged particle and photonuclear reactions and radioactive decay.

Epithermal Capture

The usefulness of gamma-ray spectra for particular resonances has been mentioned in Section II. Such results also add to the knowledge of nuclear energy levels and at times may be easier to interpret than results from thermal capture. Since a particular resonance is a maximum in capture by one isotope only, it is possible to study the properties of individual isotopes even though the natural element is used as target. However, the drastic changes in gamma-ray spectra from one resonance to another make it desirable to study the average over many resonances (see Section V).

Applications

A knowledge of the gamma rays produced by neutron capture is important in the design of shielding, in the design of reactor-based sources of relatively monoenergetic gamma rays and in other applications of neutrons for which the gamma rays may either be troublesome or useful.

The measurement of radiation from radioactive nuclei produced by neutron capture is the basis of the well-known analytical technique—neutron activation. Detection of the high energy gamma rays emitted during the actual capture process offers an alternative method for prompt, non-destructive analysis of materials. Development of this method depends on the availability of adequate data on the gamma-ray spectra from each element and the development of experimental techniques to the stage at which the complex gamma-ray spectra can be distinguished from each other.

IV. Techniques

Research into the complex topics of neutron cross sections and gamma-ray spectra has provided support and impetus for many important technical developments.

Intense Neutron Sources

Reactors can provide intense sources of thermal neutrons (10^{14} to 10^{15} neutrons cm^{-2} s^{-1}) and smaller numbers of higher energy neutrons. Pulsed beams can be produced by the use of a mechanical 'chopper' and low energy monochromatic beams by crystal-diffraction techniques. Such facilities are used for most of the detailed study of thermal capture and for some measurements with higher energy neutrons.

Developments in high energy and high intensity accelerators—whose beams are often intrinsically pulsed—have made possible pulsed neutron sources with peak intensities as high as 10^{19} neutrons cm^{-2} s^{-1}. New proposals for high flux reactors, high intensity accelerators and accelerator-reactor combinations usually highlight capture and other neutron studies (together with their practical applications) as an important justification.

Time-of-Flight Techniques

It is possible to measure the velocity of low energy neutrons with great precision by using time-of-flight methods. The velocity of a thermal neutron is 2.2 km s^{-1} and at 1 keV the velocity is 440 km s^{-1}. With electronic timing equipment and suitable pulsed neutron sources, neutrons can be timed over distances of 10 or even 100 metres. In this way, the energy of a 1 keV neutron can be measured with a precision of 0.1 eV or better. This means that the excitation of a nucleus can be studied in great detail close to the neutron binding energy (see first diagram). If the latter is of the order of 10 MeV the overall resolution achieved is 1 part in 10^8. In order to achieve this resolution neutron and gamma ray detectors, timing equipment, etc., must operate with a time precision of 10^{-8} to 10^{-9} seconds.

Gamma-Ray Detectors

Sodium iodide scintillators have been used for many years as high efficiency but low resolution (3 to 10 per cent.) gamma-ray detectors. Magnetic or crystal diffraction spectrometers give resolutions down to 0.1 per cent. but with efficiencies of 10^{-6} or less. The development of lithium-drifted germanium detectors has provided an important advance, since *a resolution of the order of 0.1 per cent. can be achieved with an efficiency of 1 per cent. or even higher.* The resolution that can be achieved with these detectors is usually limited by the performance of low-noise electronics systems required for pulse amplification. Further developments may allow improvements in both efficiency and resolution.

In the study of complex spectra, a limitation to the sensitivity of germanium detectors is introduced by the continuum of pulse heights produced by

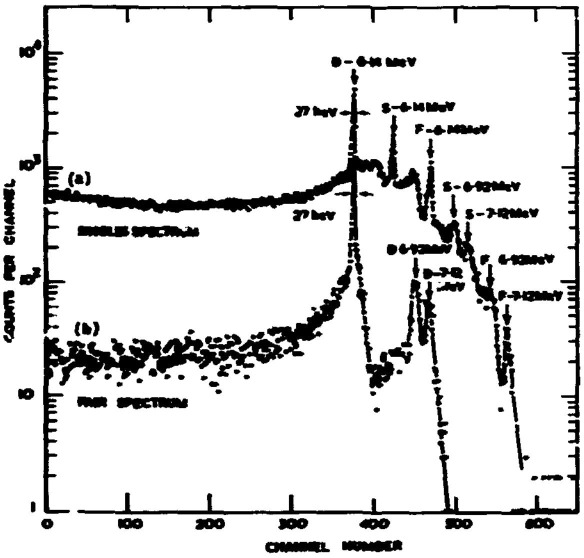


Figure 1

30-cm³ germanium detector results for (a) three monoenergetic gamma rays (6.14, 6.92, and 7.12 MeV); F= full energy peak; S = single escape peak; D = double escape peak; (b) pair spectrometer results for the same three gamma rays. (First published in Nuclear Instruments and Methods.)

Compton scattering of gamma rays. A typical pulse height spectrum for a group of three monoenergetic gamma rays incident on a 30-cm³ detector is shown in Figure 1a. Peaks caused by pair interactions and the escape of 0, 1, or 2 annihilation quanta can be seen superimposed on the Compton continuum. Figure 1b shows the spectrum measured with a germanium detector used in a 'pair spectrometer' (combination of detectors in a coincidence arrangement). The count rate in the main peak for each of the three gamma rays is reduced by a factor of three by this method, but the continuum is reduced by a factor of 20.

Part of a typical capture spectrum measured with a 10-cm³ germanium detector is shown in Figure 2. A target of iron was used in a thermal neutron beam, and the accumulation of a large number of counts allows the reduction of statistical errors so that weak gamma rays can be observed in spite of the presence of a Compton continuum.

Data Processing

At a time when most nuclear physics experiments used 100-channel analysers, neutron experiments were searching for methods which could provide 1000 or more data channels. The two-dimensional nature of capture-spectra measurements (neutron energy and gamma-ray energy) raises the need to store and process thousands of numbers at frequent intervals. The development of magnetic tape and other mass storage media, culminating in the use of small computers to replace the conventional data analyser, has solved the problem and provided a technique for sophisticated data evaluation during an experiment. This technique has broad implications and is becoming widely used in most research fields.

V. Neutron-Capture Systematics

A new technique is being developed at Lucas Heights which it is hoped will provide understanding of the systematics of the capture process. The mean value of partial capture cross-sections is measured in such a way that the resonance fluctuations are averaged out. A proton beam from the 3-MeV Van de Graaff accelerator strikes a thin lithium target and produces a beam of neutrons with a restricted energy range (e.g. 10 to 70keV). Large targets (approximately 20 kg) are placed in the neutron beam and capture gamma rays detected with a germanium detector. Time-of-flight techniques provide a control of the neutron range used and a simultaneous measurement of background. A small computer is used for data storage and processing so that the 6000 data points recorded during a 50-hour run can be analysed to give resonance-averaged intensities for each of 20 or more gamma rays.

Initial work with this technique has concentrated on common structural materials in the mass 50 to 70 range. It has been found that the average gamma-ray intensities are proportional to the cube of their energy. This is contrary to previous measurements and theoretical suggestions that a fifth power law should apply. Other systematic properties are also being studied, such as the importance of the angular momentum of the incident neutron and the effect of the shell structure of nuclei.

VI. Nucleogenesis

Terrestrial isotopic abundances and neutron capture cross-sections are not obviously related quantities. However, advanced ideas on the formation of elements in stellar environments suggest that neutron capture is responsible for the production of elements heavier than iron. A sequence of stable isotopes is formed by successive neutron captures, until a radioactive isotope occurs which by beta decay starts the process in the next higher element.

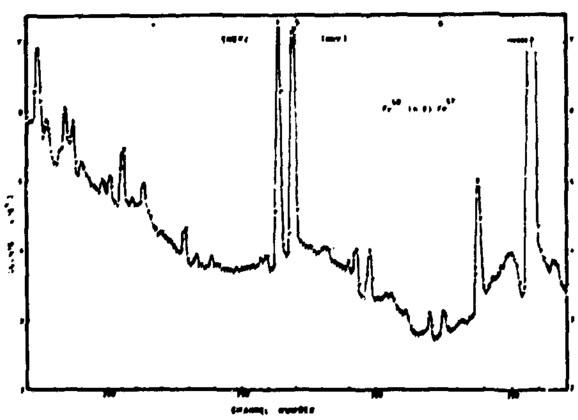


Figure 2

Part of the spectrum of high-energy gamma rays from thermal neutron capture in iron (using a 10-cm³ germanium detector).

This chain of events will take place at low neutron intensities and is called the 'slow' process. Only high neutron intensities (i.e. a 'fast' process) can cause neutron capture in radioactive isotopes before they have time to decay. The fast process is responsible for production of stable isotopes separated from others by radioactive isotopes.

In the slow process, a sequence of isotopes should show a constant value of the product: Abundance × Capture Cross-Section. Detailed tests using capture cross-sections for the neutron energy range 10 to 100 keV, which corresponds to the appropriate stellar temperature, show promise in providing a satisfactory explanation of observed abundances, although many features of the process require further clarification.

VII. Further Reading

Neutron Cross-Sections (D. J. Hughes; Pergamon, 1957) gives an introduction to neutron physics. *Fundamentals in Nuclear Theory* (Ed. A. De-Shalit, C. Valli; I.A.E.A., 1967) contains a lecture by E. R. Rae (p. 831) to the International Seminar Course at Trieste which reviews fundamental methods in neutron spectroscopy.

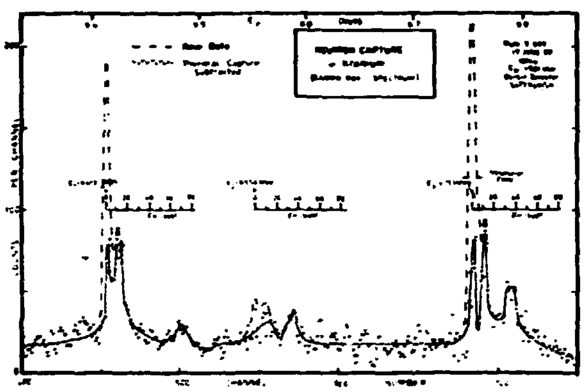
Alpha, Beta, Gamma Spectroscopy (Ed. K. Siegbahn; North-Holland, 1965) gives a description by Motz and Backstrom (Chap. XIII) of thermal neutron capture studies and references to earlier reviews. *Atlas of Thermal Neutron Gamma Ray Spectra* (G. A. Bartholomew et al.; *Nuclear Data* **A3**, No. 4-6, 1967) summarizes detailed information available on gamma-ray spectra.

Semi-conductor Nuclear Radiation Detectors (*Annual Reviews of Nuclear Science;* **17**, 1967) has an authoritative article by A. J. Tavendale (p. 17) on the rapid developments in this field.

Nuclear Astrophysics (W. A. Fowler; American Philosophical Society, 1967) is a stimulating account of the evolution of the chemical elements.

STOP PRESS . . . Germanium-Counter Revolution

Lithium-drifted germanium detectors have revolutionized precision gamma-ray energy measurements. It is now possible to observe the effects of small changes in energy of the incident particle in an (n, γ) or (p, γ) reaction. One of the first examples of this technique applied to neutron capture is shown in the figure opposite. Three gamma rays from neutron capture in titanium appear as three groups of peaks starting at 6.413, 6.550, and 6.753 MeV. In each group the left-hand peak is the result of the capture of thermal neutrons while others are from capture of 17- and 37-keV neutrons at resonances in the reaction cross-section (the 37-keV resonance is absent in the 6.413-MeV case).



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