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Title: Fast Neutron Detectors for Nuclear Physics Experiments

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Fast-neutron Detectors for Nuclear Physics Experiments

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ABSTRACT: Fast-neutron detectors are used in a wide range of nuclear physics experiments including studies of elastic and inelastic neutron scattering, photonuclear reactions, neutron-induced fission, and, especially recently, reactions of radioactive nuclei. Although many of the detectors being developed now are based on technologies that are several decades old, new physics is now accessible due to the advent of advanced accelerators, and these facilities present challenging opportunities for detecting fast neutrons. The choice of detectors, their appropriateness for particular measurements and how they are integrated into experiments erwill be discussed. Detector arrays are of particular importance these days to study angular distributions or simply to increase the solid angle coverage to increase the data rate. Modeling the response of the detectors has become much more important in order to understand better their response and to calculate effects of neutron scattering in the experimental area, including detector-to-detector scattering. Data acquisition through waveform digitizers is now common and leads to more information from each event as well as significant reductions in dead time and in the complexity of the electronics. At the same time, analyzing waveforms in real time presents challenges in terms of handling large amounts of information. Examples of significant improvements in the utilization of neutron detectors in physics experiments, in the characterization of the detector response, and in signal processing will be presented.

KEYWORDS: neutrons, fast neutron detectors, optical model, isobaric analog states, spin-obit interaction, nuclear structure, photonuclear reactions.

Contents

1. Introduction

The detection of fast neutrons has made, from the beginning, essential contributions to the development of nuclear physics. The neutron, because of its lack of electronic charge, is penetrating both in the macroscopic and microscopic senses. In the macroscopic sense, fast neutrons have typical mean free paths of several centimetres in solid matter. In contrast, protons of energies below 20 MeV have stopping lengths of a few millimetres or less. In the microscopic sense, the neutron can reach the nucleus without being repelled by the Coulomb interaction. The neutron-nucleus interaction is therefore almost entirely from the strong interaction.

The neutron also is very similar, although not identical, to a proton in its mass, spin and strong interaction with a nucleus. Both the average neutron-nucleus interaction, as pictured by the cloudy-crystal ball optical model, and the finer scale fluctuations are similar for protons and neutrons, the major difference being in the Coulomb interaction felt by the proton. At incident energies much larger than the Coulomb potential, the other difference is that the neutrons in the nucleus interact with an incident neutron via the n-n interaction, which is somewhat different from the n-p interaction with incident protons. Similarly, the interaction of the protons in the nucleus with an incident neutron via the p-n interaction differs somewhat from the strong part of the p-p interaction with incident protons on the same nucleus. The strong p-p interaction is thought to be very similar to the n-n interaction, and consequently, for a self-conjugate nucleus, namely one that has the same number of protons as neutrons ($Z = \frac{1}{2} A$), the strong part of the neutron-nucleus interaction should be very similar to the proton-nucleus interaction. Most heavy nuclei, however, have more neutrons than protons, and so comparison of p-nucleus and n-nucleus interactions gives information on the iso-spin dependence of the nucleon-nucleus interaction. This interaction can be investigated further with the (p,n) reaction where the proton leaves its electrical charge in the nucleus and then exits the nucleus as a proton.

Detection of fast neutrons also has had a very important role in the study of nuclear structure and spectroscopy. The detected neutron can be a spectator in, for example, a (d,n) reaction, where resolved final nuclear states are formed by adding a proton to the ^{A}Z target nucleus to form states in the $^{A+1}Z{+}1$ nucleus. The angular distributions of the residual neutrons give information on the spin and parity of the state of the residual nucleus. Neutron decay of nuclear states gives additional information of the structure of highly excited states. For very neutron-rich nuclei, even the ground state and other low-lying states can be unstable with respect to neutron decay and the energy distributions of the emitted neutrons give essential data on the levels themselves and on the states which are reached in the decay. Again, for nuclei but the very lightest, neutron decay is not inhibited by a Coulomb barrier so that decay energies in the 0.1 – 5 MeV range are accessible with neutrons, whereas they would not be accessible for proton decay in analogous cases even where the decay would be energetically possible.

We note that the theoretical analysis of neutron interactions is simpler and easier to understand without the complication of Coulomb wave functions. Although computers and model codes now treat the Coulomb interaction without much difficulty, this has not always been the case. Understanding nuclear interactions, sometimes in a pictorial way, is facilitated if the particle involved has no charge. In these ways, fast neutrons have contributed to the accelerated development of nuclear physics.

We also note that these advances in basic nuclear physics have been greatly encouraged by the applications of fast neutrons primarily in nuclear energy and defence. Financial support has thus been forthcoming for experimental facilities and the development of fast neutron detectors.

Because of the very wide range of experiments where fast neutrons are detected, this review cannot begin to be comprehensive, and it is not intended to be. Rather the impact of neutron detection in several areas of nuclear physics is the focus here. First, we give some historical examples, which are chosen because they made significant contributions to the field and also because they illustrate several different types of detectors of fast neutrons. Then we give very brief descriptions of present-day experiments where neutron detectors play an important role. The importance techniques, such as time of flight to determine the energy of a free neutron, should be clear to the reader. Also, the continuing improvement in facilities has made possible greatly improved measurements or, in many cases, completely new experiments. The energy range for neutrons considered here is above the resonance region, which means above a few keV, and below the high energy region of 1 GeV. This region captures most of the applications of this Workshop. We apologize in advance for not being complete in discussing either the past or present experiments. The examples chosen will be mostly taken from work in the United States, a consequence of the author's experience, and apologies are also given for this somewhat parochial view.

2. Some important developments in nuclear physics made possible by fast neutron detectors

2.1 Nucleon-nucleus interaction (optical model)

The most basic nucleon-nucleus measurement is that of the total cross section. For neutrons, which interact almost entirely by this interaction when they encounter materials, the total cross section gives the mean free path, or the average distance to first collision, for neutron transport calculations. In a nuclear physics sense, the total cross section is a measure of the effective size of a nucleus. The physics is not so simple, however, as the neutron has wave properties and the wavelength in the MeV range is similar to the size of the nucleus (Fig. 1). Furthermore, the nucleus is not totally absorbing to the incident nucleon but rather can be represented as a "cloudy crystal ball" where the degree of cloudiness expresses the absorption.

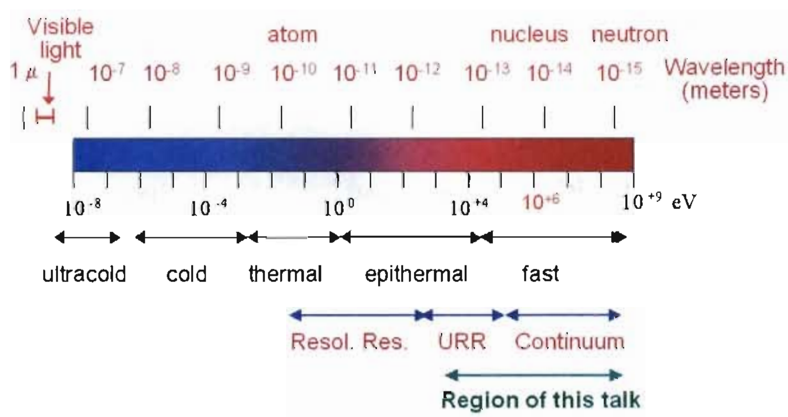

Figure 1 – Spectrum of neutron energies from ultracold neutrons to fast neutrons. The wavelength of the neutrons, the de Broglie wavelength, is also shown and compared with the dimensions of visible light waves and atomic, nuclear, and nucleon dimensions.

Total cross sections are measured by transmission through a sample of the element or isotope of interest (Fig. 2). The neutron detector counts the number of transmitted neutrons and its ratio to the number of neutrons counted with no sample in place, $N / N_0 = \exp(-\sigma \rho t Av / A)$ where σ is the total cross section, ρ is the density of the sample, t is the thickness, Av is Avogadro's number and A is the atomic mass of the nucleus of the material. The monitor detector is used to normalize sample-in and sample-out data. Thus the total cross section for neutrons can be measured without even knowing the efficiencies either of the monitor or of the neutron detector.

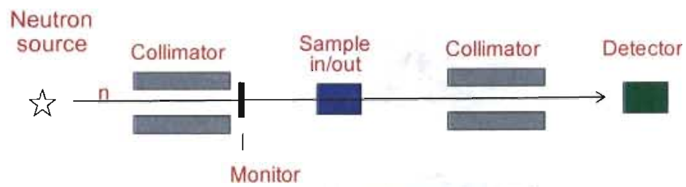

Figure 2: Schematic setup of a total cross section experiment. The neutron source is collimated into a neutron beam that passes through a monitor detector and the sample under investigation before reaching the neutron detector. This arrangement is referred to as "good geometry" in that every neutron that interacts with the sample, including those that scatter at small angles, is removed from the beam.

An example of an early total cross section measurement is that done by R. Sherr in 1940 and published in 1945 after World War II [1]. The neutron source was the ^{7}Li(d,n) reaction with deuterons of 10.2 MeV to give a broad spectrum of neutrons up to 25.4 MeV. The detector was graphite where the ^{12}C(n,2n)^{11}C took place and the activity of ^{11}C with its 20.4 minute half-life could be measured with a Geiger counter. The threshold for producing ^{11}C is 21 MeV and that allowed the total cross sections to be measured over a rather small range in neutron energy, 21 – 25.4 MeV. This experiment combined a facility, new for its time, of a cyclotron producing energetic deuterons and the energy-selective detector. The results gave neutron total cross sections on many elements from carbon to mercury and showed that there was a regular relationship between the cross section and the quantity $A^{2/3}$. The data validate the concepts that the density of nuclear matter is about the same for all complex nuclei. The nucleus therefore "grows" with the addition of nucleons unlike the neutral atom which is about the same size as the atomic charge increases.

Many other neutron total cross section measurements have been made over the years. Rather recent experiments were carried out at the pulsed spallation neutron source Los Alamos Neutron Science Center [2,3]. Neutrons are produced by a tightly bunched 800-MeV proton beam (~ 200 ps width) on a tungsten target and a continuous-in-energy spectrum of neutrons is created. For these experiments, the neutrons were collimated along a flight path of 40 meters. At 12.7 meters from the source, the sample was placed and the neutron detectors were much farther downstream at about 38 meters. The neutron energy was determined by the flight time for the neutrons to go from the source to the neutron detectors, which were fast plastic scintillators. In this way, the total cross section could be measured as a function of neutron energy in the range 5 to 560 MeV. After careful consideration of possible rate-dependent changes in the efficiency of the monitor and neutron detectors, the absolute accuracy of the data was 1% or better for nearly all of the materials over this entire range (Fig. 3). More recent experiments have used improved data acquisition based on wave-form digitizers so that the count-rate effects can be controlled at even much higher counting rates[4]. These experiment therefore combine a relatively new facility, a spallation neutron source with a very short source pulse, with scintillating neutron detectors and time-of-flight techniques to produce data to test the parameters of the "cloudy crystal ball" optical model for nucleon-nucleus interactions.

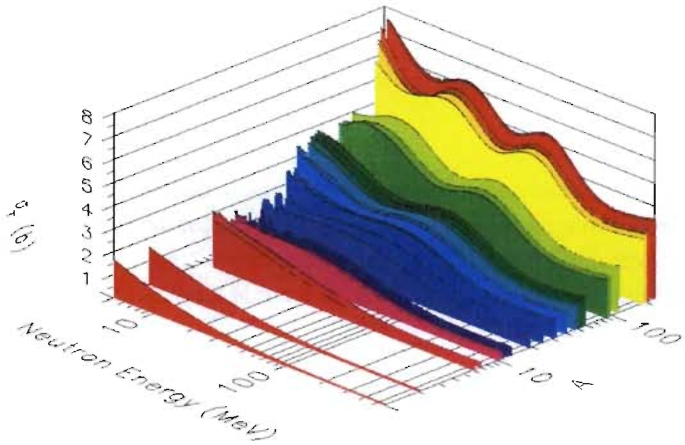

Figure 3: Neutron total cross sections from 5 to 560 MeV for nuclei with masses (A) from 1 to 238. The regular "waves" in the cross section are evidence of the interference of the neutron wave transmitted through the nucleus with that passing by the nucleus.

An additional and required term in the optical model is the spin-orbit interaction. Although this type of interaction was expected in analogy to that in atomic structure, the strength of the nuclear spin-orbit interaction was much larger. The detection of fast neutrons was crucial in this discovery [5,6]. In the experiment, mono-energetic neutrons produced in the d+d reaction were incident on a high-pressure ionization chamber containing helium gas. The neutrons were detected by measuring the ionization of the recoil ^{4}He nuclei from n-^{4}He elastic scattering [7]. For a given neutron energy, the ^{4}He recoil energy reflects the angle of the scattering and its energy distribution measured the angular distribution. To explain the ^{4}He recoil energy distribution for neutrons in the range 0.34 to 2.5 MeV, a strong spin-orbit interaction was required.

The form of the optical model is usually expressed as

$$V(r) = - \{ V_o \cdot f(x_R) + (W_1 \cdot f(x_V) + 4\, W_2 \cdot d/dx_D\, (f(x_D)) + V_{so} \cdot ((\sigma \cdot L)/\, r\,)\, (\hbar/m_\pi c \;\; d/dr\, f(x_{so}) \} + \mathrm{Coulomb}(r)$$

with

$$f(x_i) = [1 + \exp(x_i)]^{-1}$$

$$x_i = (r - r_i\, M^{1/3})/ai$$

m_π = pion rest mass

σ = Pauli spin matrix

where the spatial dependence, f (x_i), is a Wood-Saxon form and Vo (real potential), Wv (imaginary or absorptive volume interaction), Ws(imaginary or absorptive surface interaction) and Vso (spin-orbit interaction) are constants often determined from experiment. A more basic understanding of this form and the constants comes from a microscopic analysis of the optical model, where the basic nucleon-nucleon interaction is combined with wave functions of the nucleons in the target nucleus to arrive at the nucleon-nucleus interaction. Many tests of this model have been made not only on the total cross section but also on the angular distributions of elastic scattering. For example Hansen et al. [8] used pulsed 14.6 MeV neutron produced by the d+d reaction and the angular distributions of elastically scattered neutrons were measured by an array of 16 well collimated liquid scintillators placed 10.75 meters from the scattering sample. The neutron time of flight was used to separate the elastically scattered neutrons from inelastically scattered neutrons and pulse-shape discrimination separated neutrons from background gamma rays. This experiment is an example of a facility that produced a short (ns) bunch of quasi-monoenergetic neutrons combined with an array of neutrons detectors for measuring the angular distribution of elastically scattered neutrons from 9.2 to 159 degrees all in one experiment.

For the development of the optical model, these examples show a range of detectors: activation samples, gas ionization chambers, and liquid and solid scintillators. Furthermore they illustrate how important the facilities and the specialized neutron sources are: mono-energetic, quasi-monoenergetic, continuous and pulsed, and spallation ("white") neutron sources that are pulsed in time but continuous in energy.

2.2 Nuclear structure

Fast neutrons are unique probes of nuclear structure in wide range of studies including the investigation of individual excited states of the nucleus and the characterization of overlapping excited levels expressed as the nuclear level density. Here are a few examples where the detection of fast neutrons has made a difference and, in some cases, led to surprising results. Again these examples are chosen because of their importance in elucidating nuclear physics and/or because the experiments used special facilities and detectors.

The lightest nucleus that has exhibited numerous excited states is 4He, where there are states of isospin T=0 and T=1 and states of angular momentum through J=2. The ordering of the states according to their configurations was not known when an experiment in polarization transfer was undertaken using the ^{3}H(p,n) ^{3}He reaction with incident polarized protons[9]. The polarization of the outgoing neutrons at 0-degrees was measured by scattering them from a liquid ^{4}He polarimeter. Here the analyzing power of n-^{4}He scattering is very high for elastic scattering at selected angles (e.g. 115 degrees in this case) and so the polarization transfer coefficient could be measured. The results gave information to differentiate between two possible orderings of the $J^\pi = 1^-$ states in ^{4}He at excitation energies in the 26 -31 MeV range. Here we have an example of a unique facility that produced a polarized proton beam, the ability to use radioactive tritium gas as a target, and a liquid helium detector to measure the polarization of the outgoing neutrons, all of which combined gave information on the excited states of this light nucleus, which, because of the few nucleons involved, was amenable to detailed calculations of the spectroscopy of its excited states.

The (p,n) direct reaction on much more complex nuclei led to the discovery of isobaric analog states in neutron-rich nuclei. In this reaction, the proton transfers its positive charge to one of the neutrons in the nucleus and then exits as a neutron with minimal changes in the wave functions of the spectator nucleons. This direct reaction became evident in experiments that were in fact designed to look at the decay of the compound nucleus. The quintessential reaction was of 14.8 MeV protons on ^{51}V forming the compound nucleus ^{52}Cr. In addition to the statistical decay of the compound system, a peak was observed for population of the isobaric analog state (IAS) which was formed by the direct reaction (Fig. 4) [10,11]. The difference in energy of target nucleus and the IAS is found to be the "Coulomb displacement energy", that is, in lowest order, the energy of the single proton relative to that of the neutron of the same wave function. This discovery was totally unexpected as it was thought that the Coulomb interaction in heavy, non-mirror nuclei would change the wave function so much that this analog would not appear as a single state but would be spread over many MeV of energy as it mixed with other states. These measurements were made with good (ns) time of flight using a proton beam from a cyclotron and a sweeper so that only one of four successive pulses from the cyclotron hit the target. The neutron detectors were made of fast plastic or, for gamma-ray suppression, stilbene using pulse-shape discrimination. Again, the combination of a special facility and modern, for that time, detectors and electronics made this discovery possible.

As the excitation energy of a nucleus is increased, the excited levels get closer and closer together and their widths for decay become larger. For the (p,n) reaction just described, the continuum neutron evaporation spectrum probes the level density according to Fermi's Golden Rule. For excitation energies between those where the states are resolved and this continuum, the level widths and the neutron decay widths are similar to the spacings. This is the region of Ericson fluctuations [12], and the magnitude and periods of the fluctuations give information on the level density. One can see these fluctuations in the neutron total cross sections of Fig. 3 for the lowest neutron energies and A < 30 for this range of neutron energies. Fluctuations in the total cross section have been studied with other neutron sources [13]. They can also be studied with partial cross sections such as (n,p) and (n,alpha). In one study, these latter reactions were investigated on silicon, where the sample and the detector were the same, namely a silicon surface barrier detector [14]. The continuous-in-energy neutron source at LANSCE greatly facilitated these measurements.

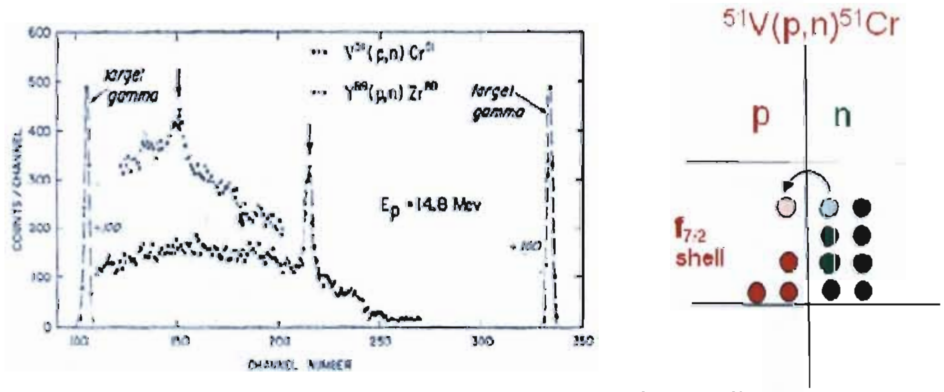

Figure 4: Isobaric analog of ^{51}V produced in ^{51}Cr by the $^{51}V(p,n)^{51}$ Cr reaction. The left panel shows the time-of-flight spectrum [10] ((copyright American Physical Society) of neutrons from the reaction and includes the evaporation component (smoothly varying) and the sharp peak around channel 210, which give evidence for the analog state reached through a direct reaction. The spectrum from another reaction, $^{89}Y(p,n)^{89}Zr$ is also shown. The right panel is a cartoon of

the change of a neutron in ^{51}V into a proton with no other change in the wave function. The other nucleons act only as spectators.

2.3 Reaction mechanisms

Understanding nuclear reactions has been and continues to be another basic goal of nuclear physics. A reaction can be resonant in the sense that a specific state or set of states is populated in the compound nucleus. Although neutron resonances are more commonly known for lower energy neutrons, the example above of the $^{3}H(p.n)^{3}He$ reaction shows that they can be important for MeV neutrons. In heavier nuclei, the compound nucleus can decay by evaporating neutrons such as shown in the continuum part of the neutron emission spectrum from the $^{51}V(p,n)$ reaction above. Direct reactions, such as in the above case of $^{51}V(p,n)^{51}Cr$ (IAS), take place very fast so that energy is not transferred to many nucleons in the nucleus but just to a one or a few, that is, to excite only a few degrees of freedom.

Reactions that take place on time scales between those for direct reactions (fast) and the formation and decay of the compound nucleus (much slower) are called pre-equilibrium or pre-compound reactions. The definitive identification of this reaction mechanism was through (p,n) reactions, e.g. [15,16], using liquid scintillation detectors with pulse-shape discrimination. It was found that the neutron emission spectra had a continuum evaporation component at low energies and another continuum component at higher energies that was forward peaked. Other reactions such as inelastic proton or alpha particle scattering also showed this intermediate component, but those data could also be explained by direct enhanced by collective multipole excitations. An excellent demonstration of pre-equilibrium reactions is that given by Grimes et al. for (p,n) reactions from 18 to 25 MeV on even-A and odd-A targets in the mass 100-110 range [17]. The pre-equilibrium component of the neutron emission spectra becomes much clearer as the incident proton energy increases. The trends in magnitude of the cross sections and in the odd-even mass differences are well described by the theory [18-20]. In nearly all of these investigations, fast neutron detectors were used with pulsed proton beams for measuring the energy of the outgoing neutrons by time of flight.

3. Some present detector arrays and the physics to be investigated

The previous examples show how important nuclear physics models were developed with the aid of fast neutron detectors. At the present time, detectors, often with the same fundamental characteristics as those used in the last 50 years, detect fast neutrons from other types of reactions. Although the basics of the neutron detectors have not changed much, new measurements are able to address new areas because of the advances in accelerators, electronics, data acquisition, and computer modeling of the experiments. Advances in accelerators such as heavy ion beams with good intensity, beams of radioactive isotopes, beams of significantly higher energy, reactions in inverse kinematics, and continuous-in-energy ("white") neutron sources have opened up many fields for study. Despite these significant forward steps, the experimenter is often challenged with counting rates that are much lower than before. Consequently, arrays of neutron detectors are employed to make the best use of beam time, or to measure the angular distribution of the neutrons, or even to study multiple neutron emission and how the neutrons are correlated in energy and angle. Several of these arrays, in use or designed to be used at the National Superconducting Cyclotron Facility, the Facility for Rare Isotope Beams, and TRIUMF are summarized in a report [21].

This section will present several examples of the nuclear physics now being studied with fast neutron detectors. Here, there will be more emphasis on the detectors. Again the selection is by no means comprehensive, either in the physics or the types of detectors. Furthermore, it is again focused on efforts in the US. The writer apologizes for the many programs that are not included here. Although these detectors are designed for specific classes of experiments, it is very likely that they have new and exciting capabilities and could well be used in other experiments in the future.

3.1 Nuclear Structure from weak interactions: Beta-delayed neutrons

A neutron-rich, radioactive nucleus decays by beta-decay, where the weak interaction part of the theory is rather well understood so that the nuclear matrix elements, which depend on the nuclear structure, can be investigated. If the beta decay populates states in the residual nucleus that are above the neutron separation energy, then neutron emission can occur in competition to radiative (gamma) decay from those states. In other words, A → B* + β + anti-ν → C+n, where the final nucleus C can be in the ground or an excited state. The neutrons are called "beta-delayed neutrons, and their energies, measured by time of flight, then gives information on the excitation energy of the nucleus B* relative to the final state of "C". The strength of the transitions to states in B* depends on the matrix elements for Gamow-Teller or Fermi transitions.

MONSTER [22]: Modular Neutron SpectromeTER (MONSTER) planned for experiments at Jyvaskyla, Finland, and other facilities: Beta-delayed neutrons are detected by an array of 80 liquid scintillators, 20 cm in diameter and 5 cm thick, placed 2-3 meters from the sample. The start time is indicated by silicon detectors and the time resolution is expected to be 1 ns.

VANDLE[23,24]: Versatile Array of Neutron Detectors at Low Energy: This array has two configurations, one being for beta-delayed neutrons and the other for (d,n) reactions in inverse kinematics (see below). There are 104 plastic scintillator bars with dimensions 3x3x60 cm^3 and another 104 bars 5x5x200 cm^3. The detectors are fast plastic scintillators, and they will be placed 54 cm from the point where the radioactive ions are implanted. Time resolution is expected to be 1 ns or better.

Both MONSTER and VANDLE are in the development and construction phases. Both plan to use waveform digitizers for data acquisition.

3.2 Nuclear structure with strong-interaction reactions

With the availability of radioactive heavy ion beams at several laboratories, the interest in reactions with inverse kinematics has greatly increased. Thus reactions on stable nuclei in forward kinematics, such as (d,n), (p,n), (alpha,n) and their counterparts with protons in the final state, which provided important tests of nuclear structure models in the past several decades, can now be carried out with radioactive nuclei, some of which are well away from the valley of stable nuclei. If the reaction results in a neutron, then fast neutron detectors are necessary. The energy of the final neutron is similar to the nucleon energy of heavy ion beam, and it can range from less than MeV to nearly 1000 MeV depending on the facility and whether the neutrons are detected in the forward or backward directions. This section gives some examples of detectors for experiments that are in progress or will soon be carried out. The order goes from neutrons of 0.1 to the few MeV range and then to much higher energies.

VANDLE: The above described array will also be used for spectroscopic studies using the (d,n) reaction. These experiments are similar to the (d,p) reactions already underway. For example the ^{132}Sn(d,p)^{133}Sn reaction elucidated the single neutron structure coupled to the doubly- closed shell of ^{132}Sn [25].

LENDA [26]: Low Energy Neutron Detector Array for Studies of (p,n) Reactions array under construction at the National Superconducting Cyclotron Laboratory (NSCL) is an array of plastic scintillators intended to study reactions in inverse kinematics, with a special focus on (p,n) reactions on radioactive nuclei. As described above, the (p,n) reaction picks out the isobaric analog state. In addition the (p,n) reaction is used to identify Gamow-Teller transitions, which are of importance in astrophysical nucleosynthesis. The final array will consist of 24 plastic scintillator bars each with dimensions of 300 times 45 times 25 mm. The neutron energy will be determined by the time-of-flight technique, while the position of interaction will be deduced using the timing and energy information from photomultipliers attached to both ends of each bar. A prototype of the final array has been constructed and characterized in a simple test setup. Results of test measurements and simulations have demonstrated a neutron energy threshold of <130 keV and overall time (position) resolution of less than 1 ns (~ 4 cm), using also pulse height information for the PMTs at each end of the scintillator bars.

MoNA [27]: The Modular Neutron Array is a large array of 144 plastic scintillators, each 200 cm long with a cross section of 10 x 10 cm^2, that can be configured as a wall or as a compact detector with a volume of 2 x 1.6 x 0.9 m^3. Because of its large volume, it has a very high efficiency such that events with more than one neutron in the final state can be studied. An example of its use is in the detection of 2 neutron decay of the very neutron-rich nucleus, ^{24}O. This isotope was prepared by a ^{26}F beam on a ^{9}Be target. Very quickly, sequential neutron decay occurred and the two neutrons were detected by MoNA. Information on the resonant state in ^{24}O and on the branchings to the intermediate states in ^{23}O was obtained [28].

MoNA-LISA [29]: MoNA+ Large multi-Institutional Scintillator Array. A second array is to be added to MoNA. The arrays are very similar, and the combination will increase the areal coverage or the efficiency, depending on the configuration chosen for a given experiment. The name was inevitable.

DESCANT [30]: DESCANT DEuterated SCintillator Array for Neutron Tagging to be used at the TIGRESS radioactive beam facility at the Canadian facility, TRIUMF . This array is unique among the modern large arrays in that it uses deuterated benzene as the scintillator. Because of the angular distribution of elastic n-d scattering, the pulse-height distribution is peaked at higher pulse heights. There is therefore some energy information in the pulse heights. The array is planned to have 70 detectors, each a tapered hexagon 15 cm long with a volume of about 2000 cm3. The front face of each detector is planned to be 50 cm from the target center, and therefore a large solid angle (~ 1 pi steradians) will be subtended. One design is to use this array in the forward direction where heavy ion beams interact with light targets in inverse kinematics to tag the reaction as, for example, a (d,n) reaction on a deuterated target. Data acquisition is planned with waveform digitizers.

3.3 Nuclear Structure with photonuclear reactions

Excitation of the nucleus through photonuclear reactions can shed light on states related to the ground state by electric dipole transitions and other low multipolarities. Major advances in the field have been realized with high energy heavy ion beams that, in passing through the Coulomb field of a heavy nucleus, undergo these excitations. Another significant advance has been the development of high intensity monoenergetic photon beams by laser backscattering on relativistic electron beams. In both cases, fast neutrons can be emitted from the excited nuclei.

BLOWFISH [31]: At the High Intensity Gamma Ray source (HIGS) at the Triangle Universities Nuclear Laboratory, an array of 88 liquid scintillators at a distance of 40.6 cm from the target center detects neutrons from (gamma,n) reactions. The solid angle coverage is about 25% of 4-pi. Measurement of the angular distribution of the emitted neutrons is especially important as the gamma-ray beam can be polarized. One recent experiment was on the splitting of the p-wave amplitudes in photodisintegration of the deuteron [31], a fundamental measurement that became possible for the first time.

Another liquid scintillator array (unnamed) has also been used at HIGS to investigate photoexcitation of ^{3}He and the angular distribution of neutrons emitted in the ^{3}He(γ,n2p) reaction [32]. Here the absolute cross section needed to be measured with good accuracy, which meant that the neutron detector efficiency needed to be known well. A detection accuracy of 2.8% was obtained in this work.

LAND [33]: One example of a detector used for Coulomb dissociation is the Large Area Neutron Detector at the Gesellschaft fuer Schwerionenforschung (GSI). A large array of plastic scintillators is interleaved with iron foils which convert the neutrons to charged particles and thereby increase the detection efficiency. This array is used to investigate both central and peripheral reactions of heavy ions with energies above 600 MeV/A. For peripheral collisions, Coulomb dissociation can be studied. An experiment presently underway [34] uses ^{60}Fe as a secondary beam to study the ^{60}Fe(gamma,n)^{59}Fe reaction with a ^{60}Fe beam energy of 660 MeV/A incident on a lead target. The resulting ^{59}Fe nuclei are identified and detected by a magnetic deflection and charged particle detectors. The neutrons go in the forward direction and are detected by LAND. Thus measurement of photodisintegration of very unstable nuclei is now possible and the data could greatly expand the knowledge of these reactions, for which much work has been done with stable nuclei [35]. It should be noted that the motivation of this particular experiment was in the field of astrophysical nucleosynthesis to obtain information on the inverse reaction, ^{59}Fe(n,gamma)^{60}Fe, at astrophysical neutron energies < 1 MeV.

3.4 Nuclear equation of state

LANA: Large Area Neutron detector Array [36]: A large array of liquid scintillators is used at the National Superconducting Cyclotron facility to measure neutron emitted in heavy ion collisions [37]. In many areas of astrophysics including the modeling of neutron stars, the nuclear equation of state plays a very important role. Heavy ion collisions in the range of 50 MeV/nucleon or somewhat greater can test models of the equation of state. Experiments concentrate on measuring neutron emission transverse to the incident beam direction, and neutron emission is compared with proton emission for beam-target combinations of neutron-rich and neutron-deficient isotopes. The detector array consists of 2-meter-long rectangular pyrex tubes with cross sections of 6.35 x 7.62 cm^2. There are 25 of these units stacked for each of two walls that cover an area of 2 m^2. Photomultiplier tubes at the ends of each tube allow the longitudinal position to be determined to 7.7 cm.

LAND (discussed above): For central collisions, the nuclear equation of state can be investigated with heavy ions with energies in the range of 600MeV/A. Up to 6 coincident neutrons can be detected separately with this array.

4. Supporting technologies

As important as the development of fast neutron detectors and the capabilities of accelerators where they are used are many supporting technologies. For example, advances in fast electronics have clearly made many experiments possible. The fact that many well developed and engineered electronic modules are available commercially has greatly expanded their use, for an experimenter needs only to have funding to buy them. The engineered options also have allowed the modules to be used in a wide range of experiments. The development of photomultiplier tubes has also had a major impact on physics experiments with fast neutrons.

Times are changing, however, and the number of vendors and hence the competition among them is decreasing both for fast electronics and photomultiplier tubes. There will necessarily be changes in the way experiments are designed and conducted.

This section treats some supporting technologies that are of continuing importance: modeling neutron transport in the experimental environment including the neutron detector, neutron detector efficiency determination, and data acquisition.

4.1 Modeling and simulations

Neutron scattering from the experimental environment can be important in the design of experiments and in the interpretation of the results. Nearly all detectors for MeV neutrons do not give a well-defined energy signal [38] and that signal, while carrying some energy information, is often not sufficient to differentiate neutrons of different energies. Neutron scattering from the walls, floors and ceiling of the experimental room can give times-of-flight signals that will be converted erroneously into neutron energy. Thus much experimental effort in the past has gone into "shadow bars" that attenuate the signal but not the scattered neutrons in order to quantify the background. Of course, these shadow bars also scatter and so their effects need to be corrected before the final correction can be made to the data.

More instructive information on neutron scattering can come from neutron transport calculations, which are made routinely now in the design and analysis of nuclear physics experiments. The two most often used codes are MCNP and its cousin MCNPX [39-43] and

GEANT, the latest version being GEANT4.0 [44]. These codes use data bases that describe all neutron interactions with materials, and the data bases have been well tested through national and international data committees and are therefore considered very reliable. With the codes, one can analyze the effect of neutron scattering as the experiment is being designed. Although there might be uncertainties in the model and, to a lesser extent in the data base, one can get a rather good picture of scattering and what might be done to minimize it. This approach should be in the "toolbox" for every experiment conducted now and in the future.

4.2 Efficiency determination of neutron detectors

For some experiments, just detecting a neutron gives the required signal as a tag of the event. For other experiments it is necessary to know the detection efficiency, which is function of neutron energy. Much effort has been spent over the years to determine these efficiencies of liquid and plastic scintillators, and the work defines a specialized area all in itself. Both experimental and calculational approaches are used together to attack this problem. Calculations are carried out with neutron transport codes such as MCNP, MCNPX, GEANT4.0 and MCNP-Polimi [45]. These calculations give the energy imparted in the detector to charged particles, mostly protons, alpha particles and recoiling carbon nuclei. The response of the detector is then calculated by folding the charged particle spectra with the light output that they create in the scintillator.

Experimental verification of the calculated response can be accomplished by neutrons from the evaluated ^{252}Cf fission spectrum [46], other neutron fields, or tagged neutrons. In the latter, a neutron beam is scattered from hydrogen, for example in a CH_2 foil. For every recoil proton detected at an angle theta, the scattered neutron goes at the complementary angle at the opposite side of the beam according to non-relativistic kinematics. Small corrections are then made to account for edge-effects in the scintillator, and the neutron detection efficiency can then be determined to approximately 2% [47].

4.3 Data acquisition

Electronics and the conversion of analog signals to digital information is always necessary for measurements. Recently, several experimental instruments are going to waveform digitizers to capture the signals from the detectors. One reason is that more information can in principle obtained by a careful analysis of the pulse shape. Another is that many electronic modules formerly used in nuclear physics experiments are not longer available. In any case, with digitizers, a large amount of electronics becomes unnecessary as the logic and pulse-shape analysis can be done in software. This does not necessarily mean that the experiments are easier. Rather the effort on hardware is shifted to a large extent to software development. The capabilities of digitizers are rapidly improving in terms of resolution and sampling rate, and it will be very interesting to witness their applications in experiments.

5. Conclusions

Detectors for fast neutrons have played a major role in understanding nuclear physics from the very basic interactions of nucleons with nuclei, to nuclear structure and nuclear reaction mechanisms. The development of these detectors has continued, not so much for new materials, but more for their application in arrays for new types of measurements. The emergence of new facilities has played and continues to play essential roles in the developments, from the early cyclotrons, to electrostatic accelerators, to pulsed neutron beams and time-of-flight techniques, to spallation neutron sources, and to the modern, energetic heavy ion beams including those of radioactive nuclei.

Whether present-day investigations will lead to giant steps in our understanding of the nucleus and its interactions is, of course, still not clear. Time will tell. We can be confident that the efforts are vigorous and that detectors of fast neutrons are playing an important part.

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