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TITLE NEW TECHNIQUES IN NEUTRON DATA MEASUREMENTS ABOVE 30 MeV

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NEW TECHNIQUES IN NEUTRON DATA MEASUREMENTS ABOVE 30 MeV

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ABSTRACT: Recent developments in experimental facilities have enabled new techniques for measurements of neutron interactions above 30 MeV. Foremost is the development of both monoenergetic and continuous neutron sources using accelerators in the medium energy region between 100 and 800 MeV. Measurements of the reaction products have been advanced by the continuous improvement in detector systems, electronics and computers. Corresponding developments in particle transport codes and in the theory of nuclear reactions at these energies have allowed more precise design of neutron sources, experimental shielding and detector response. As a result of these improvements, many new measurements are possible and the data base in this energy range is expanding quickly.

(Neutron sources, detectors, nuclear data, neutrons)

Introduction

Interest in neutron data above 30 MeV has increased in recent years due to data needs for applications and to the increased capability of sources and techniques in this region. Application include neutron therapy in the treatment of cancer, space radiation effects, accelerator shielding, and materials irradiation test facilities. [1] In addition, many experiments in basic neutron nuclear physics are being undertaken to study nuclear structure and reaction mechanisms.

This range is above that traditionally studied for nuclear energy programs. Consequently, new approaches are often needed. It is the purpose of this paper to point out some of the techniques that are being used in the range 30-800 MeV. A complete review of the field is not possible, but we hope to capture a flavor of the challenges and excitement of this quickly developing field.

Neutron Sources

Two types of neutron sources are in common use above 30 MeV: the quasi-monoenergetic ^{7}Li(p,n) source and "white" neutron sources where a continuum of neutrons is produced. Just as at lower energies, these two types of sources are complementary. A quasi-monoenergetic permits the experiment to focus on results at one energy with more control of the neutron energy spectrum. The white source on the other hand allows a detailed mapping of the energy dependence of cross sections. Both span the energy range 30-800 MeV at various facilities.

The ^{7}Li(p,n) reaction with a thin ^{7}Li production target is generally preferred to other quasi-monoenergetic source reactions because the intensity is sufficient, tritium and other gaseous targets need not be involved, and the contamination by lower energy neutrons is less of a problem. This reaction has been compared with others. [2,3]. The proton beam is usually produced by a cyclotron. A typical source spectrum is shown in Fig.1. [3] Note that in addition to the strong peak there is also a continuum at lower energies. To separate reactions induced by peak and continuum neutrons, all such sources are pulsed and time-of-flight techniques must be used. A clearing magnet is installed downstream from the production target to remove the unreacted proton beam from neutrons produced at 0°, where the maximum intensity is obtained. For both of these reasons, the target to be irradiated is placed several meters from the source. This situation is qualitatively different from that at lower neutron energies where truly monoenergetic sources are available, time-of-flight is often unnecessary, and the investigated sample can be very close to the neutron source. A facility [4] for (n,p) measurements at Uppsala is illustrated in Fig. 2.

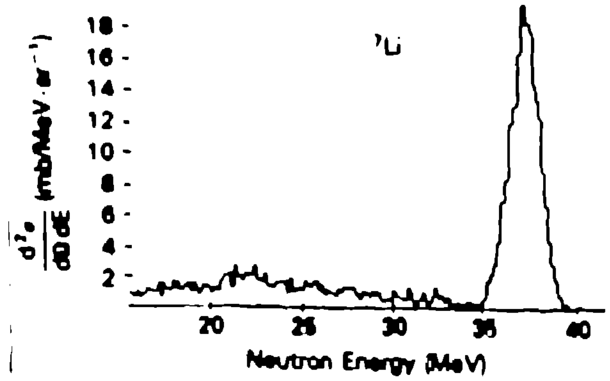

Fig. 1. Neutron source spectrum using the ^{7}Li(p,n) reaction at 39.3 MeV from the facility at the University of California at Davis. [3] Note the strong peak of this quasi-monoenergetic source and the continuum of neutrons at lower energy which, although small, is not insignificant.

White neutron sources are produced by the interaction of energetic ion or electron beams with suitable targets. For neutron energies in the range discussed here, proton or deuteron beams on thick targets offer the greatest neutron source strength. For many years a white source at Karlsruhe was used up to 50 MeV based on the ^{2}H(d,n) and U+d reactions. [5] If the ion beam has energy of several hundred MeV, neutrons are created efficiently by spallation. A facility based on an \ proton beam incident on a tungsten target has recently become operational at LAMPF. [6] This source is pulsed with a time spread at the source of less than 1 ns so that time-of-flight techniques can be used to determine the neutron energy. The neutron spectra from this source are shown in Fig. 3 for the different neutron production angles available for experiments. Calculated spectra are also shown in the figure. The neutron flux from this source extends from below 0.1 MeV to well beyond 500 MeV for some production angles. An overview of the facility is shown in Fig. 4.

The types of neutron sources described above are suitable for measurements of nuclear data at well defined neutron energies. Other facilities that produce neutrons with a broad spectrum but without time-of-flight capability could be attractive for integral tests of nuclear data. We refer here, for example, to the significant number of new cyclotrons built for neutron therapy where neutrons up to 100 MeV are routinely produced at high intensity.

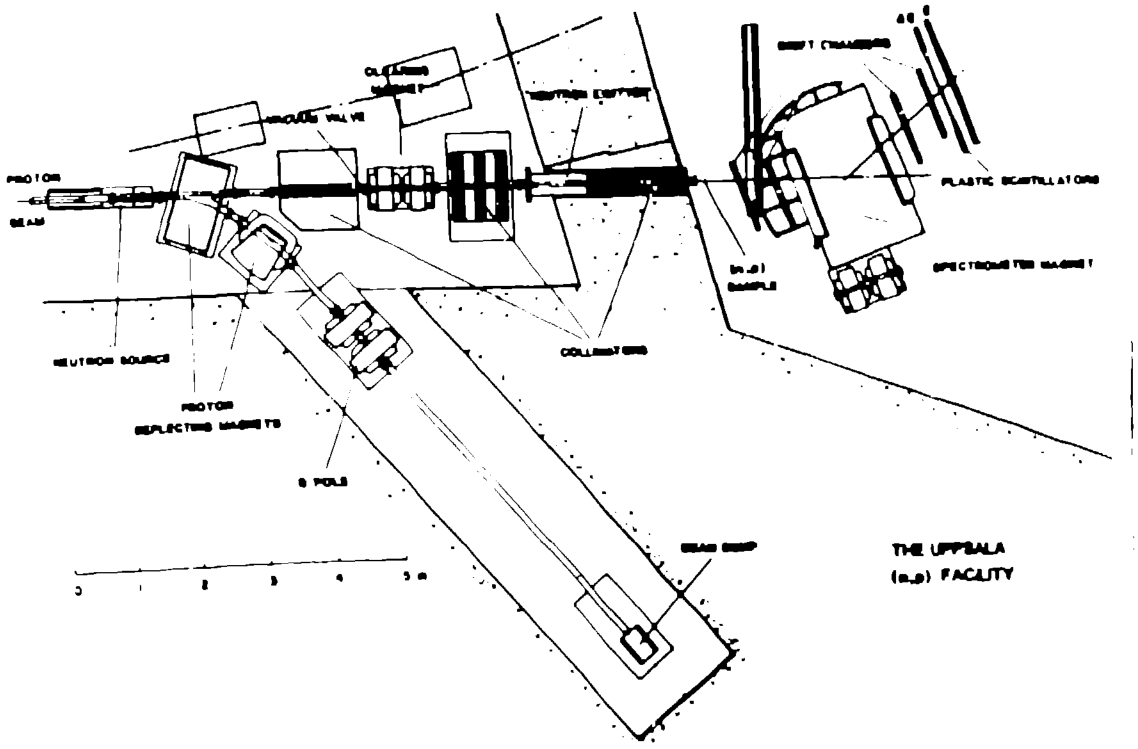

Fig. 2. Implementation of the quasi-monoenergetic neutron source at the The Svedberg Laboratory, Uppsala, Sweden. [4]

Background radiations provide new challenges for neutron sources in this energy range. Because of the higher neutron energy, the time-of-flight separation between neutrons and gamma-rays from the source is less and therefore care must be taken to separate the two. In practice this is not a big problem with ion-produced neutrons (as opposed to sources based on electron accelerators) because the so-called gamma-flash is small. A more subtle background comes from charged particles generated by neutron interactions with collimators, beam pipes, shields, and residual gas in the flight paths. Magnets can sweep charged particles out of the neutron beam, but more will be generated by neutron interactions downstream. Collimators and shields must be much thicker at higher neutron energies because of the lower total cross section. [7]

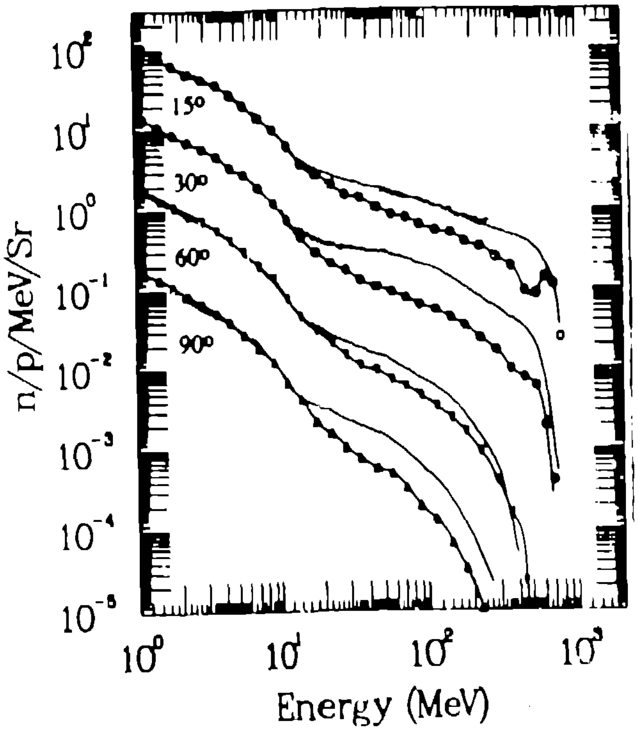

Fig. 3. Neutron source spectra for the different flight paths at the Target-4 spallation neutron source at LAMPF. The narrow curves are the measured spectra and the curves highlighted with symbols are calculations based on the LAHET code system for nuclear reactions and particle transport. [19]

Detectors

Detectors for neutron data measurements in the 30-800 MeV region have developed from those used in low and medium energy nuclear physics research. Detected radiations can be penetrating or not, so that a wide range of detector designs is necessary.

To detect neutrons in this energy range, moderately large plastic or liquid CH_x scintillators are preferred. The detection mechanism is not necessarily n-p elastic scattering as it is for lower energy neutrons, however. Reactions on carbon become more important as the neutron energy increases. Calculations of the efficiency of the detectors are then more complicated. [8,9] To enhance the efficiency of detectors to higher energy neutrons, a CH_2 radiator can be placed in front of the detector. These detectors are readily used in total cross section studies. [7]

Detection of scattered neutrons is more difficult because of the time-of-flight requirement usually imposed. For elastic scattering, quasi-monoenergetic beams can be used and the contaminant neutrons are at lower energies. [3] Beam swingers for the beams producing the neutrons allow an angular range to be covered. [10]

To investigate both elastic and inelastic scattering, a different approach must be used. One way is to convert the scattered neutrons to protons in a hydrogenous foil and then measure the energy and angle of the recoil proton. [11] This has been used at 65 MeV incident neutron energy at the University of California at Davis (Fig. 5). This technique or

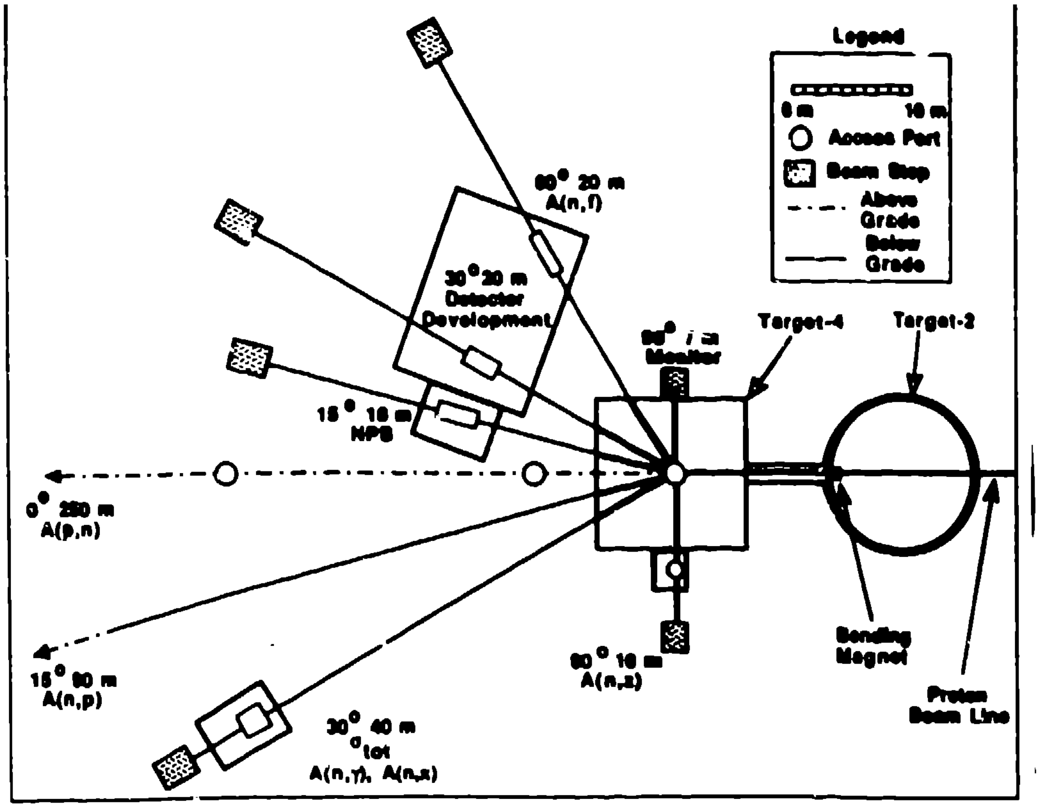

Fig. 4. Layout of the source and flight paths for the Target-4 white neutron source at LAMPF.

one similar to it needs to be exploited at higher energies where there are essentially no neutron elastic or inelastic scattering data.

Gamma-rays from neutron interactions above 30 MeV can range in energy all the way from very low energies to the energy of capture to the ground state. The low energy gamma rays, up to a few MeV, can serve as indicators of the partial reaction cross sections.[12-14] Fig. 6 shows the cross section for producing a characteristic gamma ray from the $^{56}Fe(n,2n)^{55}Fe$ reaction as a function of incident neutron energy.[12] The data were taken with a germanium gamma-ray detector. For neutron capture, much more energetic gamma rays are produced and different detectors, such as BGO, BaF_2 or NaI(Tl) are required. These detectors are

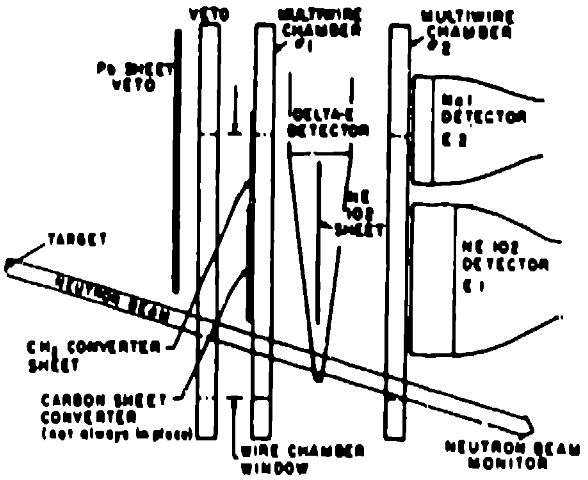

Fig. 5. Detectors for measuring elastic and inelastic neutron scattering in the 65-MeV region at the University of California at Davis [11]

basically the same as those used in charged-particle experiments. They must however be shielded better against scattered and background neutrons. Often a layer of ^6LiH or ^6LiD is placed between the sample and the detector to reduce the number of scattered neutrons.

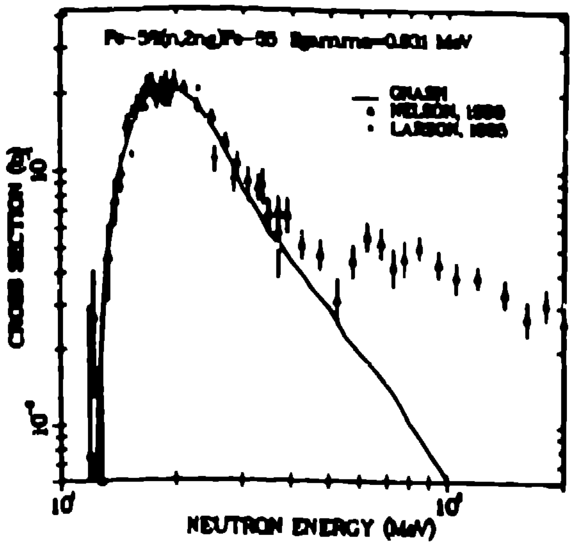

Fig. 6. Excitation function of the 0.931 MeV gamma-ray from the $^{56}Fe(n,2n)^{55}Fe$ reaction. The transition is in the residual nucleus. Data are from [12].

Charged-particle detectors are designed for different energy ranges. For particle energies up to 30 MeV or so, the detectors must be in an evacuated chamber with the target foil. [15] For higher outgoing energies, the charged particles have a reasonably long range in materials so that wire chambers and calorimeters are appropriate. Fig. 2 illustrates one arrangement of detectors.

Fission induced by neutrons above 30 MeV can be detected in a manner similar to that used at lower energy. A difficulty at energies above a few 100 MeV is that spallation can occur in materials of the fission chamber and yield large pulses from the heavy fragments. At these high energies, background measurements need to be taken without the fissionable material.[16]

Electronics

Continuing advances in commercially available electronics makes many of these experiments possible. A partial list illustrates these advances:

- CAMAC interfaces
- FASTBUS interfaces
- Multiple units per NIM module
- High voltage supplies
- Discriminators
- Logic Units
- Linear Gates
- Fast amplifiers
- Fast encoding and readout analog-to-digital converters
- Multiple-stop time digitizers
- Fiber-optic links
- Improved oscilloscopes
- Cables, connectors, etc.

Not only are new capabilities available, but the older capabilities are becoming much more reliable. This makes complex measurements possible where many components all need to be working for the experiment to succeed.

Computers and Software

For nuclear data measurements, the emergence of relatively inexpensive computers has meant that all of the data taking and most of the analysis can be accomplished with what are now considered small computers in the laboratory. This trend is certainly not finished now. Advanced workstations are beginning to appear in nuclear laboratories and will likely continue to change the way we handle data and control the experiments.

As important as the computer hardware are the software data collection programs. We use the XSYS and Q systems.[17,18] The first of these was written at Triangle Universities Nuclear Laboratory and at Indiana University. The latter was written at our laboratory. Other laboratories have their favorites. We predict that the sharing of software will continue to increase because of the great expense associated with writing it.

Tools to Design Experiments

In designing experiments, one needs to estimate counting rates and assess the probable radiation performance of shields, collimators, and other components. Codes exist now to permit calculation of many of these parameters. The predictions of one code are compared with experiment in Fig. 7. [19] In this case the only available data are for proton-induced reactions. It will be interesting and important to compare calculations and experiment for neutron-induced reactions.

In the future there will be data bases above 20 MeV that will provide data for neutron transport codes. At present, the beginnings of data bases are appearing. (See for example [20,21].) Integral benchmarks do not now exist to test the data and transport codes. A future program to provide such integral data will certainly be required.

Nuclear data measurements in the region above 30 MeV are progressing rapidly due to new techniques and new capabilities. Neutron sources, detectors, electronics, computers, software and tools to design experiments all have advanced significantly in the last few years. The next few years should show accelerated developments.

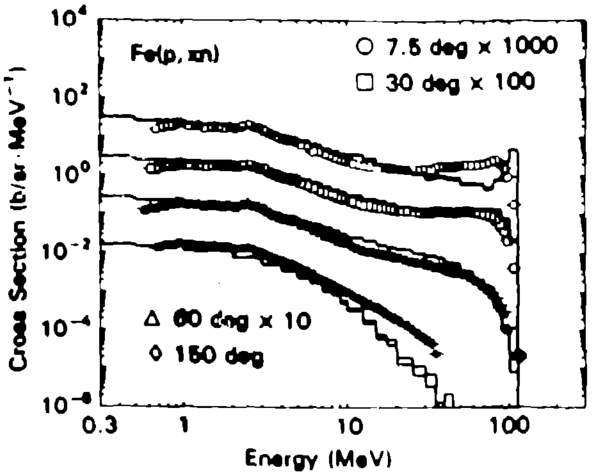

Fig. 7. Double differential cross-section data for 113 MeV protons incident on Fe compared with calculation.

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