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Neutron experiments with underground nuclear explosions*

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Abstract: Techniques have been developed that use nuclear explosions as pulsed neutron sources for time-of-flight experiments. Measurements of capture and fission cross sections have been made. Some preliminary results are presented.

1. Introduction

The Los Alamos Laboratory has developed techniques for using nuclear explosions as neutron sources. The experiments are similar in many ways to the pulsed beam time-of-flight work performed with electron linacs at Saclay, Harwell, and elsewhere. The flight paths of 200 to 300 meters are similar to those in use with the linacs. Pulse duration is about a tenth of a microsecond which is a commonly used resolving time in the laboratory experiments. The main difference is in beam intensity and repetition rate. The nuclear explosion produces 10^{24} neutrons per burst and has a repetition rate of about two per year compared to 10^{12} neutrons per burst and hundreds of pulses per second from accelerators.

2. Source Characteristics

The neutron sources that we have used are small nuclear explosive devices that emit neutrons with a degraded fission spectrum. The peak intensity is at about 1 MeV. If desired, thermonuclear devices can be used to produce 14 -MeV neutrons in addition to the fission neutrons.

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Construction materials in the device contain hydrogen which acts as a moderator and contributes neutrons with energies down to a few hundred electron volts.

An additional moderator is usually used to increase the flux of neutrons in the energy region from a few eV to a few keV. The moderator is designed to enhance neutrons in some particular energy region. It consists of a few centimeters of polyethylene shielded from the source with lead and located about 30 centimeters from the centre of the neutron source. The exact details of the moderator depend on the neutron spectrum that is desired. The moderator used on the Petrel experiment of June 1965 consisted of 5 cm of polyethylene with 6 cm of lead on the side toward the source and 2 cm of lead on the other side of the polyethylene. It was 29 cm from the centre of the source to the nearest lead. The lead serves to absorb gamma rays and help keep the moderator cool and also to control the velocity of the moderator. The neutrons are emitted from the source in less than a tenth of a μ sec and slowed down in the moderator. The moderator temperature rises to a few electron volts from the neutron heating and very shortly thereafter a shock strikes the lead and the polyethylene is heated again and compressed to a thickness of 8 millimeters. At the time the thermalized neutrons are emitted the moderator velocity is 5.5 cm per μ sec, its temperature 25 electron volts, and its density six times normal. The neutrons are emitted from the moving moderator and therefore the lowest energy neutron has a velocity equal to that of the moderator. In the Petrel experiment the cutoff was 18 eV corresponding to the 5.5 cm per μ sec velocity. The peak of the thermal flux occurs at about 60 eV in the laboratory system corresponding to

about 25 eV in the moving moderator.

While the Petrel moderator was designed to concentrate neutrons in the 20-100 eV region, the temperature and velocity can be adjusted to place the thermal neutrons at any desired energy, from a few eV to a keV. Also suitable holes can be placed in the moderator so that the source can be viewed directly to enhance the flux at a keV and above. It is possible to design a moderator that will provide a signal with a roughly constant number of events per resolving time from a few eV to 100 keV.

The neutron flight path extends from the moderator to the surface of the ground. It consists of an evacuated pipe with suitable baffles to eliminate effects of neutrons scattering from the walls. Six to twelve steel baffles are used, each 60 cm thick with a circular aperture. The baffles define a circular field of view of the moderator about 30 cm in diameter. Just below the surface of the ground one or more beams are formed by a collimator which consists of two meters of brass and steel with suitable apertures to form the desired beams. In the case of the Petrel experiment one beam emerged from a slit 1 to 2 mm wide and 10 cm long and another from a circular aperture 3 cm^2 in area. The flight path can be made as long as desired but if the device is buried just deep enough to contain the explosion then the depth will be proportional to the cube root of the yield of the device. Under these conditions the number of neutrons per square centimeter reaching the surface is proportional to the depth of the hole and the number of neutrons per square centimeter per second reaching the surface is independent of the depth so that if we always use the largest device that is safe on a given flight path, we have always the same intensity

of beam but better energy resolution, the deeper the hole.

The experiments are mounted in a tower above the hole. Since several beams can be provided and many experiments put on each beam, a very large number of measurements can be made at once. When the explosion occurs, neutrons traverse their flight path in a few milliseconds and a hundred or more milliseconds later a mild shock reaches the surface of the ground. After a few minutes a crater forms with a violent collapse of the ground. During the interval before collapse all equipment which must be saved is pulled away automatically to a safe distance. Figure 1 shows schematically a typical experimental arrangement.

3. Comparison to Other Methods

The explosion source differs from accelerators mainly in its intensity. About 10^{24} neutrons are produced in 10^{-7} seconds for a production rate of 10^{31} neutrons per second. A pulse rate of two per year provides more neutrons per year than any accelerator, but only by a few orders of magnitude whereas the source intensity is enormously greater than that available from accelerators. Because intensities are so high, individual events are not observed in detectors but rather currents whose amplitude is proportional to a reaction rate must be measured. As a result of this limitation, we cannot make use of pulse height discrimination to reduce backgrounds or identify particles. Neither can we use coincidence criteria. However, we have an enormous advantage over conventional experiments when we use a sample that is highly radioactive. We can produce nuclear reactions in a sample at a rate high enough to overwhelm any sample-produced

backgrounds. For this reason we will concentrate on experiments with short lived and highly radioactive substances.

4. Experiments

Several kinds of neutron experiments have been developed with the explosion source. The first was the "neutron wheel" experiment of Cowan¹⁾ in which ~~he~~^{they} ~~measures~~^d the peak-to-valley ratio of fission products from resonance to resonance. These experiments have been very successful but will not be described here. This discussion will be confined to capture and fission cross section measurements using time-of-flight identification of neutron energy and electronic recording of the data.

Fission cross section measurements are especially attractive with the explosion source because very thin deposits on nearly massless backings can be used and the samples interfere very little with the beam so that many fission cross sections can be measured simultaneously. A deposit of fissionable material of about 500 μg per square centimeter is placed on a thin backing and oriented at 45° to the direction of the 3 cm^2 beam. Solid state detectors 3 cm^2 in area are located out of the beam 5 cm from the beam centre. The detectors catch fission fragments from the foil. Figure 2 shows a stack with detector and fission foils. Nine samples are contained in this array. Typically very many fission fragments strike the detector in one resolving time ($0.1\text{ }\mu\text{sec}$) so that a continuous current is produced that is proportional to the product of the fission cross section and the neutron beam intensity. The current as a function of time can then be converted to cross section as a function of neutron energy. In order to take into account the angular

distribution of fission fragments, three detectors are used on each fission sample. These are placed at 15° , 55° , and 90° to the neutron beam and all are located at 45° to the plane of the sample. A blank backing is used to obtain a background measurement and a ^6Li sample in a similar arrangement provides a measurement of neutron flux as a function of time. On the Petrel experiment we measured fission cross sections of ^{233}U , ^{235}U , ^{239}Pu , ^{240}Pu , ^{241}Pu , ^{241}Am . The energy range covered was 20 eV to 8 or 10 MeV.

Capture cross sections are measured in a similar manner. A thicker sample is required so that the measurement has a more severe effect on the neutron beam. A reasonable sample is 0.025 cm thick for a material like ^{240}Pu so that a few grams are required. The capture is observed by means of the capture gamma rays which are detected with a solid state Moxon-Rae detector²⁾. This detector has the advantage of being insensitive to the decay scheme of the gamma-ray cascade following the capture event. As in the fission experiments, the output of the detector is a current whose magnitude is proportional to the product of capture cross section and neutron flux.

Scattering cross sections can also be measured with the explosion source. A detector for scattered neutrons is being developed which uses high density ^3He as a scintillator. The ^3He has been used both as a liquid, and as a gas cooled with liquid ^4He . This detector is designed to observe scattering cross sections from the resonance region to a MeV.

Total cross sections are measured with the usual transmission techniques, using two or three samples of different thickness in

series with a flux measurement before and after each sample. Only one total cross section can be measured on each beam. Our method has little advantage over accelerators for transmission measurements except that intensity is great enough that small samples can be used.

5. Data Recording

Because of the very great range of intensity and large variations of cross section with energy, our signals vary in amplitude from a fraction of a millivolt to several volts. We compress the signals into a usable range by means of logarithmic amplifiers³⁾ which cover 0 to 10 millivolts linearly and 10 mV to 100 V logarithmically. Ten millivolts into the amplifier gives 2-1/2 volts out, 100 mV in gives 5 V out, etc., so the range of inputs of 10 mV to 100 V is compressed into 2-1/2 to 12-1/2 V on the output. The amplifier output is sent down a long cable to the recording station three or four hundred meters away where it is recorded on at least two oscilloscopes. The oscilloscope is photographed on a moving film camera in one of two ways. The simpler uses the moving film (30 meters per second) as the time base and no time base is used on the oscilloscope. This system provides one microsecond time resolution which is adequate for late times (low neutron energy) and is simple and unambiguous to read. Figure 3 shows a sample of this type of recording. The problem of recording at 0.1 μ sec resolution for several milliseconds is solved by use of a raster system in which the oscilloscope is provided with a time base 20 μ sec long with a fast 0.2 μ sec flyback so the oscilloscope beam is nearly all of the time writing horizontally at 0.5 cm per μ sec and the moving film serves to separate the sweeps so that data appear as

signal above a series of sloping base lines which are repeated indefinitely. This method suffers the disadvantages of data loss during the oscilloscope beam flyback time and problems of overwriting of successive beams when signals are fluctuating rapidly as in the resonance region. Figure 4 gives an example of a raster display. In the future we shall use high speed drum cameras in which the film moves at 300 meters per second and provides 0.1 μ sec resolution for 3 milliseconds with film motion alone.

6. Data from Petrel Experiment

Since several months are required to analyze the data from one shot, only a small part of the Petrel data have been analyzed. We have obtained the cross section of ^{239}Pu from the Petrel experiment and it is shown in fig. 5 as an example of the data that can be obtained. Only the data with one μ sec resolution have been analyzed thus far so that the resolution which appears here is approximately 10 nsec/meter. When the film with the raster system has been analyzed, the resolution will be 1 nsec/meter for those neutron energies where the better resolution is needed.

7. Conclusion

A method for cross section measurement using a nuclear explosion as a pulsed neutron source has been developed. This method is capable of providing data with good energy resolution from a few eV to 14 MeV and can do so for highly radioactive samples which would contribute impossible backgrounds in the usual laboratory experiments. The experiments preceding the Petrel event were mostly involved with

learning the method. On Petrel some well known cross sections were measured as a proof of the method and some experiments produced new information. We shall plan future experiments to exploit the intense beams available, especially to measure capture cross sections of intense gamma-ray emitters and fission cross sections of highly radioactive nuclides.

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Figure Captions

Fig. 1. Layout of a set of experiments using a nuclear explosion as a neutron source. The nuclear device was exploded a few seconds earlier two or three hundred meters underground. The vacuum pipe through which the neutrons traveled extends to the ground surface and on up the tower that houses the experiments. Two sleds containing experimental equipment are being towed to safety by winches while a third winch is pulling a package from the top of the tower. A few minutes later the ground will collapse and the tower will drop into a shallow crater.

Fig. 2. Stack of seven detector stations. Five hemispheres contain a thin foil each with fissile material; one has ${}^6\text{Li}$ and one is a blank foil for background determination. Each hemisphere has 2 or 3 solid state detectors to catch fission fragments from the foils. The beam passes vertically through the stack through the foils and through beam ports in each hemisphere so that only the thin foils interfere with the beam.

Fig. 3. Sample data recorded on 35 mm moving film in the streak mode. The film motion provides the time base and the signal after logarithmic amplification is displayed as an oscilloscope deflection perpendicular to the direction of film motion. The top trace is a set of 20 μsec time marks, time moving from right to left. Outputs of two different detectors viewing a ${}^{235}\text{U}$ foil are shown.

Fig. 4. Output of two detectors viewing a ^{240}Pu foil. The centre of the record is about 50 eV and the right hand edge about 2 keV. Individual fission events are seen in many resonances some of which are in ^{240}Pu and some in the ^{239}Pu contaminant. The large deflections are caused by gamma rays from resonances in the platinum backings. Each sweep is 20 μsec long.

Fig. 5. Sample cross section data of ^{239}Pu . Several corrections have not yet been applied so that these data are somewhat in error but suffice to indicate the lack of background between resonances.

Fig 1

Fig 2

STREAK RECORD

U 235

FLYBACK RASTERS