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EXPERIMENTS Using Single Neutron Pulses

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ABSTRACT

The combination of intense neutron pulses from the LANSCE or ISIS sources with modern detectors of neutron currents, has allowed work to begin on exciting new experiments using single neutron pulses. To illustrate this field we shall describe three applications which make use of the transmission of neutrons through a sample as a function of their energy. The three examples are (i) the measurement of the temperature along the body of a projectile after launching, (ii) a strobo-scopic study of the warming cycle of a jet engine at full power and (iii) the study of phase transitions under extreme conditions. To prepare for experiments of this kind a 40 m special flight path is being built at LANSCE, and preliminary experiments to demonstrate the method have been made with an existing 10 m path.

I. INTRODUCTION AND DESCRIPTION OF THE METHOD

The advent of pulsed neutron sources driven by high powered accelerators, has opened up the possibility of doing both transient and stroboscopic measurements with neutrons (e.g. Egelstaff[1]). These experiments would require good data to be taken with a single neutron pulse, either because one pulse represents the whole experiment or because we wish to compare the data taken with the first pulse to that taken with each subsequent pulse.

Over the past year sources such as LANSCE or ISIS have provided proton pulses of about 3 μC each, which is on the lower limit of usefulness. In 1991 it is expected that LANSCE will deliver 5 μC pulses at 20 Hz, and for single shots may deliver a 10 μc pulse. Thus it is worthwhile preparing some test experiments which will help define the fields in which single pulse experiments could be useful and which would clarify the experimental methods.

Figure 1 shows a sketch of the apparatus that would be used. Sufficient neutrons must be absorbed by the Li-glass scintillators during the transit of the pulse, that smooth current variations occur in the photomultiplier circuits which may be digitized and recorded. At present flux levels this requirement restricts the measurement technique to the transmission method. A burst of fast neutrons would be moderated in a light water slab, and a beam of resonance and thermal neutrons would be collimated on to the chosen sample. On passing through the sample the neutron beam intensity is changed by the events in progress there, and this information is carried to the end of the flight path where it is recorded by the Li-glass photomultiplier system. One advantage of this method is that, due to the flight times of the neutrons, the information impressed on the neutron beam in time Δt is expanded to $(L_2/L_1)\Delta t$ at the detector, (where L_1 and L_2 are the distances from the moderator to the sample and to the detector respectively).

The transmission (T) of a sample is defined as the ratio of the intensity of the beam with the sample present to that in the absence of a sample. In the resonance region dips in the curve of T vs neutron energy, can occur due to neutron absorption resonances. A possible energy range for these effects is 1 to 100 eV, but the exact range of usefulness will vary from case to case. For example in the case of Ta there are 9 resonances between 60 and 20 eV, which may be used to measure the temperature of a sample as a function of time. The width of the resonance has two components, first nuclear absorption and scattering and secondly Doppler broadening due to the nuclear velocities. We are interested in the latter effect which is given by the formula:

$$\Gamma_D = \sqrt{4E_R\, k_B T / A} \tag{1}$$

where E_R is the resonance energy, T the sample temperature and A the atomic weight of the nucleus. It can be seen that Γ_D is large for high values of E_R and/or temperature and in many cases will be the dominant component. For example at 40 eV in Ta at room temperature the value of Γ_D is 0.15 eV compared to a nuclear width of only 0.05 eV. In such cases the resonance width technique will provide a temperature measurement deep inside a sample in a time of about 1 μsec.

The thermal neutrons in the pulse have longer wavelengths (λ) and are sensitive to Bragg reflections from the sample. They are found when the Bragg condition is satisfied:-

$$\lambda = (2d/n)\sin\theta_B \tag{2}$$

where d is the interplanar spacing, n the order of reflection and θ_B the Bragg angle. A strong Bragg reflection will remove neutrons from the beam and hence reduce the transmission: an effect which increases as θ_B (or λ) increases. Because the maximum value of θ_B is π, this effect switches off as λ increases past the point where $\theta_B = \pi$ for any choice of d. The rises in T at these points provide information on the positions and widths of the Bragg reflections, and hence a range of structural information. For simple structures (e.g. fcc) there would be a range of suitable Bragg reflections, and each reflection would be covered in about 50 μsec with separations between reflections of 0.5 to 3 ms.

By using both of these techniques a range of experiments are possible, and some selected examples will be described here. Stroboscopic measurements are possible on several time scales, successive resonances occur on a 5 μsec scale, while successive Bragg reflections occur on a 500 μsec scale. In contrast at 50 Hz or 20 Hz, successive pulses would occur at 20 or 50 ms respectively. If a sample is moving, one could build neutron absorbers into its structure at specific points to act as markers, and so define both its position relative to the beam and its bulk velocity. In favourable cases the bulk velocity might be determined by the resonance method, since there is an additional bulk shift in the resonance energy due to the component of velocity along the neutron beam. A similar shift would occur in Bragg peak positions but maybe harder to observe.

Thus there are a large number of simple observations that may be made in this field, and both the experiments and the observational methods need to be chosen with care in order to exploit the technique properly.

II. MEASUREMENT OF THE TEMPERATURE ALONG THE AXIS OF A PROJECTILE AS A FUNCTION OF TIME AFTER FIRING

A simple sketch of the geometry which might be used in this case is shown in figure 2. A special projectile is envisaged which might be 30 cm long and 1 cm x 5 cm cross section, with a 0.2 mm thick Ta strip dividing the 1 cm section down its centre (this projectile would be strip shaped and its rotation would be prevented, for simplicity, in this demonstration). If the projectile crossed the beam at an average velocity of 1 cm/μsec the data of interest would be impressed on the beam in ~30 μsec. However if the sample were

4 metres from the moderator and the total neutron flight path was 40 metres, the data would be spread out to 300 μsec at the detecting station. Each resonance in Ta would need about 1 eV of energy to define the transmission dip, and at 40 eV this would be covered in 0.7 μsec at the sample and 7 μsec at the detector. We note also that in this experiment, and in similar ones, the neutron itself is the detector at the site of explosion/projectile/etc and is unharmed, while the fragile detection apparatus for the neutron is ~30 m away and is also unharmed.

In order to determine the exact time of the passage of the projectile across the beam and its exact velocity (if normal to the beam), the projectile would be equipped with ^{10}B markers which would produce additional characteristic dips in the neutron transmission curve. For example if the ^{10}B rings are 0.5 cm wide and deep, a nearly triangular transmission dip of 95% would be seen at 40 eV having a width of ~0.7 eV. By tipping the projectile to an angle of 13° away from the normal, a 2 eV transmission dip shift would occur and the two methods of measuring projectile velocity could be compared.

Several measurements might be made with the starting length, ℓ, being varied. In this case a picture of the temperature profile in space and time can be built up. It is hoped that the conditions of any experiment of this type could be controlled so that the temperature profile could be calculated theoretically and compared to the experimental results. If successful a program of this kind would establish the base for more ambitious experiments.

Projectiles are used also for experiments with shock waves. In this case the time scale for the initial shock is too short for these techniques, but temperature measurements after the shock may be useful. There are two time scales, first there is a shock die-away time of ~10 μsec, and temperature measurements synchronized to follow the shock by 1 μsec steps would be useful. Secondly there is a residual effects recovery period of about 1 msec, and temperature measurements at 10 μsec intervals to 100 μsec, followed by intervals of 100 μsec to 1 msec could be informative. Such data appear to be difficult to obtain by other methods, but relatively straightforward by this method.

III. STROBOSCOPIC MEASUREMENTS ON A ROTOR UNDER STRESS

Another example of a stroboscopic study with neutron pulses may be provided by experiments on rotating systems: in this case a continuous stream of pulses is used unlike the single pulse of the previous section. To illustrate this field we shall consider the stresses in a jet engine as it accelerates to full power, and hence maximum stresses, and subsequently as it warms to its maximum temperature while operating at full power. Figure 3a is a sketch showing an impeller blade attached to the rotor. The neutron beam should be directed in successive experiments at points of high stress in the rotor (e.g. near the root of the blade or near the centre of rotation). At first, some demonstration experiments would be done with a simple rotor, and if successful with increasingly realistic set-ups. The rotational frequency and neutron pulse frequency should be simply related so that a time sequence for a chosen point on the rotor is obtained. Resonance widths and positions would be measured to determine temperatures and velocities, while structural data would be obtained from widths and shifts of Bragg reflections.

Figure 3b shows the time structure for a 20 Hz neutron beam. The resonance data (for temperature) is obtained first, followed at about 5 ms by the thermal neutron structural information. These data are repeated at 50 ms intervals. One might take one second of such data, and repeat it at one minute intervals for example. Normally it would be possible to make such measurements for only one point on the rotor at one time. Thus the whole program would consist of a number of runs, starting the rotor from rest, each looking at a different site. If the rotor is taken close to its limit, suitable safety precautions would be built into the set-up and these would include heavy shielding. Consequently there would be an advantage to the transmission method of detection since it requires relatively small entrance and exit windows for the neutron beam.

IV. A DEMONSTRATION EXPERIMENT

In order to demonstrate the practicality of this technique, Priesmeyer et al[2] have carried out a demonstration experiment. They used a stationary sample of iron 2.5 cm thick and a beam area at the sample of 5 cm x 2.5 cm. The charge in the pulse was only 3 μC, and the distances from source to sample or detector were 8 m and 11.7 m respectively. With this set-up they obtained the data shown in figure 4 with a single pulse. The thermal neutron wavelength region is shown from 1.5 to 5 Å, and six Bragg reflections are observed clearly in 8 ms at the detector. The rising character of the overall intensity follows the Maxwellian shape of the thermal neutron distribution. Taking this and the instrumental resolution into account, the d-spacing in iron was determined to a precision of $\sim 5 \times 10^{-3} = \Delta d/d$ in ~100 μsec (e.g. at the 211 reflection). If the charge in the pulse were increased to 10 μC or greater it would be possible to decrease the sample width from 2.5 to 1 cm, and with more optimum path lengths to improve the precision and with longer paths to improve the time resolution. It is hoped that such improvements will be possible with a new set-up under construction at LANSCE.

V. CONCLUSIONS

Experiments with a single neutron pulse are theoretically possible[1] at LANSCE or ISIS and three kinds of experiments were described in this paper. In addition a demonstration run at LANSCE in which the d-spacing of iron was measured to a precision of 0.5% in 100 μsec was described. This has opened the door to some new and exciting fields of research. With longer flight paths, an improved sample installation and pulses of ~10 μC many such experiments appear to be possible. A number of other areas, in addition to those described above, may be considered. They include — transient methods with pulsed electric or magnetic fields, and phase changes in geological minerals (e.g. olivine which has a phase change at $\sim 10^5$ atm, as a test case) using pulsed pressure fields.

An initial series of test experiments is required in order to establish these methods and to define their current limits. It is hoped that such a program may be commenced with a new long flight path installation at LANSCE.

References

1. Egelstaff P.A. "New Directions in Neutron Diffraction", ICANS-VII, p. 271, Report AECL 8488, Ed. Schriber, S.O., (1984).
2. Priesmeyer H.G., Bowman C.D., Yuan V.W., Seestrom S.J., Wender S.A., Richardson R., Wasson O.A., Xzu X. and Egelstaff P.A. Unpublished Memo entitled: Fast Transient Diffraction at LANSCE (1989).

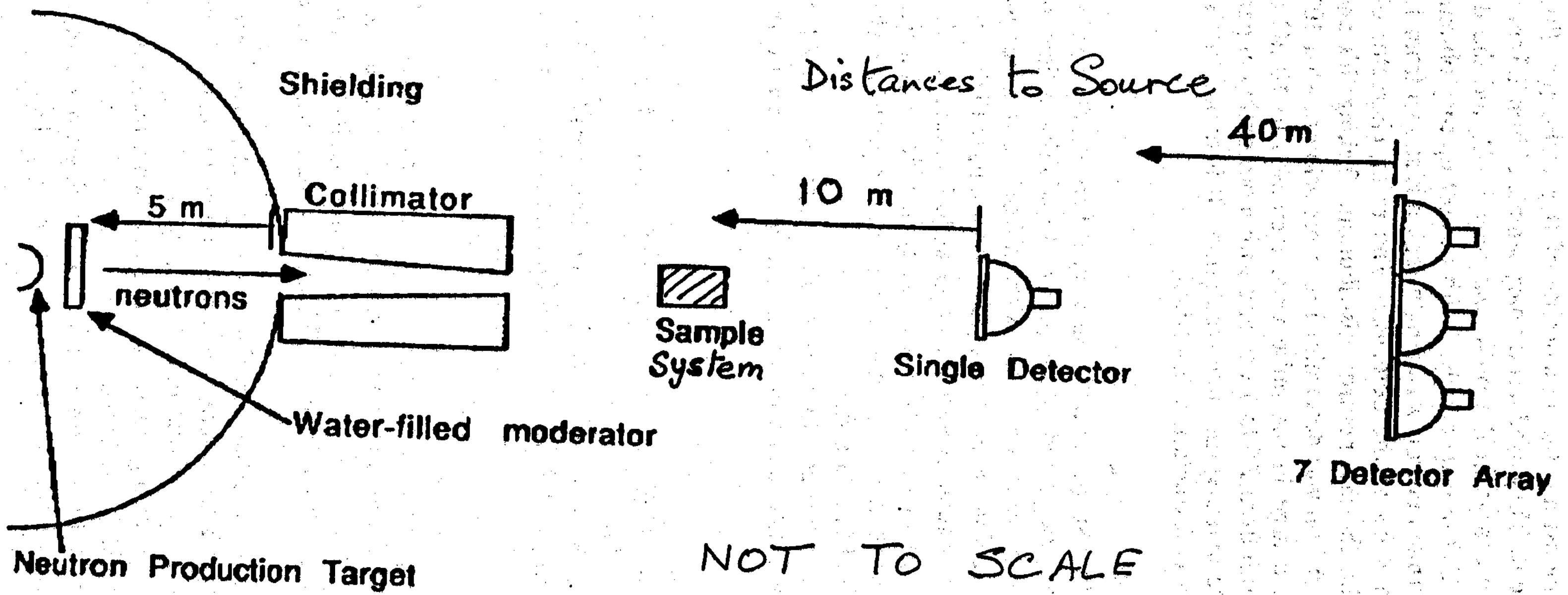
Figures

1. The layout for single pulse experiments. A 10 μC proton pulse strikes the neutron production target, and fast neutrons are moderated to resonance and thermal energies in the moderator. They are collimated onto the sample, and after passing through it the beam diverges to a large detector array at about 40 m from the moderator. For initial tests a single detector may be placed at ~10 m from the moderator.
2. The geometry for a projectile experiment. A special projectile would be made with a 0.2 mm thick Ta strip along its axis for temperature measurements and ^{10}B markers for velocity measurements. The distance ℓ would be varied for different shots.

3a. A sketch of a rotor showing blades attached and two possible points at which stress and temperature measurements would be desirable.

3b. The time structure of the information obtained in single pulse sequence-experiments on rotors. Each arrow marks a set of either temperature or structural data.

FIG. 1



NOT TO SCALE

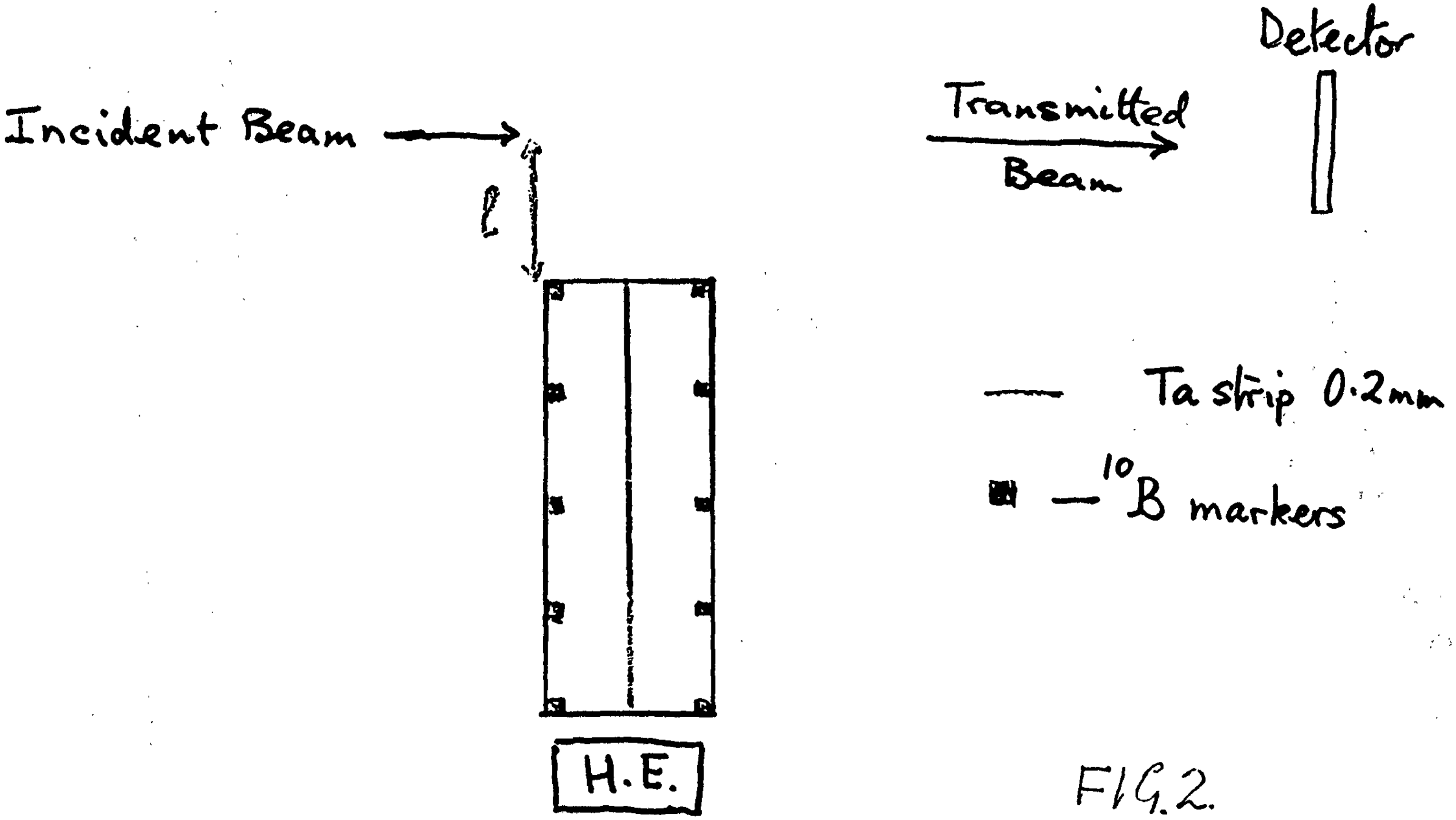
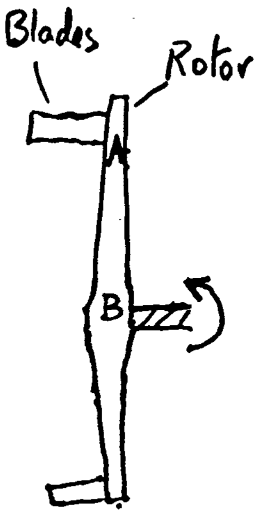

Detector
Incident Beam
Transmitted Beam
l
Ta strip 0·2mm
■ — ^{10}B markers
H.E.

FIG. 2.

3 (a)



Points of measurement marked A and B

3(b)

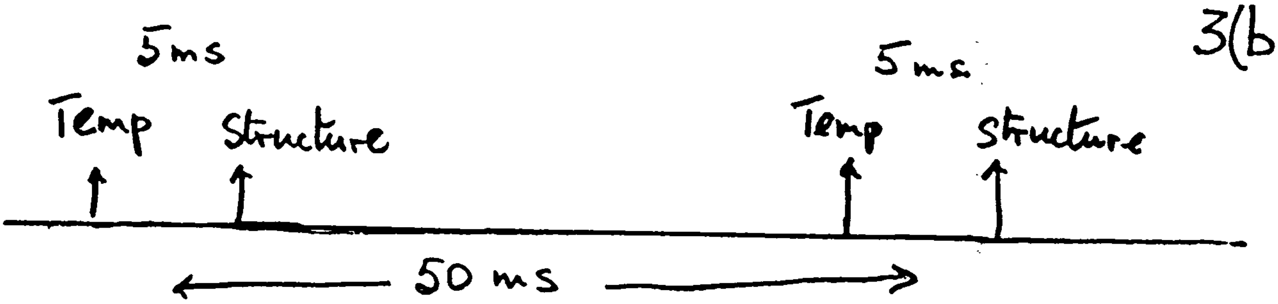
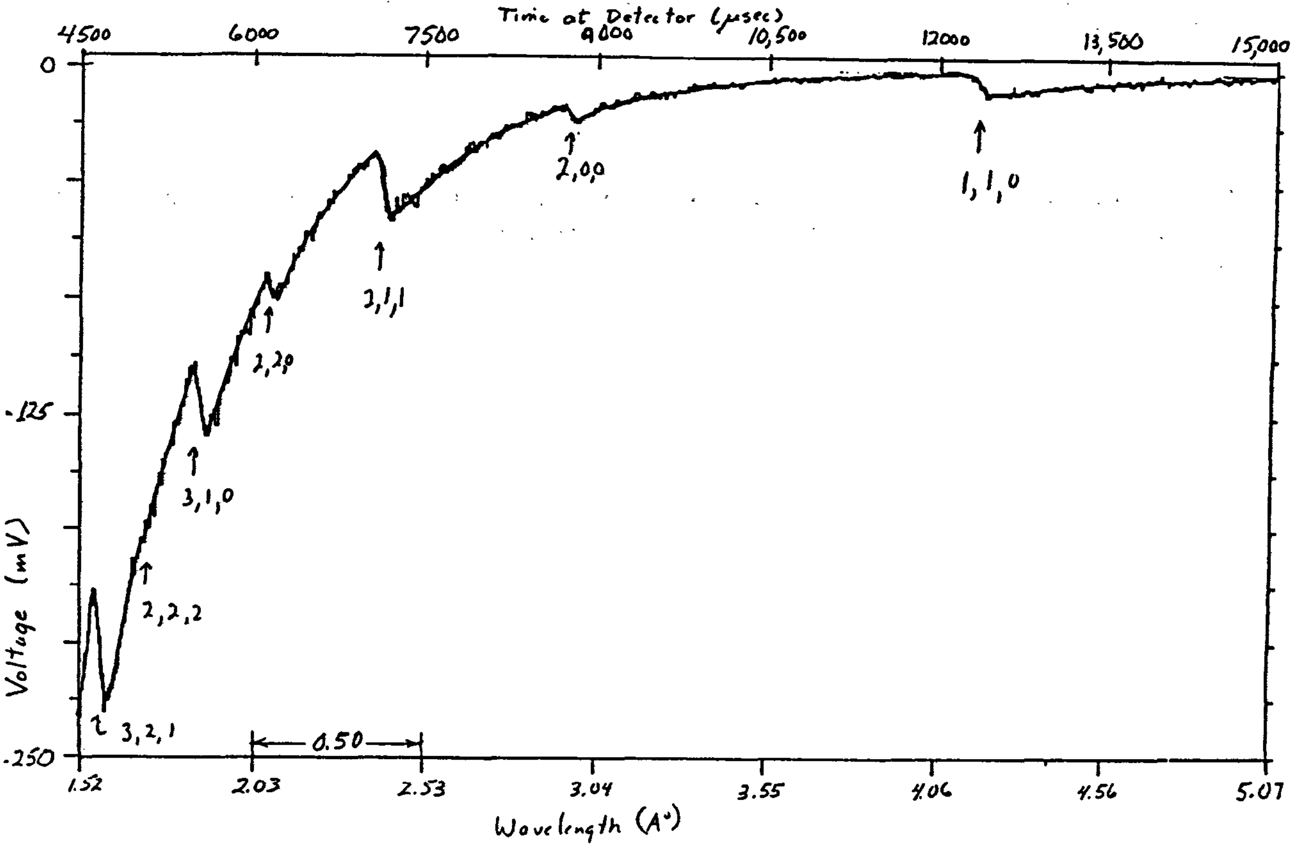


FIG 4


Time at Detector (μsec)
4500
6000
7500
9000
10,500
12000
13,500
15,000
0
-125
-250
Voltage (mV)
2,0,0
1,1,0
2,1,1
2,2,0
3,1,0
2,2,2
3,2,1
0.50
1.52
2.03
2.53
3.04
3.55
4.06
4.56
5.07
Wavelength (A°)

4. Experimental data obtained with a single 3 μC pulse at LANSCE in the thermal neutron region. The sample was a block of iron 2.5 cm thick, and the d-spacing may be determined from any of the indexed steps in the transmitted intensity (assuming the crystal structure is known). The overall shape of the intensity vs wavelength curve is due to the Maxwellian shape of the thermal neutron intensity distribution.

Q(J.M.Carpenter): Does the method really profit from use of analog detectors, sacrificing quantum statistical accuracy? Would not it do to use a stack of low-efficiency pulse counters?

A(P.A.Egelstaff): N/A