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DEVELOPMENT OF A RESONANCE DETECTOR SPECTROMETER ON THE HARWELL LINAC

M P Paoli,
E W J Mitchell
Clarendon Laboratory
Oxford University
Parks Road
OXFORD
OX1 3PU

R N Sinclair
AERE Harwell
DIDCOT
Oxon
OX11 0RA

and

A D Taylor
Neutron Division
Rutherford Appleton Laboratory
Chilton
DIDCOT
Oxon
OX11 0QX

Abstract

Intense beams of epithermal neutrons are now available from accelerator based neutron sources. The neutron beam can be made monochromatic by using materials which resonantly absorb neutrons in this epithermal region. A Resonance Detector Spectrometer (RDS) uses a γ-ray detector to observe the γ-rays emitted when a neutron is absorbed by such a material. Development of an RDS system has been made at Harwell. This work included a background investigation, a comparison between a high resolution and a low resolution γ-ray detector, experiments using the double difference technique and experiments at high Q.

1. INTRODUCTION

Accelerator-based neutron sources provide intense beams of epithermal neutrons. These may be used to perform two new types of measurement. The first involves studying the excitation of single particles at large Q values, $\geq 100 Å^{-1}$, where the impulse approximation may be valid and so the final state of the particle can be neglected. The second is where excitation energies are large, ~ 1 eV, and Q values are small allowing magnetic and electronic excitations by keeping the magnetic form factor large [1].

For neutrons with energies above 1 eV rotors and crystal analysers are inefficient at monochromating the neutron beam. To make an epithermal neutron beam monochromatic it has been proposed that materials in which resonance absorption of neutrons occur can be used. There are two possible ways of using these materials. The first involves using the material as a filter. Performing with and without filter experiments then taking the difference gives the TOF spectrum due to neutrons with energy equal to that of the resonance. Experimental work using such a Filter Difference Spectrometer (FDS) is given in [2]. The second method, the Resonance Detector Spectrometer (RDS), makes use of secondary particle emission, particularly γ rays, when a neutron is resonantly absorbed [3]. In this paper we summarise the development work performed on an RDS system at the Harwell Linac. Further development will take place on the eV spectrometer on the SNS at the Rutherford Appleton Laboratory where RDS and FDS techniques will be pursued in parallel [4].

2. EXPERIMENTAL LAYOUT

The Harwell Linac accelerates electrons which then hit a Ta target. The bremsstrahlung radiation produced as the electrons slow down in the target cause (γ,n) reactions with the Ta nuclei and so give a pulse of high energy neutrons. These neutrons are then slowed down by an ambient water moderator. For the RDS, moderator to sample distance is 7m and the sample box to detector box distance is 2.4m. This was originally to allow scattering down to $2\frac{1}{2}°$. Shielding outside the detector box consisted of 10 cm of Pb surrounded by 25 cm of borated resin. The shielding inside the detector box varied but typically consisted of Pb to shield the γ ray detector and B_4C plates to screen all Pb blocks from neutrons. This internal shielding is shown in Figures 1a and 1b for scattering at 60° and 15°.

3. BACKGROUND INVESTIGATION

The first experiments were performed using a high resolution high purity germanium γ ray detector (HPGe). As the Linac uses γ rays to produce neutrons and as the target, moderator and spectrometer beam line are all colinear there is an intense γ flash when the electrons hit the target. Fast electronics are needed otherwise the γ flash saturates the detector which may not recover for several milliseconds, covering the time region of interest. Using the fast electronics enabled the detector to recover in times $\sim$ 10 μs.

A typical γ ray spectrum from a resonance capture consists of a continuum up to around 7 MeV with additional sharp γ ray lines. Figure 2 shows the lower end of the γ ray spectrum for neutron capture by Ta. There are Ta (n,γ) lines at 173 keV, 271 keV and 403 keV with background lines from Boron neutron capture at 482 keV and the positron annihilation line at 511 keV. A high resolution detector is needed if we wish to use the signal from the narrow (n,γ) lines as well as monitoring wide bands in the continuum. The initial experiments used a Ta analyser foil. Ta has two strong (n,γ) lines at 271 keV and 403 keV and these were used along with several broad bands in the region 520-3000 keV. The background was investigated using a Ta foil sample, and pure Pb sample scattering at 70° and 10° and a ZrH_2 sample scattering at 10° and 3° (both were $\sim$ 10% scatterers). The main source of background was caused by sample scattered neutrons being captured in Pb shielding. The Pb shielding blocks contain an Sb impurity which has neutron capture resonances and gives off γ rays when neutrons are captured. These resonances gave rise to a time structured background. To reduce this background B_4C plates were used to capture neutrons before they could be captured in the Pb blocks. Although boron also has a (n,γ) reaction, all the γ rays have energies around or below 482 keV. The other important background line was the 511 keV position annihilation line, thus most of the background occurs below this energy. Using B_4C plates improved the signal to background ratio above 520 keV but made worse the signal to background ratio below it.

The signal to background was best for the 1000-3000 keV band but very poor for the (n,γ) lines which both occur below 511 keV. If the sample is moved further from the detector this background problem is reduced

as the scattered neutron capture also occurs further from the detector. When the ZrH_2 sample was placed 2.3m from the detector, scattering angle 3°, the background level was reduced by 5 to the level if no sample were in the beam. However, the signal countrate was very low, being approximately one count per 1 μs channel per hour. This showed that the intensity of the Linac was too low to allow investigations of small angle scattering and so all further experiments were done at higher angles, 10°-70°.

4. COMPARISON OF HPGe AND BGO DETECTORS

As we had previously found that the best signal to noise ratio with the HPGe detector occurred when using a broad γ ray energy band rather than a specific (n,γ) line, this suggested that there may be advantages in using a higher efficiency, low resolution detector. A comparison was made between a high resolution, high purity intrinsic Ge detector consisting of a cylindrical crystal of Ge 6 cm long and 6 cm diameter and a low resolution Bismuth Germinate scintillator detector (BGO) consisting of a cylindrical Bismuch Germinate crystal 7.5 cm long and 7.5 cm diameter. The resolution of the HPGe was better than ¼% and for the BGO was in the range 20-30%.

Three types of comparison were made :

(i) Using a Ta foil as a sample.

(ii) Using Pb as a sample and scattering at 60° onto a Ta analyser foil.

(iii) Using ZrH_2 as a sample and scattering at 10° using Sm and Ta analyser foils.

For each type of experiment the geometries for the HPGe and BGO detectors were kept identical as was the internal collimation and shielding in the detector box. The external shielding close to the detector was marginally better for the BGO, as it would indeed be when the detectors are used in other experimental situations. However, in most previous experiments the external shielding was found to have little effect on the total background. For the Pb experiment the

incident flight path is around 9.4m and the secondary flight path 21 cm. For the ZrH_2 experiment where the scattering angle was 10°, the incident flight path was 8.75m and secondary flight path 75 cm. The principle background γ-ray lines came from boron capture, 482 keV, and the positron annihilation line at 511 keV. To avoid these lines using the low resolution BGO detector, a lower limit of 900 keV was chosen. Since the best signal to background ratio found previously occurred below 3000 keV, the principal comparison between the detectors used the gamma ray energy band 900-3000 keV.

For each type of experiment, the signal to background ratio and signal countrates were calculated and the results are shown in Table 1. These values are accurate to 10%. As expected when using the 900-3000 keV band, the signal to background ratios for both detectors were similar but there was a higher signal countrate for the larger BGO detector.

We also observed (n,γ) lines using the HPGe detector, 403 keV for Ta and 333 keV for Sm. The signal countrates for these lines are much lower than for the wide energy band. Previously we found that sample scattered neutrons were an important contribution to the background. A large amount of boron has to be used to stop neutron capture by the Sb impurity in lead shielding blocks. This produces a large number of background γ-rays of energy 482 keV and below. This background is highest when the sample is close to the detector as the neutron capture then also occurs near the detector. Thus we expect the background to be highest for the Pb scattering experiment, smaller for ZrH_2 experiments and insignificant for the thin Ta foil experiment. This explains our observations for signal to background. No signal could be seen on the background for the Pb experiment where as for the Ta experiment the signal to background was actually better on the 403 keV line than on the 900-3000 keV band.

An overall comparison does favour BGO as it is possible to get as good a signal to background ratio with a higher signal countrate than the high resolution detector and it is less expensive and more convenient to use (e.g. doesn't need to be cooled). Also a coincidence detector system, made of several BGO detectors, can be used and may improve the signal to background. However, using boron to capture sample scattered neutrons put observation of (n,γ) lines at a disadvantage. The signal

to background may improve if it becomes possible to use large amounts of Li instead of boron or if the sample is far away from the detector.

5. DOUBLE DIFFERENCE EXPERIMENTS

Improvements to the resolution of a spectrometer using resonance absorption foils can be made using the double difference technique [2c]. This method involves making measurements with two thicknesses of analyser foil. At the edges of the resonance absorption peak, the cross section is small and so the absorption scales linearly with foil thickness. At the centre of the resonance peak the cross section is high and the absorption scaling is not linear, (the exponential nature of absorption as a function of thickness is now important). If the fraction thin foil thickness divided by thick foil thickness is β ($\beta \leq 1$), then scaling down the thick foil spectrum by β and subtracting it from the thin foil spectrum cancels out the absorption at the edges of the resonance peak and leaves a contribution at the centre of the resonance peak equivalent to a narrower resonance. Any background, no foil spectrum, will have to be removed from both thin and thick spectra. The double difference spectra is given by

$$\text{D.D.} = (\text{Thin}) - \beta(\text{Thick}) - (1-\beta)(\text{No foil})$$

The pulse width of the linac was 5 μs for the experiments. If a Ta analyser foil was used, E_{res} = 4.28 eV, the linac pulse width would give a 132 meV resolution contribution whereas for Sm, E_{res} = 0.872 eV, it would only give a 12 meV resolution contribution. Hence Sm was used. A ZrH_2 sample was used and the scattering angle was 15°. The BGO detector was used as it had a greater countrate and the γ ray energy band 900-3000 KeV was selected.

The experiments consisted of a background run (no foil), a thin foil run and a thick foil run. The thin Sm foil was 0.107 mm thick (51% absorption) and the thicker foil was 0.348 mm thick (90% absorption). Figures 3 and 4 show the raw TOF spectra for the thin foil and thick foil runs respectively. The first excitation in ZrH_2 can be seen in the thin foil spectrum before the main elastic peak whereas with the thicker foil the resolution is too poor to see it, as expected. Figure 5 shows the double difference spectrum converted onto an energy

transfer scale. This spectrum shows two excitations in ZrH_2, the first can be seen much clearer than in the case of the original thin foil spectrum. From the spectra we estimate that the single foil spectrum has a resolution of 100 meV which is improved to 75 meV for the double difference data.

6. HIGH Q EXPERIMENTS

Due to the low intensity of the Linac, most experiments were performed at high scattering angles (high Q) with the sample close to the detector. Experiments were performed investigating recoil scattering from liquid He and from hydrogen in ZrH_2 and V_2H. At large Q, the Impulse Approximation may be valid so that the scattering function depends only on the initial state of the atom, the final state and interference effects being negligible.

In metal hydrides we wish to study the momentum distribution of the hydrogen and so get information on the potential that it is in. For these experiments a Ta analyser foil was used, E_{res} = 4.28 eV and the scattering angle was around 45°. This gave a Q value ~ 50Å^{-1}. The BGO detector was again used selecting the gamma ray energy band 900-3000 keV. At this Q value the resolution of the spectrometer is not a problem as the H recoil scattering distribution becomes much broader than the instrument resolution. The TOF spectra for scattering from ZrH_2 with the background (no foil) spectrum removed, is shown in figure 6. The spectrum shows an elastic line from the metal a 365 μs and the broad recoil scattering from the hydrogen between 220 μs and 340 μs.

There is much interest in measuring the Bose-Einstein condensate fraction (zero momentum fraction) of the superfluid liquid He-II, particularly at large Q where the Impulse Approximation is valid. There is, however, a resolution problem as the scattering distribution from both the condensate and normal fractions of He-II are very narrow and so the instrument resolution must be kept to a minimum. The geometric arrangements of the moderator, sample and absorption foil cause variations in flight path length, scattering angle and so recoil energy of the He atoms. These variations cause a change in time of arrival of neutrons and can broaden a signal. The effect is particularly important for light atoms. Details of the theory of this

effect are given in [5]. Minimising this effect leads to a reduction in signal as the solid angles of the sample and detector foil are reduced. In this experiment a U^{238} analyser foil was used, E_{res} = 6.67 eV, and the scattering angle was 165° giving a Q value of 150$Å^{-1}$. An only 1 cm thick sample was used, ~ 2% scatter, as the time difference between scattering from the front and back of the sample also broadened the signal. Again the BGO detector was used with a gamma ray energy window of 1300-3000 keV. The effects of having a greatly reduced signal, a sample container that was a 4% scatterer and limited time available to investigate background, made obtaining a good signal to background ratio impossible. The statistics on the data made it difficult to determine if a He signal was present, however, some indications of how to improve the signal to background were made and it should be possible to improve the experiment on the SNS. Reference [6] gives more details of a similar high Q experiment performed on liquid He on the KENS neutron source.

7. SUMMARY

Initial development of the RDS at the Harwell Linac has proved helpful for the development of the eV Spectrometer on the SNS at RAL. Although the epithermal neutron intensity from the Linac is much lower than will be available from the SNS, useful information has been found.

Firstly the need for extensive screening of Pb shielding by B_4C plates in order to reduce the background caused by sample scattered neutrons. This put observation of specific (n,γ) lines from the absorption foil, most of which have an energy below the (n,γ) line for boron, at a disadvantage. This meant that wide high energy bands had to be selected and so a high resolution γ detector had no advantage over a low resolution detector. In fact low resolution detectors have an advantage as they are less expensive, can be more efficient and a multi detector coincidence system may improve signal to background even further. However, high resolution detectors must still be considered if the sample scattered neutron background is reduced by, for example, increasing the sample-detector distance or replacing boron with lithium which does not give off γ rays when it captures neutrons.

The double difference technique was shown to improve the resolution for the RDS system. Also several high Q experiments were performed on

metal hydrides and He. The lack of neutron intensity made it difficult to extract information from the experiments but the results indicate that we may be optimistic for similar experiments on the SNS.

References

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Experiment			Detector	Gamma ray Energy (KeV)	Signal to Background	Relative Signal Countrate
Sample	Scattering Angle (deg)	Analyser Foil				
Ta	—	—	BGO HPGe HPGe	900-3000 900-3000 400-405	54 69 82	1.0 0.47 0.02
Pb	60	Ta	BGO HPGe HPGe	900-3000 900-3000 400-405	3.95 3.73 —	1.0 0.25 $\leq$ 0.02 (1)
ZrH_2	10	Ta	BGO HPGe HPGe	900-3000 900-3000 400-405	1.73 1.87 —	1.0 0.41 — (2)
ZrH_2	10	Sm	BGO HPGe HPGe	900-3000 900-3000 330-335	1.36 1.67 1.8	1.0 0.59 0.14

(1) No signal could be seen above the background

(2) Countrate too low to make measurements.

TABLE 1 Comparison of BGO and HPGe Detectors

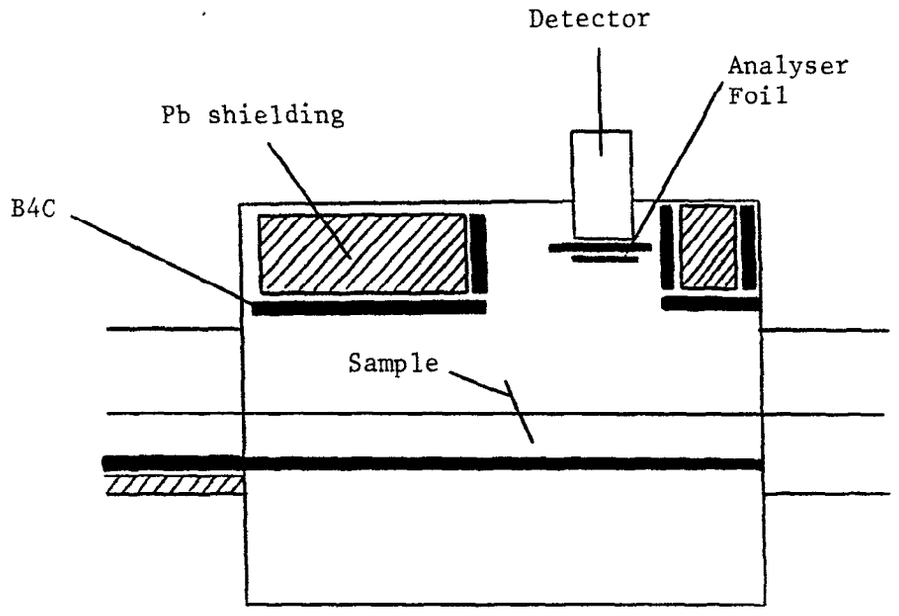

Figure 1a Internal shielding for scattering at 60°

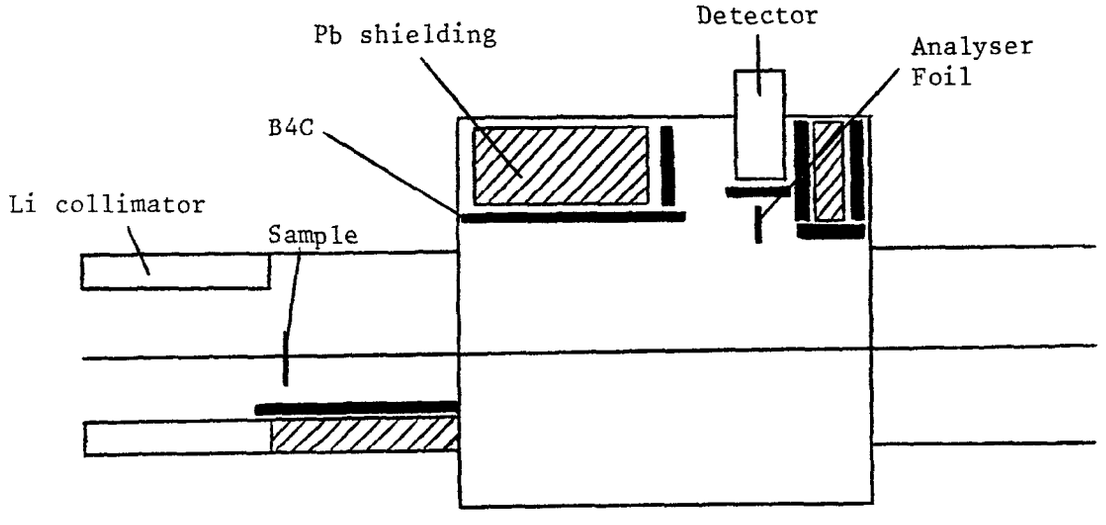

Figure 1b Internal shielding for scattering at 15°

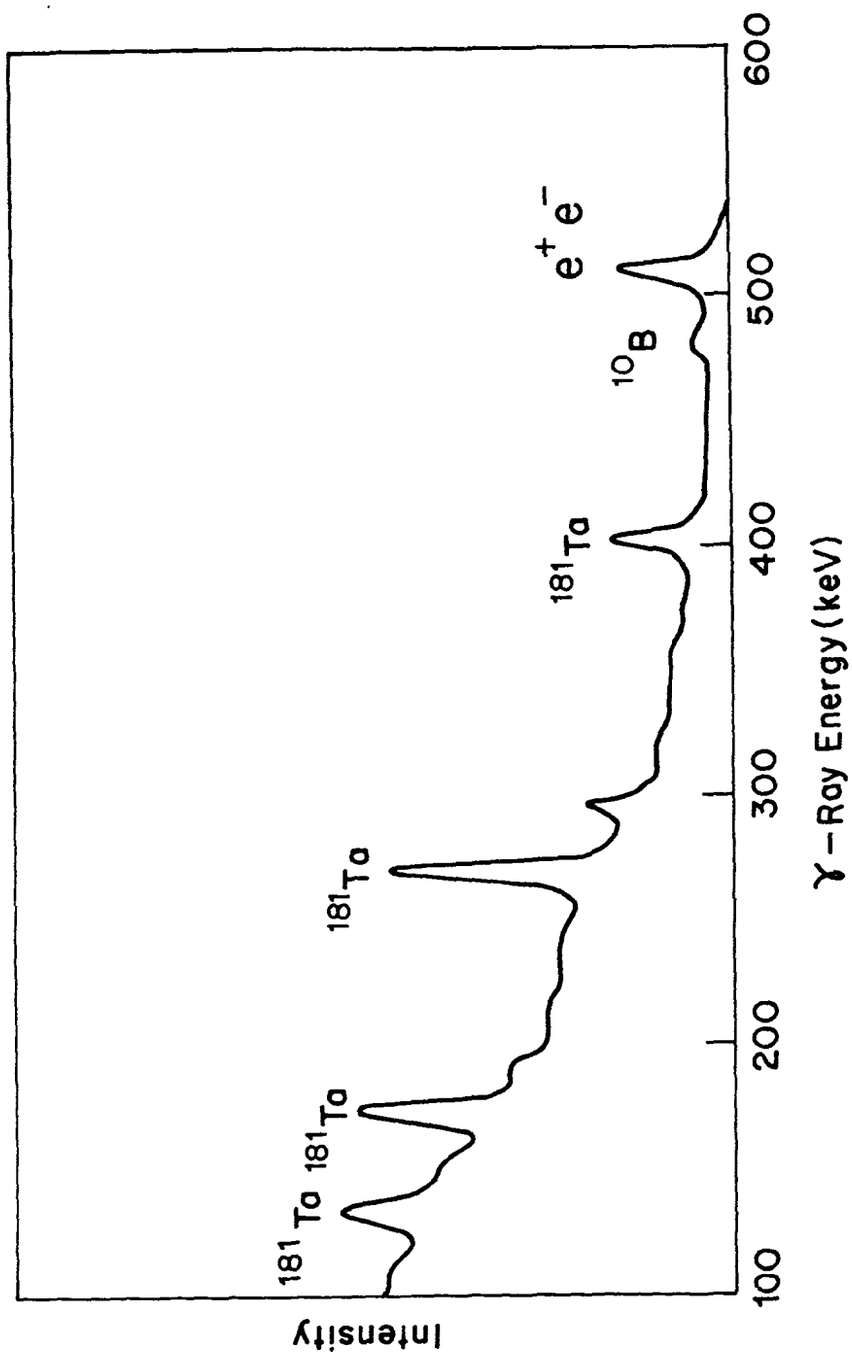

Figure 2 γ-ray Spectrum for neutron capture by Ta

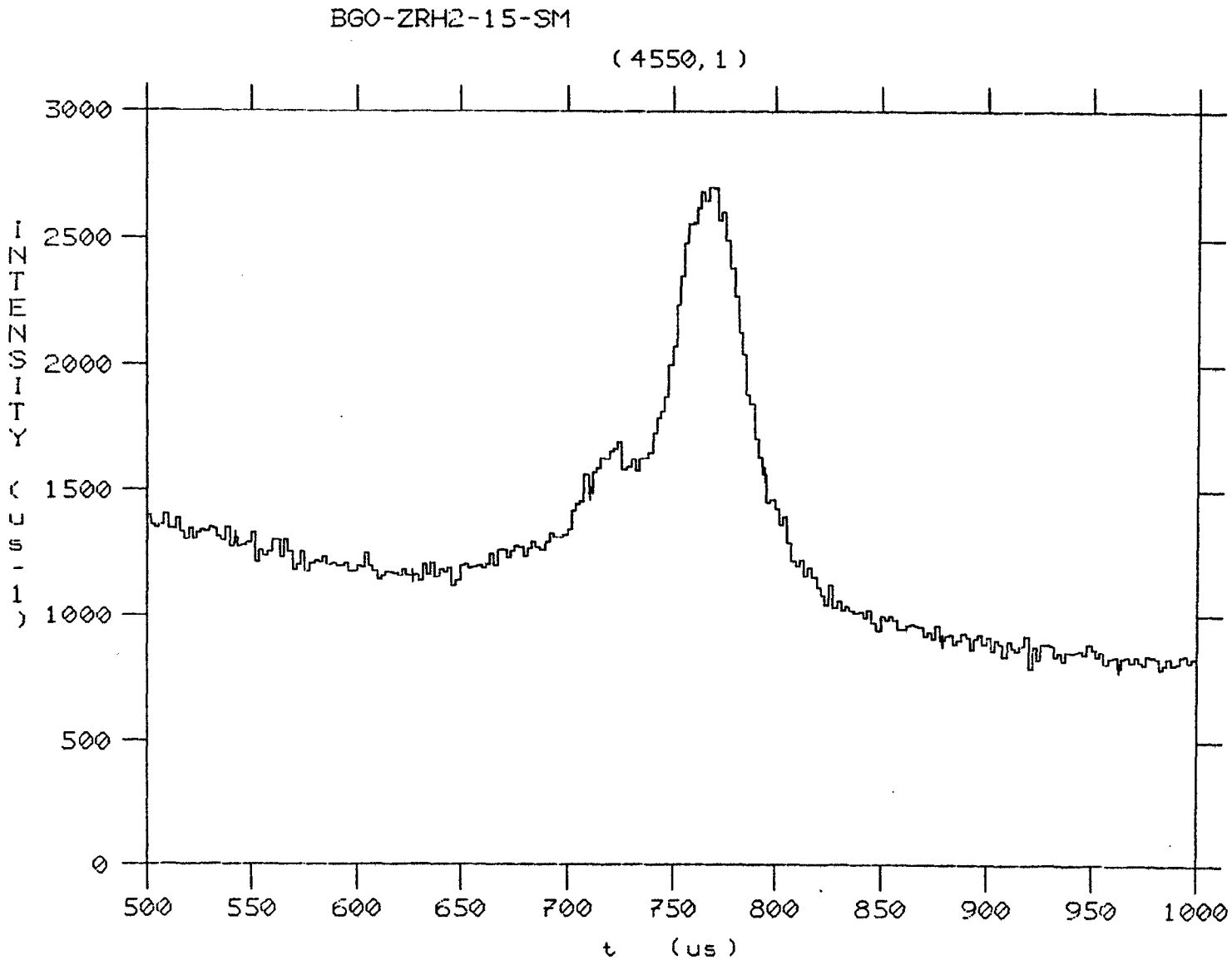

Figure 3 Scattering from ZrH2 at 15° using a thin Sm foil

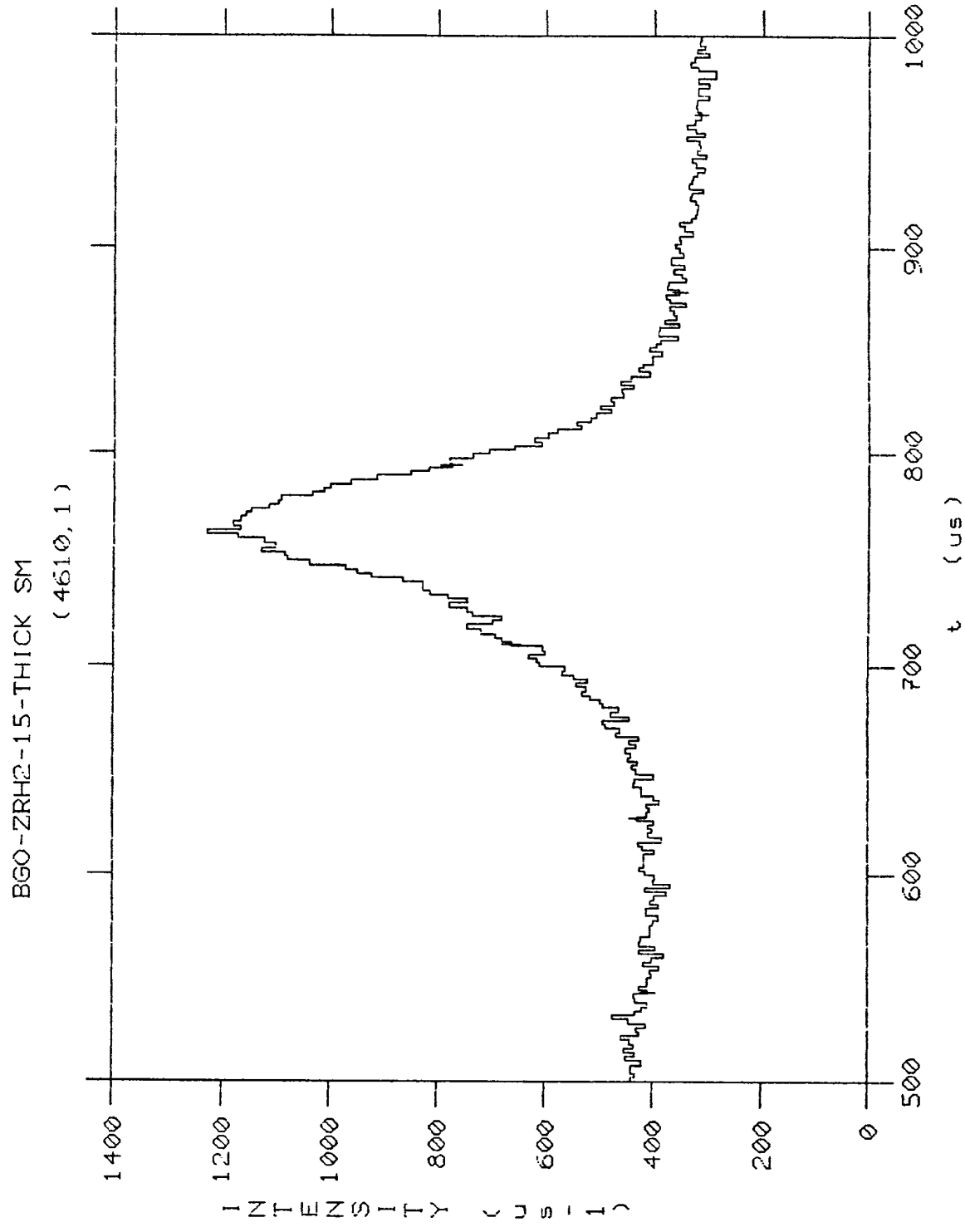

Figure 4 Scattering from ZrH2 at 15° using a thick Sm foil

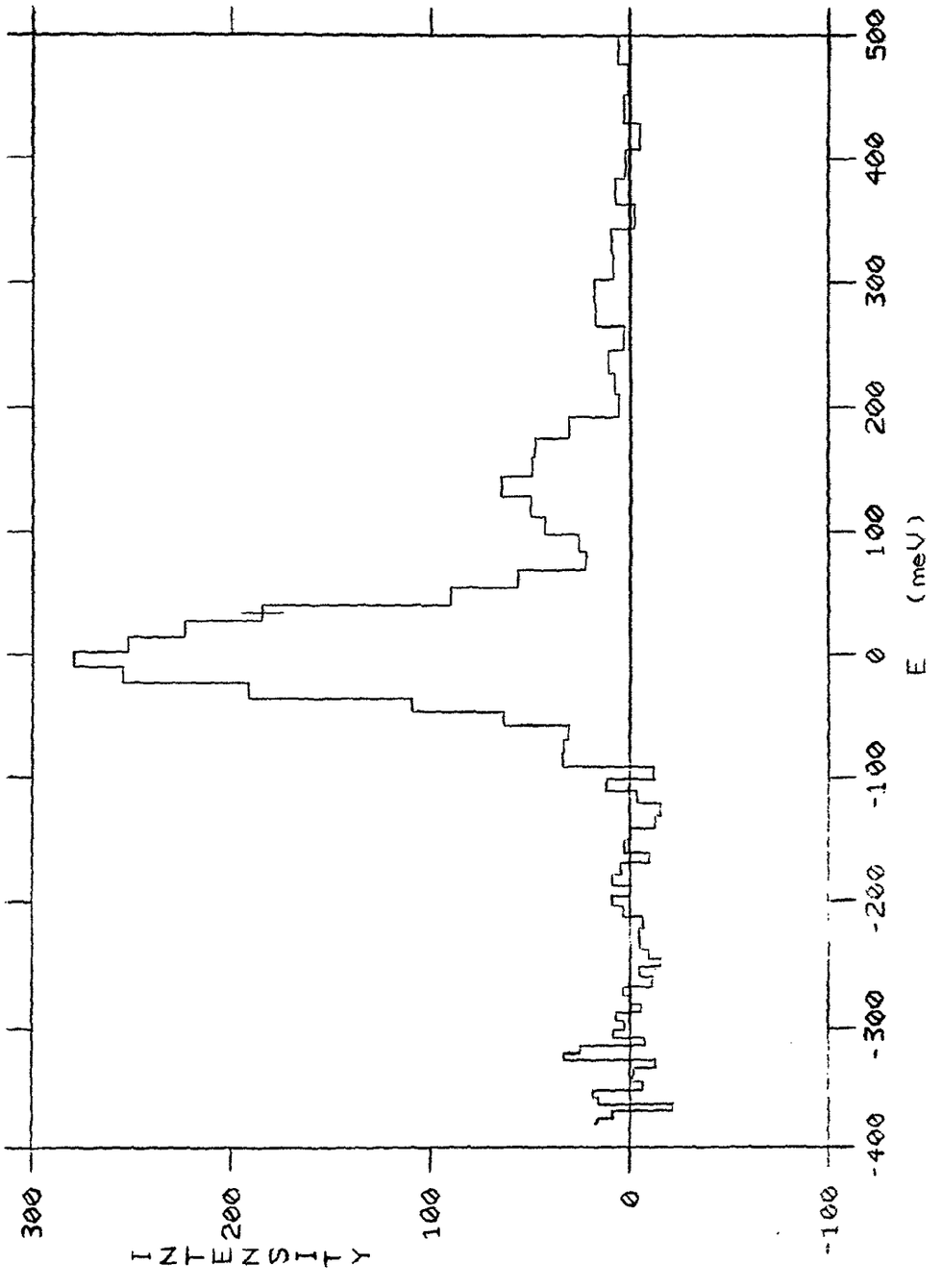

Figure 5 Double difference spectrum for ZrH_2 using Sm analyser foils.

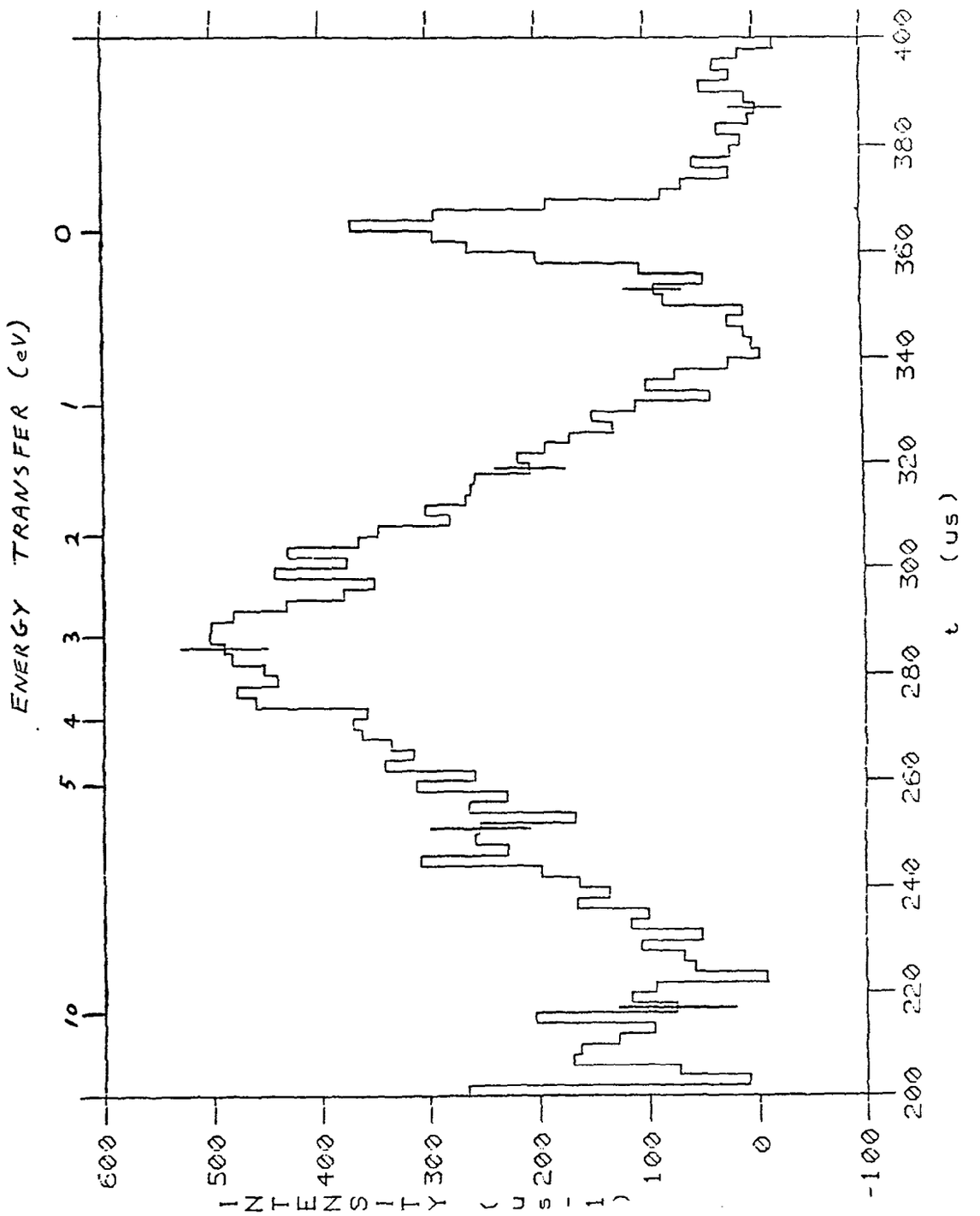

Figure 6 Scattering from ZrH_2 at 45° (Background subtracted)