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Remote Temperature Measurement Using Resonant Epithermal Neutrons and the Need for a Compact Pulsed Source

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My work in this area arose out of a visit I made to Rolls Royce in Spring 1984 to see how the Bristol University Physics Department might play a part in the developments in Rolls Royce. A need for a non-invasive measurement of temperature of critical parts of aero-engines while running was stressed upon me. As a result a test exposure was made in September to epithermal neutrons at Los Alamos by Dr. A.D. Taylor of Rutherford Appleton Laboratory (RAL) and myself using test specimens of Tantalum and a high temperature alloy MARM 002 that contained W, Ta and Hf in suitable proportions. The specimens were held in an evacuated instrumented oven - and held at several temperatures up to 1,000^{o}K.

As an introduction to results we obtained from these test exposures Fig. 1a sketches the main components of the beam line, and Fig. 1b shows a typical time of flight spectrum with a thin tantalum foil in the oven that was in this case at room temperature. The most prominent feature at 1111μsec corresponds to the 4.28eV tantalum resonance, and that at 718μsec to the 10.6eV resonance. Many of the remaining features are due to cadmium in the beam line employed to remove thermal neutrons - the strongest being at 440 sec. Figure 2 shows the effective cross section for the 4.28eV tantalum resonance for five different temperatures spaced by 200^{o}K. The effect of temperature is due to the well known phenomenon of Doppler broadening which is pronounced on the intrinsically narrow resonances of the heavy elements. Also shown is the difference in cross section for a change of 200^{o}K in temperature. The sensitivity to temperature change takes the approximate form of the second derivative of the cross section with energy. Two of the main measurements are displayed in Fig. 3 which shows time of flight spectra at two temperatures using 8mm of MARM 002 as the specimen. Direct comparison with Fig. 1b shows at once the presence of many additional deep resonances due to the hafnium and tungsten, as well as those due to the tantalum in the specimen. However casual inspection of the two spectra

shows little obvious difference with temperature. The differences can however, be vividly revealed by dividing one spectrum by the other bin by bin. Clearly, if nothing had changed, the ratio should be a constant, and unity if the exposures were the same. What is seen is displayed in Fig. 4a. Each well separated resonance is replaced by the form indicated in Fig. 2b, and the effects are quite large - in some bins up to a factor of two either way. Fig. 4b shows an enlarged version of the 1.10 eV Hf^{177} resonance, together with the counting errors in each bin. Our analysis of this resonance yields an estimated accuracy ΔT of $\pm$ 11°K, which is reduced to $\pm$ 5°K when one includes the information contained in the other resonances. The six most informative resonances are tabulated below, two pairs overlap and each yield one estimate.

TABLE

E_o eV	Nuclide	Flight time μ sec	μ_o Attenuation lengths	ΔT °K	
1.10	Hf^{177}	2194	2.4	$\pm$ 11.1	
2.38	Hf^{177}	1489	4.9	$\pm$ 10.4	
4.16	W^{182}	1127	5.6	$\pm$ 8.3	Overlapping
4.28	Ta^{181}	1111	14.6		
7.65	W^{183}	831	2.2	$\pm$ 14.2	Overlapping
7.78	Hf^{178}	824	8.0		

μ_o is the number of attenuation lengths that the specimen presented at the centre of the resonance in the absence of any Doppler broadening.

The temperature measurements described above are in detail the mean temperature of the atoms of the particular nuclide that forms the resonance, the mean being taken over the neutron path. If, say, tantalum is present in a blade - and not in any other material in the beam - the temperature applies to the blade only. If, for a special purpose, one was allowed to coat several particular surfaces one could get several temperature measurements from the same exposure for each pixel. Such a case might occur, for example, for a static blade in an engine where one could use for the front surface Hf, for the inside of the air vents Re, and the rear Pt; with the blade itself containing W and Ta one could form a potentially most informative picture of the temperature distribution.

The detector employed in the measurements was 15 metres away from the oven as shown in Fig. 1, thus the measurements outlined briefly above met the requirement of a "remote and non-invasive temperature measurement", and we viewed the specimen through about 2 cm of stainless steel. The accuracy of temperature assignment demonstrated was $\sim \pm 5^{o}K$ at all temperatures covered $\sim 300^{o}$-$1000^{o}K$.

At Los Alamos each time of flight spectrum took us about 8 hours to accumulate, a feature which must be remedied. A higher neutron flux and an improved detector are clearly called for. During the early commissioning phase the SNS will give us more neutrons than were available at Los Alamos in 1984. (Considerable enhancement has also taken place there in the intervening period), and that will increase by a further factor approaching 10^{2}. The SNS at the Rutherford Appleton Laboratory can provide us not only with adequate neutron fluxes, but also with an ideal environment for the development of the technique so as to prove (or otherwise!) its practicability.

With regards to the detector system - much must be done to improve performance. For a start I am proposing an instrument based on scintillators whose form is as approximated in Figs. 5 and 6. The initial specifications I have in mind are along the following lines:-

a) A high neutron count rate capability - initially at an instantaneous rate $> 10^{5}$/sec in each independent detector element - i.e. $> 10^{2}$ neutrons per pulse per detector. This should be increased to $\sim 10^{6}$/sec for the next phase.

b) A reasonable position sensitivity $\sim \pm$ 1mm FWHM for both Δx and Δy. Δx is given by the partition of light between the pairs of photomultipliers that view each scintillator. Y is determined from the actual detector in which the neutron is in fact captured. With a scintillator thickness of 1 mm the effective value of FWHM for Y is $\sim$ 0.8 mm. The white device will have $\sim$ 2000 such pixels.

c) The expected good time resolution for each neutron giving an energy estimate accurate to one part in 1000.

d) Adequate defences against background γ-rays from the target - delayed by β-decay. To this end Li^{6} is superior to glass scintillators as a neutron has the same pulse height as an electron of $\sim$ 4 MeV. In the glass the neutron appears similar to an electron depositing an energy of $\sim$ 1 MeV only.

This brings me to the second part of this talk. There is an additional constraint that Rolls Royce feels to be essential. If this technique - or any related one - is to be of quite widespread use in Industry - then the neutron source must be where the work is - and not the other way round. This implies

for Rolls Royce that the neutron source be

compact and possibly mobile

cheapish

and be sited at Bristol and/or Derby.

The SNS does not appear to approach this Rolls Royce wish! But is there a possible system when one tailors the accelerator to meet the main requirement. The SNS is designed to produce $\sim 4.10^{16}$ neutrons/sec. I believe that a yield $\sim 10^{14}$/sec of pulsed epithermal neutrons would be of great use. It is however the brightness of the neutron source (n/cm^2.sec.sterad.) that is the most important characteristic - and not the yield.

In Fig. 7 I give a rough sketch of a possible compact system for producing a suitable neutron beam. The following comments apply to the various elements:-

a) In the accelerator area one has the choice of energy, the higher the energy the better the figure for joules/neutron that is to be traded off with the increase of cost and size with energy. Deuterons must also be considered for their higher neutron yields at a given speed and their lower sensitivity to synchrotron stripping of the negative ion.

b) To get the pulsed beam a storage ring may be necessary, separated as suggested in the figure, but also the storage could be made in the outer regions of the accelerator. The maximum storable current increases with increasing energy. The amount of storage required is reduced if one can operate at $\sim$ 1 kHz which is possible if a short flight path D $\sim$ 10 m is satisfactory. As drawn in Fig. 7 a superconducting cyclotron offers the possibility of a compact accelerator.

c) In the target and moderator areas the difference in emphasis occurs because of the need for a bright source. With any energy $\lesssim$ 100 MeV the range of the accelerated beam in the target is small, say $\lesssim$ 1 cm. This enables the moderator to be well coupled to the target. The neutrons are peaked forward at production which helps. So possible target materials are, say, Li or Be for either D or low energy H beams, and perhaps U if a higher energy is chosen - say, $\gtrsim$ 40 MeV.

d) The moderator needs to have as high a figure as possible for the density of H, possible materials that come to mind are VH_2, dense polyethylene or solid unbranched paraffins, or even $N_2H_4.H_2O$. With the much lower energy input heat problems for the moderator should not be a problem so that the overall H density can remain high. The desired energy band for which one is aiming to optimise the brightness is $1 < E < 100$ eV, and not thermal energies, so the amount of moderator necessary is not as large as in the SNS systems.

e) One is also aiming to feed one beam line only so reflectors of say, natural Ni (or even Ni^{58}) all around the moderator will help. The neutrons enter the moderator with E $\sim$ 1 MeV where the cross section is low ($\sigma\sim$ 3 barns), and after a few collisions on H their energy is ideally so reduced that the "reflector" has become efficient - as the cross section of Ni is $\sim$ 17 barns. The reflector may also with advantage incorporate a thin layer of Mn, V and Co to take advantage of their very large resonant scattering cross sections in the range $100 < E < 20000$ eV.

f) Outside the nickel reflector U^{238} could usefully be employed as an additional blanket, especially in the beam direction where most of the high energy neutrons go, to help the neutron economy by fission.

The aim of this neutron system when feeding an appropriate detector is to give an exposure E_x given by

$$E_x \sim 10^7 \frac{dE}{E} \quad \text{detected neutrons/cm}^2,$$

in a "reasonable" time, say, $< 10^3$ sec,

with an angular spread at the detector $\theta_{max} < 10^{-3}$ radians,

and with a flight path D $\sim$ 10 metres.

A yield from the target of N neutrons/sec should produce a moderated spectrum at the exit slit of:

$$dN_E = \frac{N}{18} \cdot \frac{f g}{4\pi^2 a^2} \cdot \frac{dE}{E} \quad \text{neutrons/cm}^2\text{.sec.ster},$$

where $4\pi a^2$ is the surface area of an assumed spherical moderator, with a $\sim$ the RMS migration of a neutron in moderation to $\sim$ 10 eV, the factor 18 normalises the dE/E spectrum from thermal energies to 1 MeV, the extra π is of course the effective number of steradians fed by the output, and the factors f and g are "fudge factors".
The factor f is concerned with the coupling of the target to the moderator and allows both for the forward peaking of the neutrons and for the penetration of a fraction without interaction. The factor g applies to the moderator and its coupling to the exit slit, it represents the enhancement over a spherical moderator due to the Ni reflectors, for losses due to escape and capture, and for an extra contribution to the neutrons from fission in the uranium blanket backing up the nickel. A plausible range for each of the factors f and g seems to be $1 \lesssim f, g \leq 3$.

To meet our requirements at the detector, we must restrict the aperture to $\theta_{max}^2 D^2$ cm^2 if D, the flight path, is measured in centimetres; the value for the solid angle is then fixed at $1/D^2$ per cm^2 of detector. Thus at the detector we can expect to have

$$dN_d = \theta_{max}^2 \frac{N}{18} \frac{f\,g}{4\pi^2 a^2} \frac{dE}{E} \quad \text{neutrons/cm}^2\text{,sec.}$$

Substituting $f = g = 1$, $N = 10^{14}$, $\theta_{max} = 10^{-3}$ and $a = 4$ cm,

we obtain as an approximate estimate for the neutron flux at the detector;

$$dN_d \sim 10^4 \frac{dE}{E} \quad \text{neutrons/cm}^2\text{,sec.}$$

Thus we could hope to meet our target exposure E_x in a time of less than 1000 seconds. Such an exposure would - with a suitable specimen - give temperature estimates accurate to $\pm 5^{\circ}$K for each cm^2. Clearly, there is considerable work to do so as to approach the most suitable system - and realise a practical compact pulsed neutron source. I believe these aims to be within reach, and if so the system could have quite widespread use. I therefore invite your comments.

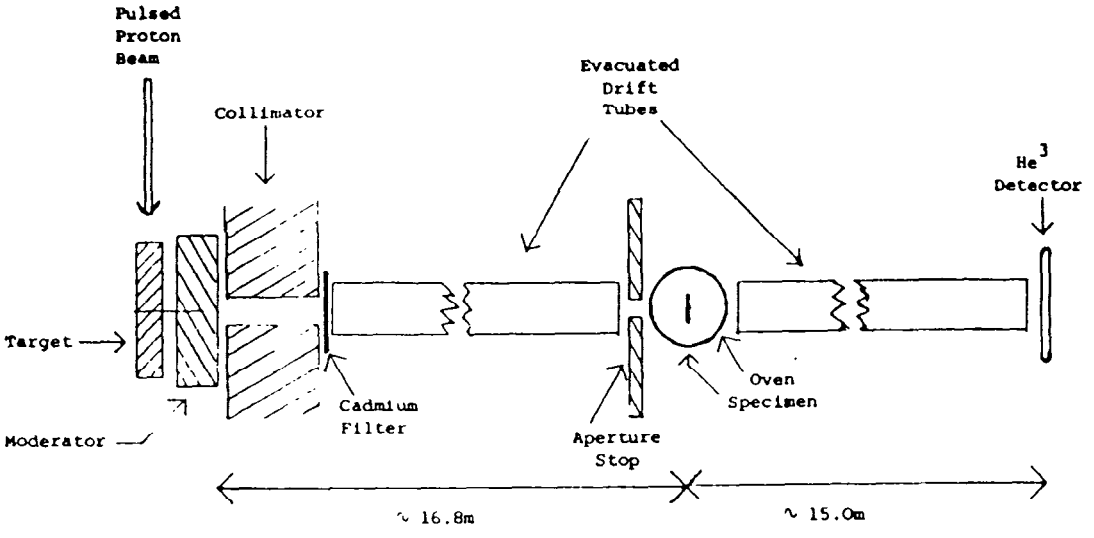


Fig. 1a Sketch of the experimental arrangement used at Los Alamos

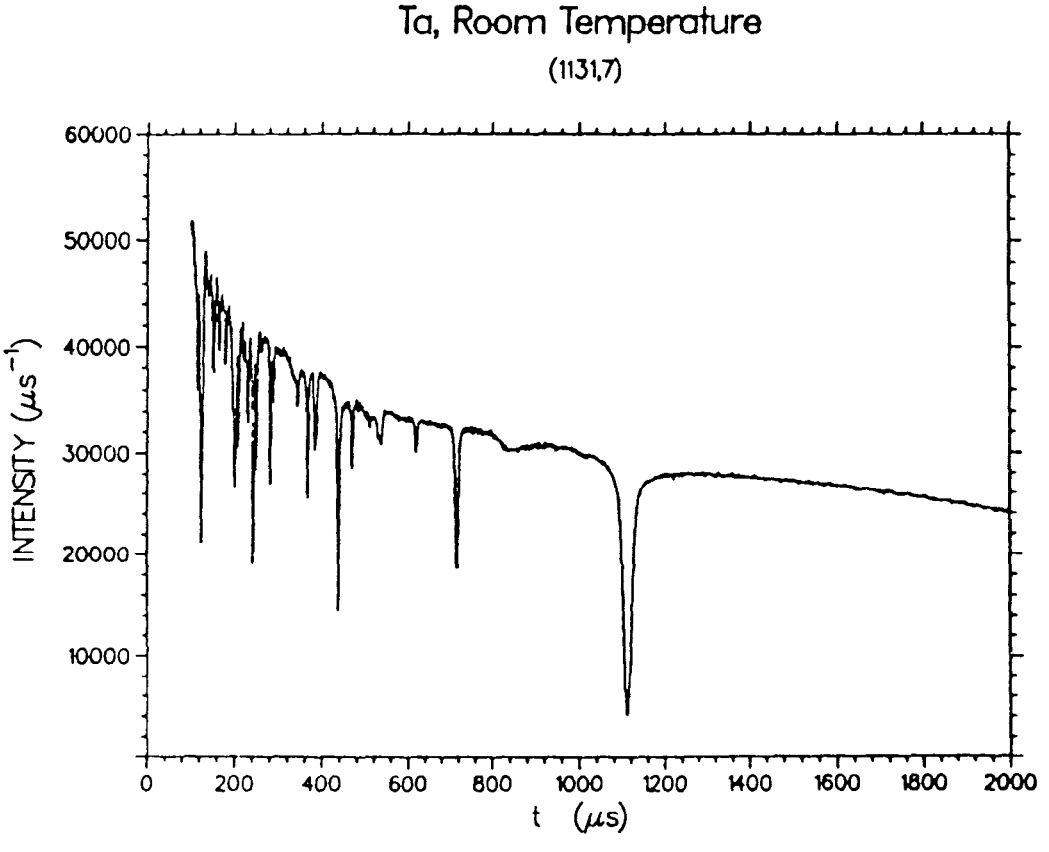
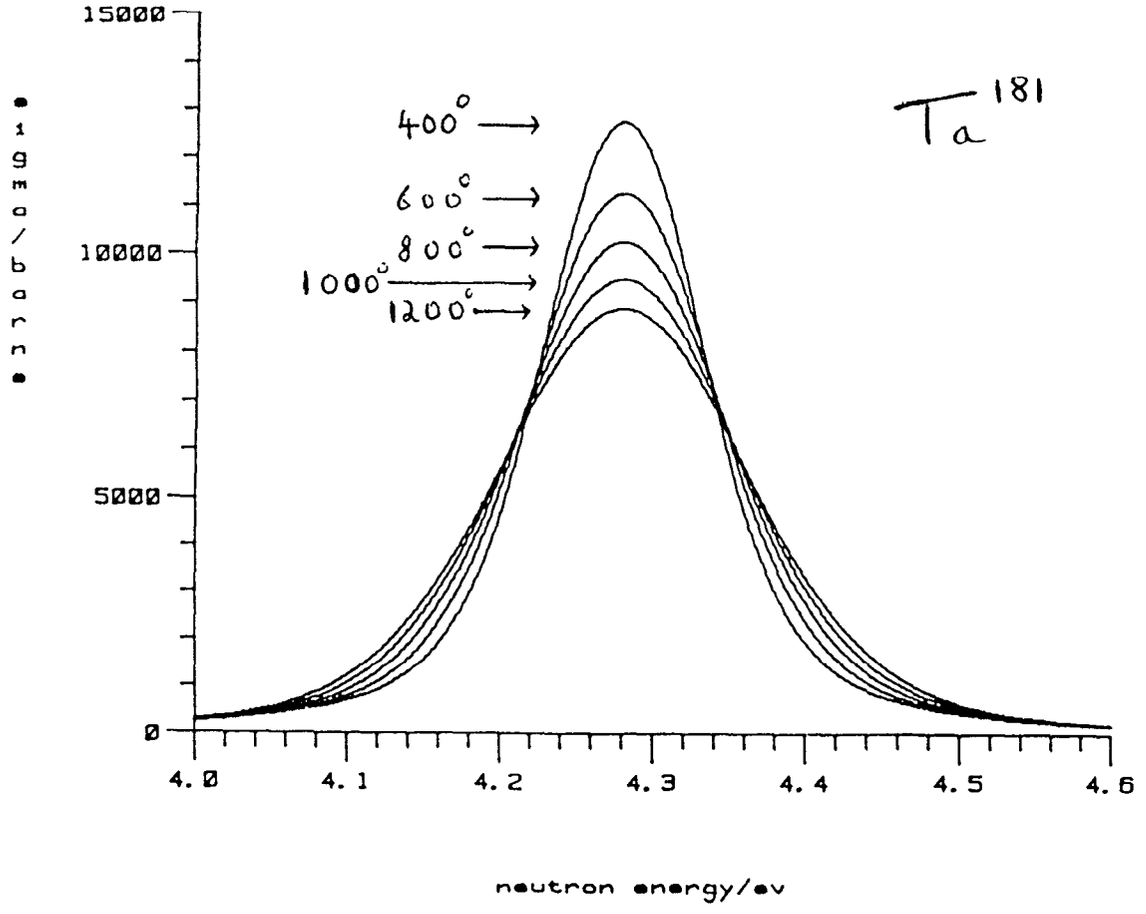


Fig. 1b The time of flight spectrum using a thin (27 μm) Tantalum foil



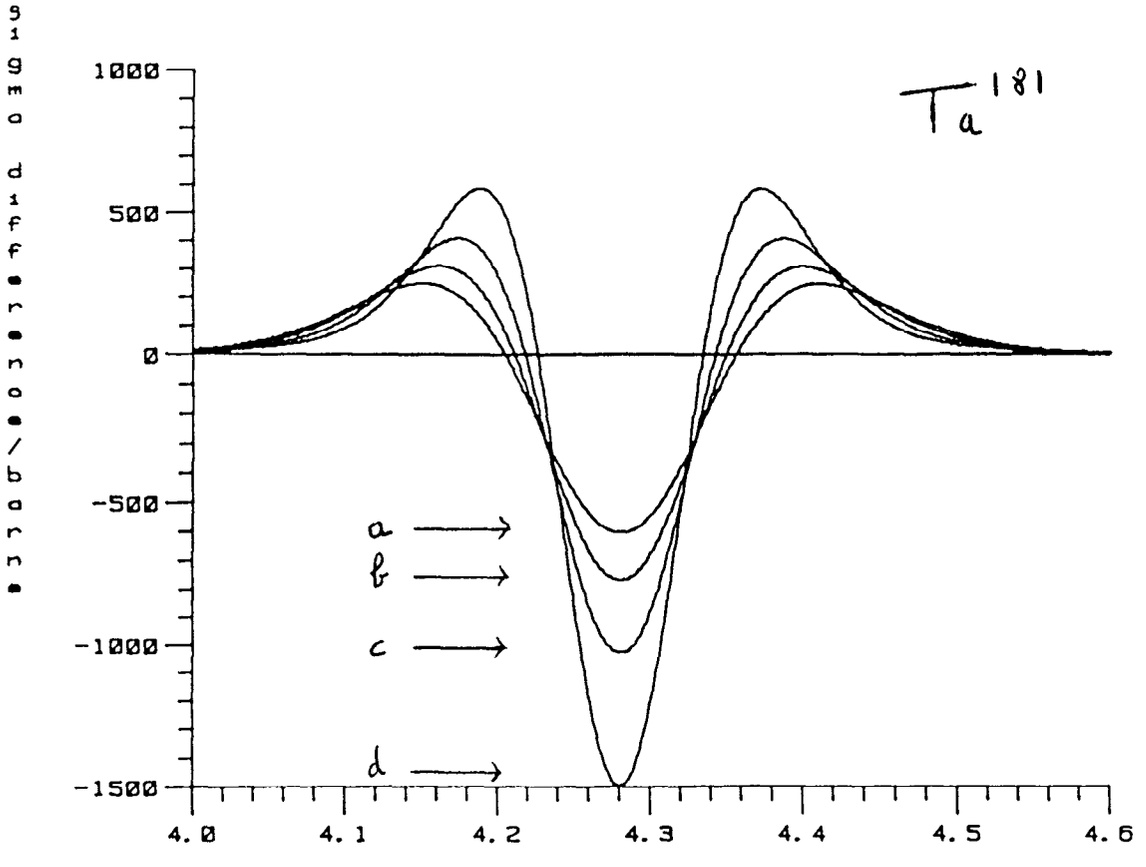
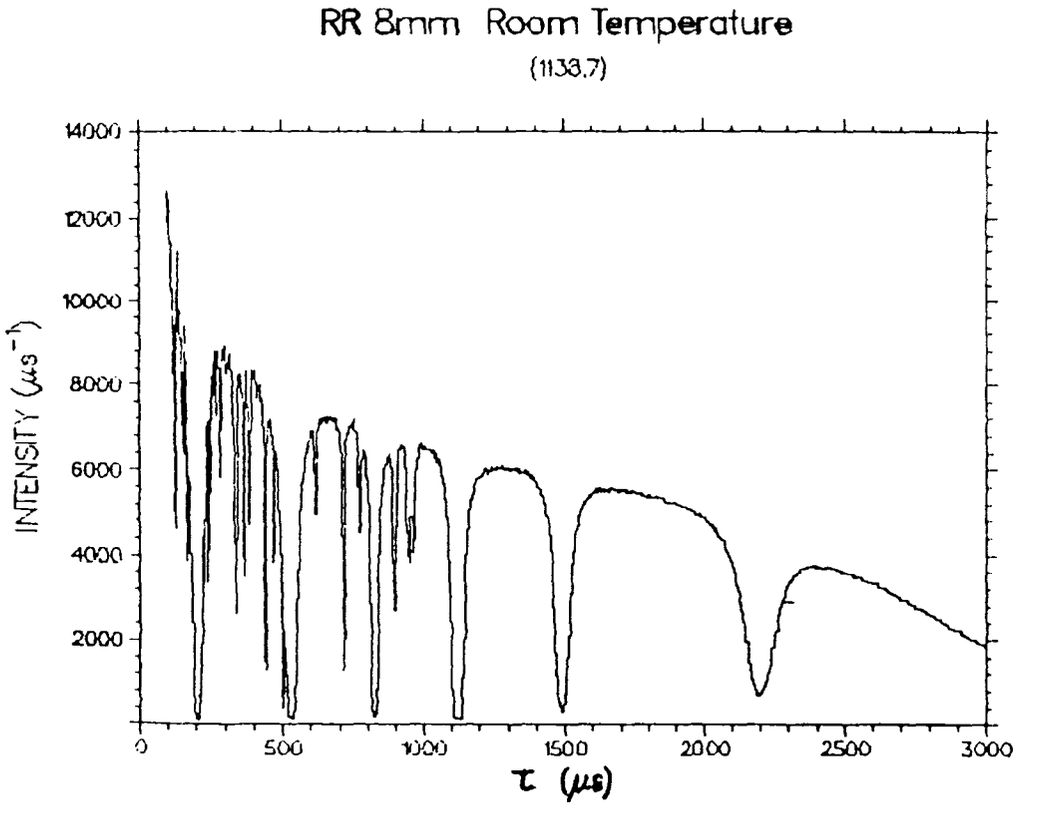


Fig. 2a,b Computed cross sections at 5 temperatures for the 4.28 eV Tantalum resonance, and the change in cross section for successive 200°K temperature increases.



INTENSITY VERSUS DRIFT TIME

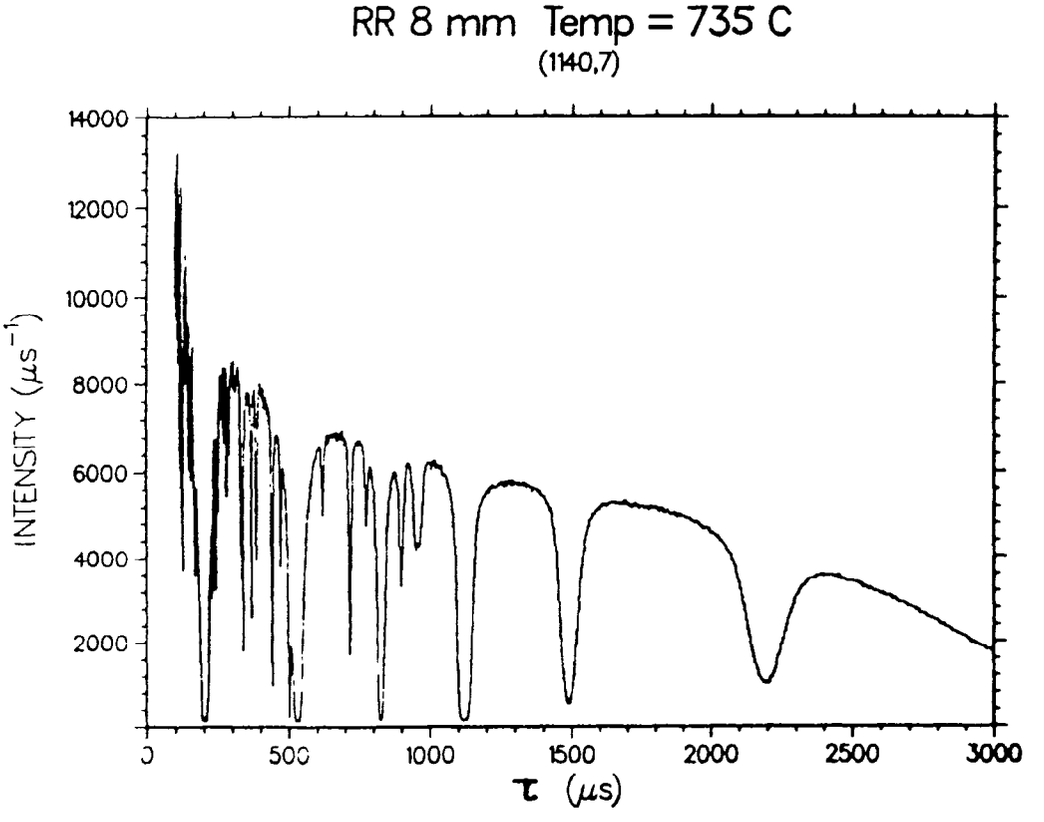


Fig. 3a,b **Time of flight spectra at 20°C and 735°C using 8 mms of MARM 002**

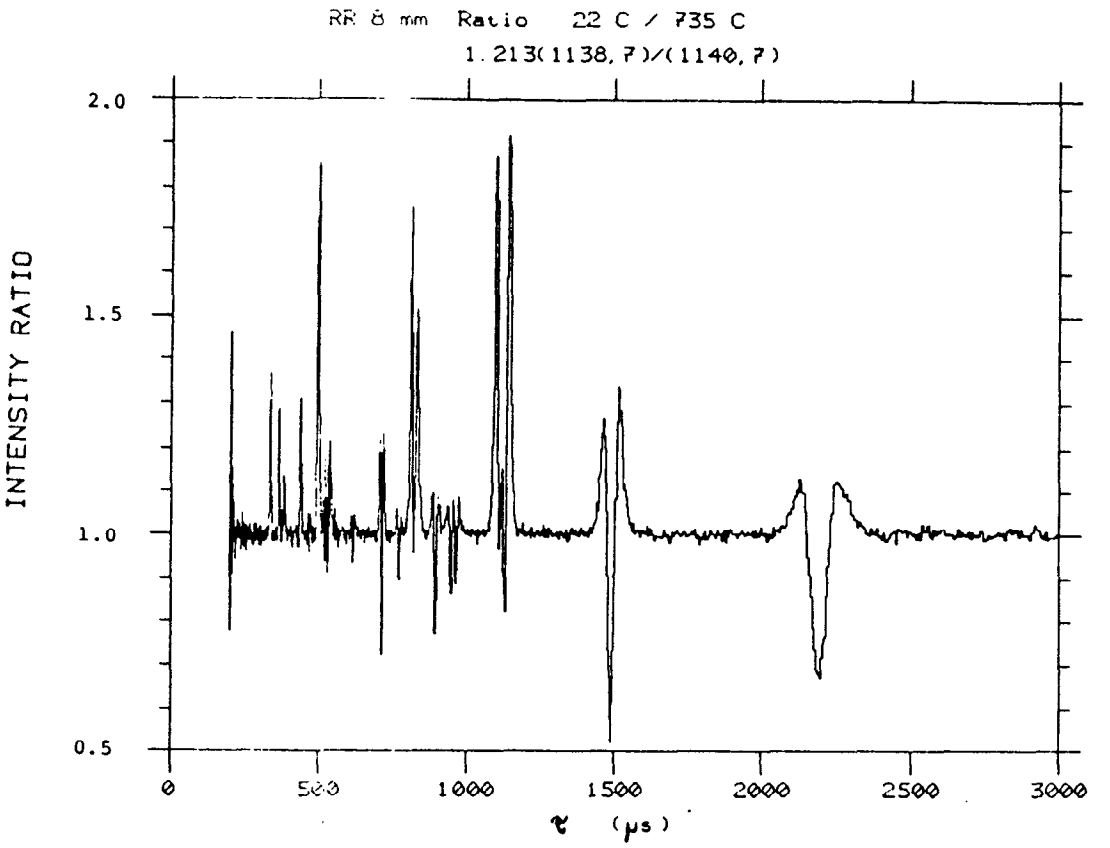


Fig. 4a The intensity ratio versus time of flight from the data given in Figs. 3a and b.

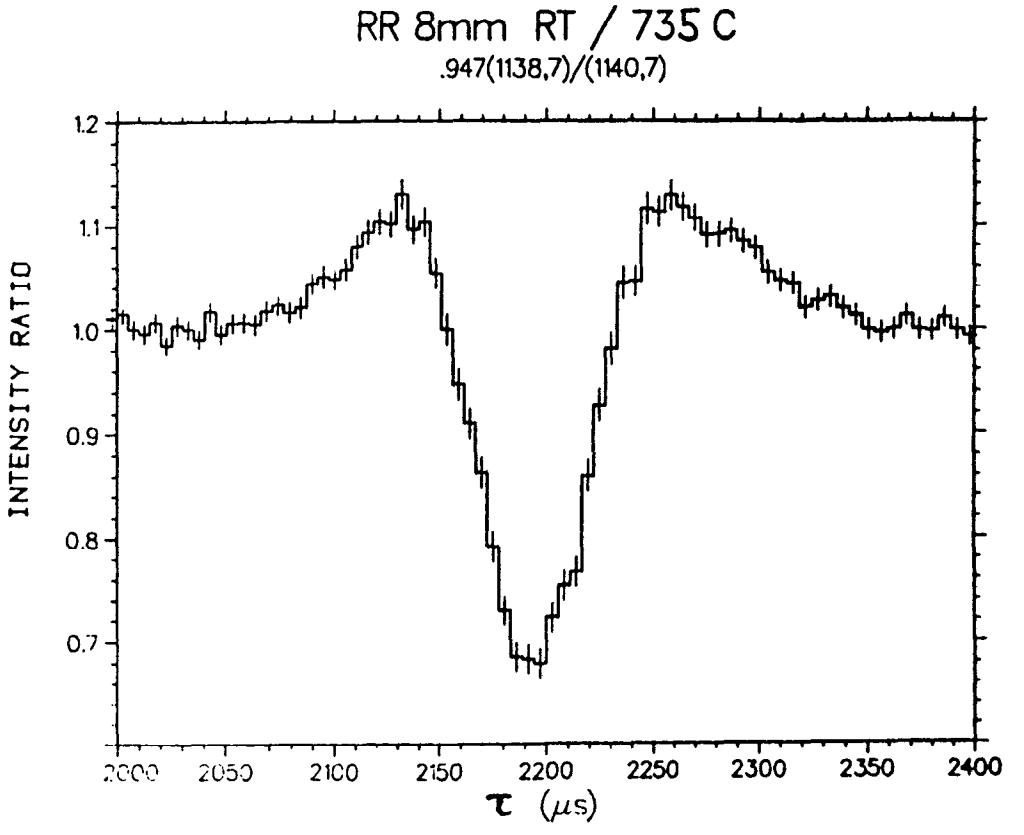


Fig. 4b Details of the intensity ratio from Fig. 4a above for the resonance at ~ 2200 μsec due to Hf^{177}. Statistical errors are given for each bin.

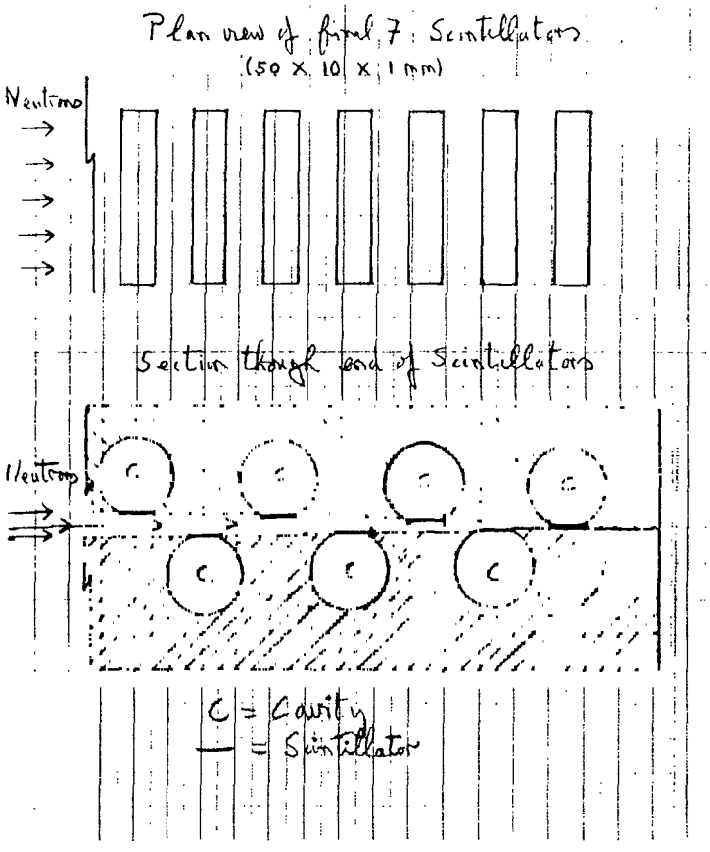


Fig. 5 The plan and side views

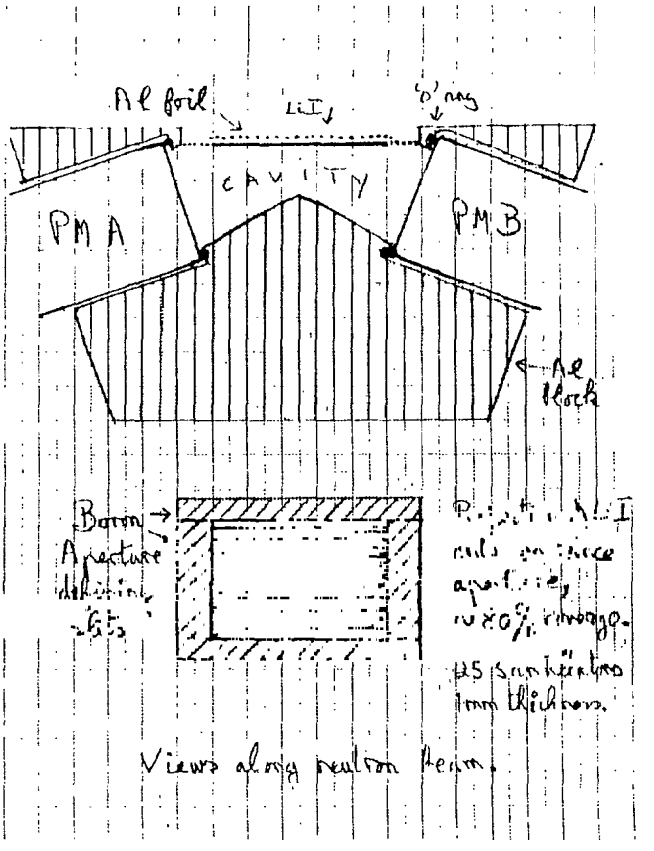


Fig. 6 Two sections as viewed along the neutron beam axis

Figs. 5 and 6. Suggested arrangement for an efficient positional sensitive epithermal neutron detector based on scintillators

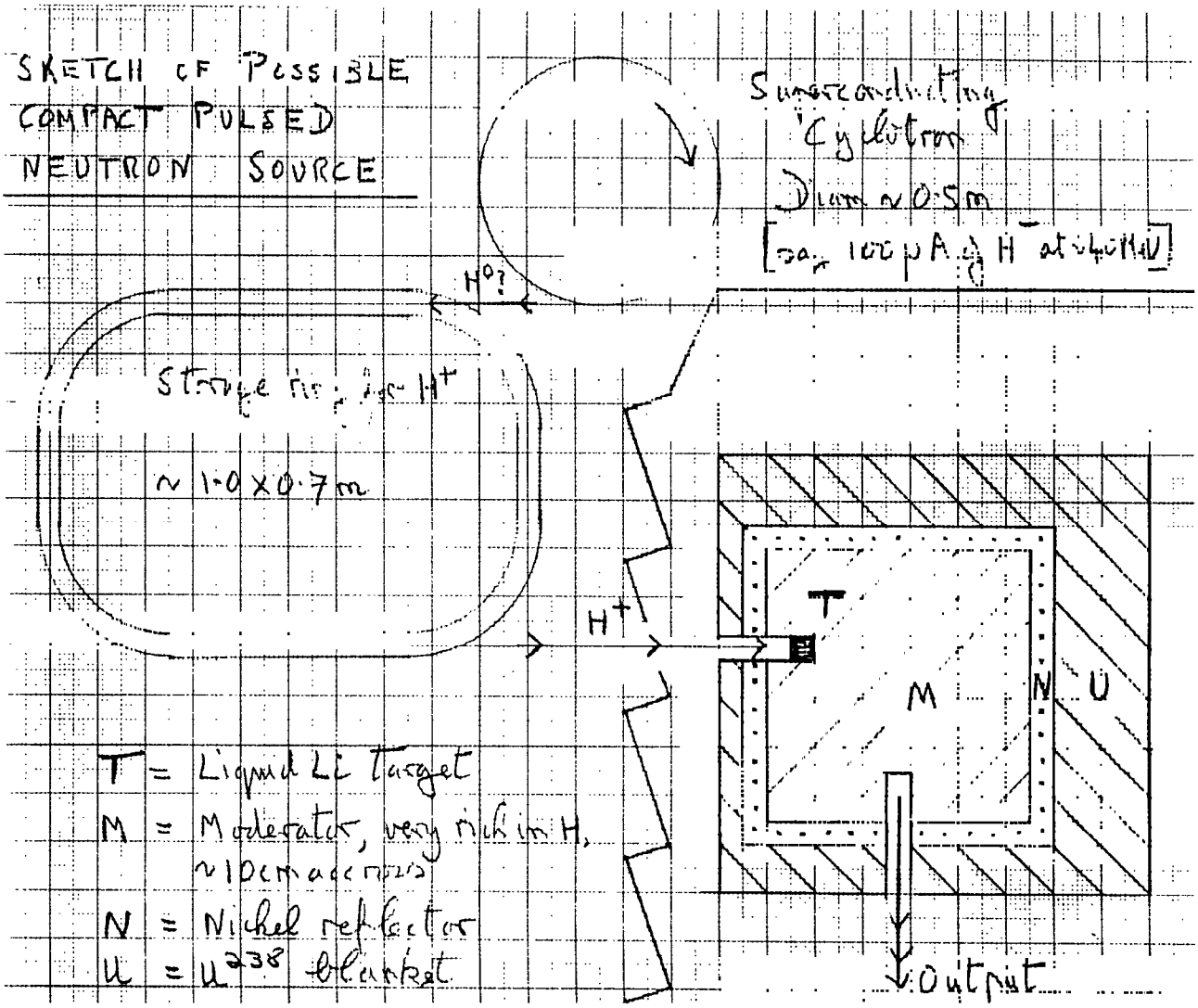

SKETCH OF POSSIBLE
COMPACT PULSED
NEUTRON SOURCE
Superconducting
Cyclotron
Diam ~ 0.5m
[ca. 100 μA of H⁻ at 4 MeV]
H⁰?
Stripper for H⁺
~ 1.0 × 0.7 m
H⁺
T
M
N
U
T = Liquid Li Target
M = Moderator, very rich in H,
~ 1 Dem accuracy
N = Nickel reflector
U = U²³⁸ blanket
Output

FIGURE 7