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ABSTRACT

As part of the design effort for a 14 MeV neutron spectrometer for the Joint European Torus (JET), computer codes were developed to calculate the response of a proton recoil telescope comprising a proton radiator film mounted in front of a proton detector.

The codes were used to optimise the geometrical configuration in terms of efficiency and resolution, bearing in mind the constraints imposed by the proposed application as a JET neutron diagnostic for the Deuterium-Tritium phase. A prototype instrument was built according to the optimised design, and tested with monoenergetic 14 MeV neutrons from the Harwell 500 keV Van de Graaff accelerator. The measured energy resolution and absolute efficiency were found to be in acceptable agreement with the calculations. Based on this work, a multi-radiator production version of the spectrometer has now been constructed and successfully deployed at JET.

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INTRODUCTION

With a proton recoil telescope, one can obtain a high resolution measurement of an intense neutron source, without the complexity associated with a time-of-flight spectrometer. The principle of operation is shown in Fig.1. Neutrons irradiate a thin polyethylene film or ‘proton radiator’, and knock protons out by elastic collisions. The energy distribution of the ejected protons is measured in a semiconductor detector, and the original neutron energy distribution is deduced. For work with 14 MeV fluxes, the detector has to be protected from the neutron beam, for example by placing it behind a shield or shadow bar. A vacuum vessel, not shown in the Figure, encloses the proton radiator and detector.

The out-of-line scattering geometry of arrangement (a) in Fig.1 is straightforward to implement and provides good spatial resolution, but the efficiency of the annular geometry shown in (b) is greater (assuming that it is not possible to use a complete ring of detectors in arrangement (a)).

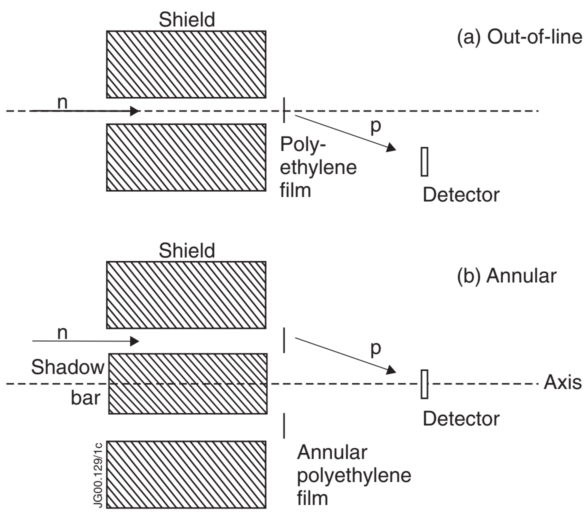

Fig.1: Principle of Proton Recoil Telescope

The relatively sharp resolution of these devices arises from the limited range of n-p scattering angles that can result in a proton hitting the detector. A smaller or more distant radiator gives better resolution, but also reduces efficiency. Likewise a thinner radiator gives better resolution because the protons (which are born uniformly throughout the radiator) encounter a smaller range of radiator thicknesses as they emerge, and their energies are therefore subject to a smaller range of decrements. However, the number of scattering events is of course smaller. Hence in the design of a proton recoil telescope it is necessary to trade efficiency against resolution to achieve the best compromise.

DESIGN TARGETS

In order to obtain useful information from the JET neutron flux over an acceptably small time interval, the specification called for an energy resolution of 2.5% or better in the range from 13 to 15.5 MeV, and an efficiency of about 10^{-4} counts $n^{-1}cm^{2}$. It was soon clear that the greater efficiency of arrangement (b) would be necessary, and furthermore that no configuration with just a single radiator-detector pair would be able to meet both targets simultaneously. It was therefore decided to base the design on three identical radiator-detector modules placed one behind the other, each of which would require a resolution of 2.5% and an efficiency of about 3.3×10^{-5} counts $n^{-1}cm^{2}$.

CALCULATIONS

In order to find a configuration capable of meeting these demanding criteria, we wrote computer programs to calculate the efficiency and resolution of a proton recoil telescope with a circular detector and an annular proton radiator centered on the same axis. These calculations are based on the numerical integration of analytical functions.

The incident neutrons are assumed to be monoenergetic. They may either diverge from a point on the axis, or be effectively parallel to it. A non-isotropic scattering cross section, and relativistic kinematics with unequal neutron and proton masses, may be used.

The geometric parts of the programs calculate the probability that a proton ejected at an angle θ to the incident neutron direction, from a given point P on the radiator, will strike the detector. The possible trajectories of the proton lie a cone of half angle θ, with vertex at P, centered on the initial neutron direction; this corresponds to the $0 - 2\pi$ range of the azimuthal angle of the interaction. The programs use the geometry of conic sections to calculate what fraction of the cone (in terms of azimuthal range) is intercepted by the detector. The function is integrated numerically over the whole radiator to give the total contribution to the geometric resolution function at the energy corresponding to angle θ.

Rectangular smearing of the geometric resolution function is included to allow for the slowing down of the protons within the radiator itself. Energy and angular straggling within the radiator are neglected.

A typical resolution calculation for a parallel beam of 14.1 MeV neutrons is shown in Fig.2. The dashed line shows the distinctly non-Gaussian function that results from the geometry alone, while the continuous line includes the effect of 182 keV rectangular smearing due to a 50 μm thick (45.9 μg mm^{-2}) proton radiator.

On the basis of such calculations, a design was produced for a spectrometer for JET, taking account of the geometric constraints of a practical beam line at JET. Using a figure of 65 μm for the thickness of the proton radiator, in accordance with the polyethylene material available at the time, the calculated efficiency and resolution of a single radiator-detector pair in the optimised configuration were 3.6×10^{-5} $n^{-1}cm^{2}$ and 370 keV (2.8% of the mean detected proton energy) respectively. To confirm the accuracy of the calculations, a prototype based on the proposed design was constructed and tested using monoenergetic DT neutrons from the Harwell 500 keV Van de Graaff accelerator.

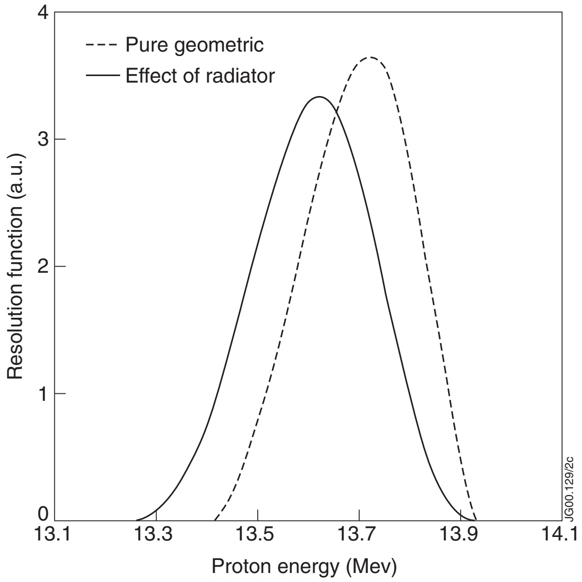

Fig.2: Typical resolution calculation for 14.1 MeV neutrons. Dashed line: geometrical effects alone. Solid line: including the slowing down of the protons within the proton radiator film.

EXPERIMENTAL METHOD

The prototype spectrometer consisted of a single 57.7 μg mm^{-2} annular proton radiator with an inner radius of 60 mm and an outer radius of 78 mm, mounted approximately 400 mm in front of a silicon surface barrier diode 1643 μm thick and 30 mm in diameter (the largest available at that time with sufficient thickness to stop 16 MeV protons). The prototype was placed in the Beam Room of the Van de Graaff experimental area, and allowed to view the neutron-producing target through a collimator embedded in a thick wall (see Fig.3). A shadow bar mounted centrally in the collimator produced the required annular beam.

Monoenergetic neutrons were produced by directing a 21 - 28 μA, 440 keV deuteron beam onto a water-cooled TiT_x ($x \approx 1.65$) target of thickness 10 μg mm^{-2}. The absolute neutron yield was measured by counting the alpha particles from the D-T reactions, using a semiconductor detector with well-determined geometry (the so-called Associated Particle Detector; see, for example, Ref.[1]).

Standard spectroscopic electronics were used: a pre-amplifier (Canberra 2004), a main amplifier (Ortec 673) and an ADC/MCA

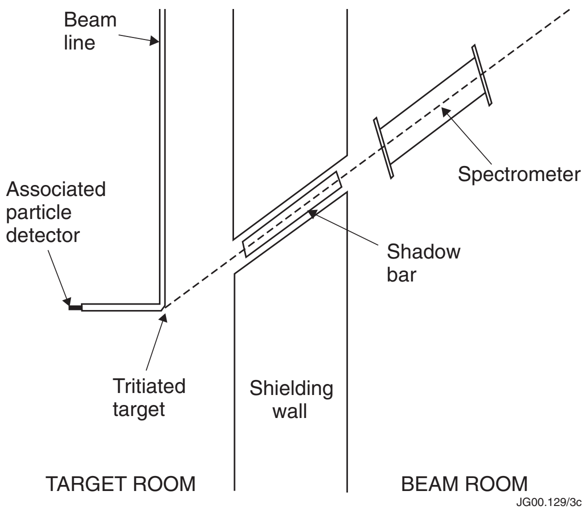

Fig.3: Experimental arrangement for tests on prototype spectrometer

(Canberra Series 80). The series resistor in the pre-amplifier was reduced to 1 MΩ to lessen the effect of leakage current variations on the detector voltage (with the standard value of 110 MΩ, a leakage current variation of 2 μA would effectively switch the detector off). The resolution of the electronics was monitored by feeding pulses from an Ortec 448 Research Pulser into the Test input of the pre-amplifier.

An ^{241}Am alpha source was incorporated into the spectrometer for energy calibration and for monitoring the energy resolution. This source was mounted about 200 mm in front of the detector, and the alpha particles were tightly collimated by a narrow tube several cm long.

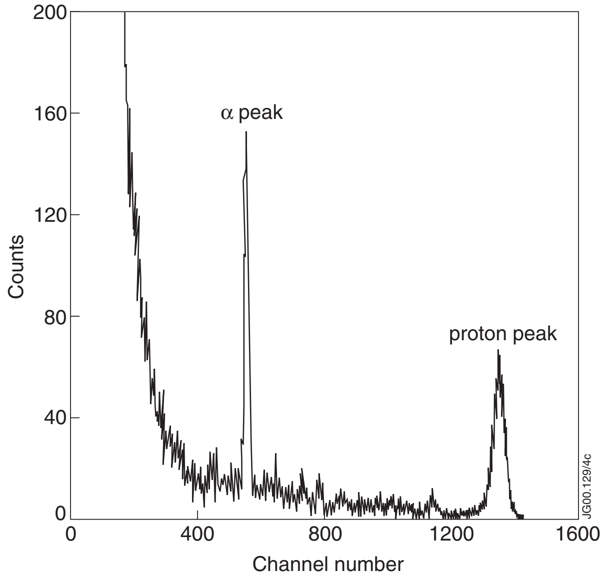

Fig.4: Proton spectrum obtained with prototype spectrometer

Typically about 10 hours of running were required to accumulate 3000 - 6000 counts in the proton peak. The detector used for these measurements was a prototype, and unfortunately the leakage current fluctuated on a time scale of about 1 hour between 2 μA and 4 μA approximately. This resulted in degradation of the pulse height resolution. In an effort to overcome this effect, some runs were carried out at a reduced detector bias (125 V instead of the 200 V recommended for the detector).

A typical spectrum obtained from the prototype spectrometer is shown in Fig.4.

The experimental results set out below are based on three long runs, two of which were carried out with a distance of 2.20 m between the neutron target and the proton radiator, and one with a distance of 2.70 m. Various background runs were carried out in addition.

EXPERIMENTAL EFFICIENCY AND RESOLUTION

From the number of counts in the proton peak (corrected for the small number of background counts recorded in the absence of the radiator film) and the total number of alpha particles recorded by the Associated Particle Detector, the efficiency of the prototype spectrometer was found to be $(3.392 \pm 0.12) \times 10^{-5}$ $n^{-1}cm^2$ (taking the flux value at the radiator). This figure allows for the attenuation of the neutron beam in the material of the target assembly but not in the chamber entrance window. The mean incident neutron energy was estimated to be 13.89 MeV.

From the energy calibration provided by the alpha peak, the FWHM of the recoil proton peak was found by Gaussian fitting to be to be 429 ± 8 keV when the diode was operated at 125 V, and 447 ± 6 keV when it was operated at 200 V. Both these figures are for a target-to-radiator separation of 2.20 m. The mean proton energy recorded was 13.28 ± 0.04 MeV.

COMPARISON WITH CALCULATED EFFICIENCY AND RESOLUTION

There are two significant resolution-broadening mechanisms present in the Harwell tests but neglected by the program: the effect of D-T kinematics, and the resolution of the diode and electronics. The kinematics effect is a consequence of the slowing down of deuterons in the TiT target, and the variation of D-T reaction angle across the face of the spectrometer. Its magnitude was estimated from kinematics tables. The diode resolution was estimated by measuring the width of the alpha peak in the experimental spectra. Both values were added in quadrature to the calculated resolution.

The final calculated results (for a target-to-radiator separation of 2.20 m) were:

Efficiency:	(3.587	±	0.13) $\times 10^{-5}$ $n^{-1}cm^2$
Resolution from program (FWHM):	370	±	10 keV
Contribution from diode & electronics:	125	±	5 keV (at 125 V)
Contribution from DT kinematics:	80	±	10 keV
Total calculated peak FWHM:	399	±	10 keV

The uncertainty in the calculated efficiency is dominated by how well the active radius of the silicon diode is known. A figure of 15.0 ± 0.25 mm was assumed.

The ratio of calculated to experimental values is 1.057 ± 0.053 for the efficiency and 0.929 ± 0.028 for the resolution, which constitutes acceptable agreement. On this basis we were confident to proceed to the production version of the spectrometer.

PRODUCTION VERSION OF SPECTROMETER

A production version of the spectrometer has now been constructed and successfully deployed at JET [2]. This version is very similar to the prototype, but consists of three radiator-detector modules placed one behind the other, giving a total efficiency calculated to be about 2.86 times that of the front module alone. (The factor is less than three because of the of decrease in neutron flux with distance from the plasma.) The decision was taken to use a thinner but higher quality polyethylene film (50 μm thick instead of 65 μm, but with better uniformity of thickness), giving a calculated resolution of 2.2% and a predicted efficiency (based on the measured value from the prototype) of $(7.35 \pm 0.26) \times 10^{-5}$ $n^{-1}cm^2$ at 14.1 MeV.

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