Fits to neutron multiplicity spectra in coincidence with fission

A. Chatterjee, Saneesh N. and P. Sugathan
NAND Group, Inter-University Accelerator Centre, Aruna Asaf Ali Marg, New Delhi 110067 INDIA
email: DrAmbar@gmail.com

Introduction

Measurements of neutron multiplicities in coincidence with fission fragments are widely used to obtain information about fission time-scales and the underlying dynamics. Typically, measurements are made at several fission-neutron correlation angles and the kinematic focusing effect for fragment emission allows the separation into pre- and post-fission components. In the early measurements of this type [1] the spectra were analyzed using kinematics for compound nucleus and two fission fragments. However in later measurements e.g. [2-3] fits to the data are made using the Watt expression [4,5] which is an approximation. Since the Watt expression is easy to use, most experimenters continue to analyze their data in this way to extract multiplicities: M_{pre}, M_{post} and temperatures: T_{pre}, T_{post}. The purpose of the present contribution is to show that the empirical Watt expression deviates systematically from complete kinematics. Secondly, we would like to point out that making the fit using full kinematics is neither difficult nor computer intensive. Hence there is no reason to use the approximate Watt expression.

A large neutron detector array with 100 5"x5" BC501A liquid scintillators has been recently setup at IUAC. To analyze the data from such an array it will be better to use full kinematics instead of relying on the approximate Watt expression.

Watt Expression

The Watt expression for each of the 3 sources is given by [4,5],

$$\frac{d^2M}{dEd\Omega} = \frac{M_n\sqrt{E}}{2(\pi T)^{3/2}} \times \exp\left(-\frac{E+E_s/A-2\cos\theta\sqrt{EE_S/A}}{T}\right) \qquad (1)$$

where M_n is the multiplicity, E is the neutron lab-energy, θ is the relative angle between neutron source and neutron, E_s and A are the source energy and mass number and T is the temperature associated with the source. To fit data consisting of spectra at several angles, one can use a chi-squares minimization program either varying only 2 parameters: M_{pre}, M_{post} or 4 parameters: $M_{pre}, M_{post}, T_{pre,} T_{post}$. In the literature, the quality of fit is often not very good and it is sometimes needed to fix the temperatures at their expected values.

Plots are often shown on a semi-log scale thereby hiding details. Chi-square values are not always quoted, but are generally about 3 or more. By contrast, works using full kinematics e.g. [1] show detailed linear plots in terms of neutron velocity going down to En=0.1 MeV and report chi-square values close to 1.

Full Kinematics

In the frame where the source is at rest, the statistical model expression for neutron emission is

$$\frac{d^2M}{d\bar{\Omega}d\bar{E}} = K\,\bar{E}\sigma_{inv}(\bar{E})\exp(-\bar{E}/T) \qquad (2)$$

where $\bar{E}$ is the neutron energy in the rest frame and K can be found by normalization. Inverse reaction cross sections σ_{inv} can either be taken as constant, or better from available empirical expressions [6]. The conversion from rest-frame to lab-frame can be carried out by using standard kinematics, including the Jacobian determinant.

Application of (2) appears more complicated. The normalization factor K needs to be found for each spectrum and re-determined when temperatures are varied. The ANU group used an iterative method [1,5] for 2-3 neutron detectors. However in the present work we have written a program using standard chi-squares minimization for any number of neutron detectors. Fits using our program are practically instantaneous and computational convenience should not be considered a reason for using the approximate Watt expression.

Comparison with Full Kinematics

Digitizing the data reported in the literature to carry out a comparison is difficult because usually only representative samples of spectra are shown. We have instead generated simulated data for 80.7 MeV ^{12}C+^{194}Pt using full kinematics with multiplicities and temperatures from [3]. A fit with full kinematics then gives the same parameters with Chisq≈ 1 as expected. Results of the Watt fit and comparative plots are given in Table 1 and Fig 1.

Table 1: Results for 80.7 MeV ^{12}C+^{194}Pt (E*=59.4 MeV)

	Mpre	Mpost	Tpre	Tpost	Chisq
Watt fit	2.33±0.42	0.80±0.20	2.24±0.28	1.66±0.31	4.96
Kinematics	2.59±0.16	0.66±0.06	1.52±0.04	1.05±0.05	1.17

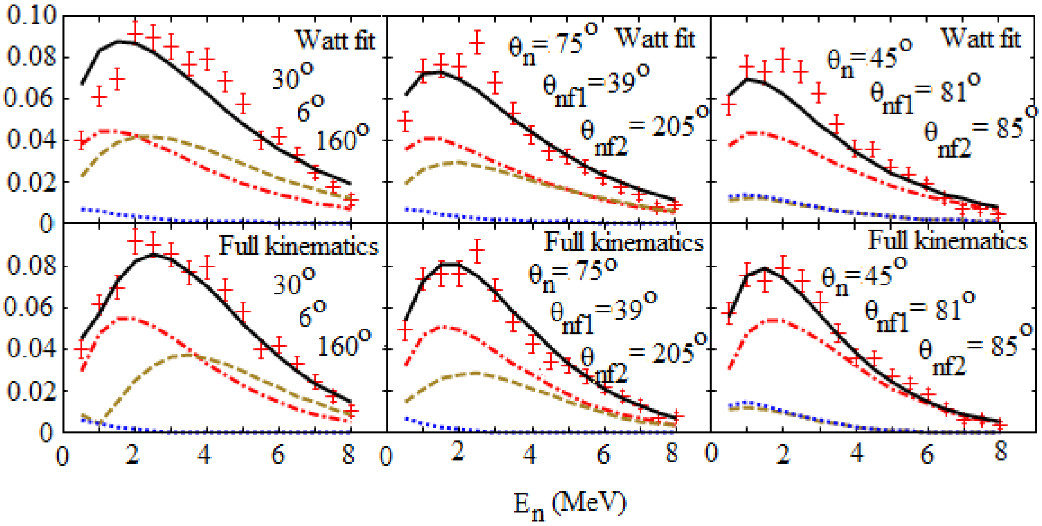

Fig. 1 Neutron spectra d^{2}M/(dE dΩ) (MeV^{-1} sr-^{1}) with Watt fits (upper panels) and full kinematics (lower panels). Dotted and dashed lines are fragment emission, dot-dash is compound nucleus emission and solid line is total.

Conclusions

Although he extracted multiplicities do not differ very much, the temperatures in the case of the Watt fit are significantly higher. This has bearing on the neutron thermometer method [7]. The better quality of fit with full kinematics can be seen in linear plots. The Watt expression deviates systematically at lower energies and small θ_{nf} angles. The resulting peak shift causes higher temperatures in the Watt fit. A low energy kink [1] for the focused fragment arising from "turned back" neutrons is missing in the Watt expression. These details would not be clearly seen on a semi-log plot.

In the work of Golda et al [3] the experimental data were fitted with $T_{pre} = 1.48$ and $T_{post} = 1.05$. However if the data are digitized and then displayed on a linear scale, very large deviations at low E_n and small θ_{nf} can be observed.

References

[1] D.J.Hinde et al, Nucl. Phys. A**452** (1986) 550
[2] H.Rossner et al, Phys. Rev. C**45** (1992) 719
[3] Golda et. al., Nucl. Phys. A**913** (2013) 157
[4] B.E.Watt, Phys. Rev. **87** (1952) 1037
[5] D.Hilscher and H.Rossner, Ann. Phys. Fr. **17** (1992) 471
[6] A.Chatterjee et al, Pramana **16** (1981) 391
[7] D.J.Hinde, Nucl.Phys. A**553** (1993) 255c