# Measurement of neutron multiplicity from fission of $^{227}$Pa

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## Introduction

The National Array of Neutron Detectors (NAND) facility at IUAC is an upcoming major nuclear physics facility for the study of reaction dynamics in heavy ion induced fission [1]. Measurement of neutron time of flight in coincidence with fission fragments allow to determine the pre and post scission neutron multiplicities ($\upsilon_{pre}$ and $\upsilon_{post}$) that can be used to get information on the timescale and the dynamical behavior of the fissioning system. Conventionally, three sources of neutron are assumed in heavy ion induced fusion-fission reactions: the compound nucleus (CN), and two fission fragments (FF). Neutrons emitted from the CN are nearly isotropic since the recoil velocities are small compared to those from fully accelerated fission fragments where focusing effect is large at smaller relative angles. As is evident, pre-fission neutrons are evaporated during the evolution of the system from formation to scission. Any enhancement in $\upsilon_{pre}$ from the transition state model can be attributed to dynamical effects. This article reports the extraction of neutron multiplicity and comparison of the results with statistical model prediction for estimation of fission time scale.

## Experimental method

The experiment was performed at IUAC Pelletron accelerator facility using the reaction $^{19}$F+$^{208}$Pb and detecting neutrons using 50 liquid scintillators mounted in NAND facility [1]. Pulsed beam of $^{19}$F at 110 MeV lab energy (~18% above barrier) was bombarded on a $^{208}$Pb target of thickness 700 μg/cm$^2$ and the beam monitoring was done using two silicon detectors mounted on 13.5$^0$ ring w.r.t target center in the beam direction. Two Multi Wire Proportional Counters (MWPC) were mounted at folding angle (160$^0$) for fragment detection [2] at 40$^0$ and 120$^0$ on either sides w.r.t beam direction. The neutron detectors were mounted on a geodesic dome structure both in plane and out of plane positions giving a flight path of 175 cm. The detectors were tuned to have threshold of nearly 300 keV. The list mode data collection was done with acquisition software LAMPS with fission detector as the trigger generator.

## Data analysis

Data analysis comprised of various stages: conversion of neutron Time Of Flight (TOF) spectra into energy spectra, efficiency correction, etc. The fission fragments were identified by TOF correlation in the MWPCs. TOF spectra from neutron detectors were gated with fission fragments and n-gamma discrimination was applied (by gating in the zero cross v/s TOF correlation plot). In order to avoid angular uncertainty caused by the finite size of fission detectors, we considered slices of six rectangles each of size 38 mm x 42 mm. The neutron TOF data were converted into energy histogram with bin size of 0.25 MeV. Mass distribution and mass angle correlation study have been performed for this system at nearly same excitation energy and their results show the absence of non-equilibrium fission process like quasi fission. Hence the selected fragments can be thought of as predominantly from fusion-fission.

The intrinsic efficiency calculation of neutron detectors for 300 keV threshold was carried out using FLUKA [3]. We developed a computer program using a vector formulation for the calculation of relative neutron-fission fragment angles. For the array of neuron detectors and different slices of the fission detectors, there were 270 sets of relative angles.

Neutron multiplicity values ($\upsilon_{pre}$ and $\upsilon_{post}$) were extracted using moving source fit prescribed by Watt formula, comprising of three terms representing each source of neutrons with kinematic focusing caused by source velocities as given below:

$$\frac{d^2 M}{dE_n \, d\Omega_n} = \sum_{i=1}^{3} \frac{M_i \sqrt{E_n}}{2\left(\pi T_i\right)^{3/2}} \times \exp\left(- \frac{E_n + E_i/A_i - 2\cos\theta_i \sqrt{E_n E_i/A_i}}{T_i}\right)$$

where $M_i$ is the multiplicity, $E_n$ represents neutron lab energy, $T_i$ is source temperature, $\theta_i$ is the relative angle between neutron source and neutron, $E_i$ and $A_i$ represent energy and mass of neutron source. The fission fragment energies were calculated by Viola systematics [4] assuming symmetric fission. A fit to the full set of experimental spectra $d^2M/dE_n d\Omega_n$ was made in terms of the Watt expression, minimizing chi-square considering both multiplicities and temperatures as free parameters.

Global fitting of data from all the neutron detectors were used to extract the parameters. Reasonable results were obtained only when slices in the MWPC was applied. The extracted values are shown in table 1.

**Table 1:**Fit value of multiplicity and temperature

| $\upsilon_{pre}$ | $\upsilon_{post}$ | $T_{pre}$ | $T_{post}$ | Chisq/n |
|---|---|---|---|---|
| 1.11+/-0.01 | 0.21+/-0.01 | 1.31+/-0.01 | 0.85+/-0.02 | 2.99 |

One of the 270 decomposed spectra with contributions from each source is shown as a sample in Fig 1.

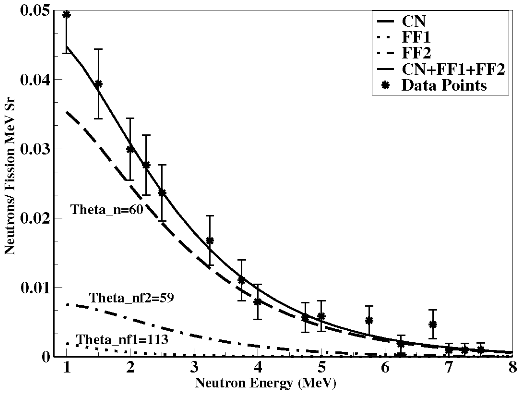


**Fig.1** Double differential neutron multiplicity spectrum showing the contribution from $\upsilon_{pre}$ and $\upsilon_{post}$ to data points in one of the detectors.

In order to estimate the transient time delay in the fusion-fission process, the statistical code JOANNE2 [5] was used and results compared with experimental multiplicity value. Input to the statistical code, such as ratio of level density parameters at equilibrium deformation and saddle point, fusion cross section, etc. were taken from literature [6]. Multiplicity ($\upsilon_{pre}$) value for zero time delay was found to be 0.52. A total time delay of ~$30 \times 10^{-21}$s was required to reproduce the experimental $\upsilon_{pre}$. Separating $\upsilon_{pre}$ into pre-saddle and post-saddle components would require further knowledge of parameters like $K^2_0$.

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