Artificial diamonds as ultra-fast fission trigger

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http://www.jrc.ec.europa.eu/
• Introduction

• Concept of the TOF spectrometer VERDI

• Fission timing with artificial diamonds

• First experimental results

• Summary

• Applications in nuclear data measurements

• Outlook
**MONNET MONo energetic Neutron Tower**

7 MV Van-de-Graaff accelerator (0.1 – 24 MeV)

- $^7\text{LiF}(p, n)^7\text{Be}$, Ti:T$(p, n)^3\text{He}$, D$_2$(d, n)$^3\text{He}$, Ti:T(d, n)$^4\text{He}$
- DC ($I_{p,d} < 50 \mu A$), ns-DC pulse mode (2.5 or 1.25 MHz)
- 4 + 1 non-T beam line

$\Phi_n < 10^{10} \text{ /s /sr}$

**NEPTUNE isomer spectrometer**

Accessible for external research groups via the EUFRAT program

Reliable predictions on fission product yields relevant in modern nuclear applications (GEN-IV, ADS…)

- Radio-toxicity of the nuclear waste
- Decay heat calculations
- Delayed neutron yields relevant during reactor operation

- Prediction of fission-fragment mass and kinetic energy distributions
- Emission spectrum and multiplicity (as a function of fragment mass) of prompt $\gamma$-rays and neutrons
- Delayed neutron emission pre-cursor yields
Motivation

- 2E measurement with a twin Frisch-grid ionisation chamber:

  ✓ Pre-neutron fragment masses and total kinetic energy iteratively determined
  ❖ Using “known” prompt neutron emission data (multiplicity, TXE dependence)

😊 Experimental neutron data only for a few isotopes
😊 Mass resolution usually worse than 4 amu
Simultaneous measurement of kinetic energy and velocity of both fission fragments

- $2\nu \rightarrow$ pre-neutron masses, $A_i^* (i = l, h)$, TKE
- $\nu, E \rightarrow$ post-neutron masses, $A_i, E_{k,i} (i = l, h)$

- $\nu_i(A_i^*)$ from the difference $A_i^* - A_i \rightarrow TXE(A_i)$
- complete data set: $\nu_i\{A_i^*, TXE_i, R(Z_L, Z_h)\}$

*Cosi Fan Tutte (ILL)*
Goals:

- spectrometer efficiency $\varepsilon \approx 0.005 - 0.01$
- for a mass resolution of $\Delta A < 2$

- High resolution energy detector ($\Delta E/E = 0.006$)
- High precision (transmission) time pick-up with $\tau \approx 150$ ps @ $L = 50$cm

- radiation hardness of the time pick-up

$\checkmark$ Cosi Fan Tutte ($\varepsilon \approx 5 \times 10^{-5}$)
VERDI - the design

- 2 x 19 PIPS detectors (450 - 900mm²)
- pcCVDD (or MCP) ultra-fast time pick-up detectors
- set-up can be handled with NIM electronics
- development of an AMUX + tag-word coder module
VERDI – the energy side

- Axial ionisation chamber:
  - Limited timing characteristics
  - Difficult to make a large area detector
  - Energy loss in the entrance window

- Large area silicon detectors:
  - Relatively cheap
  - Easy to use
  - Excellent pulse height stability
  - Excellent energy resolution
  - Promising timing characteristics
  - Subject to radiation damage
VERDI – the timing side

○ μ-channel plate detectors:
  ✓ Very good intrinsic timing characteristics
  ❖ Difficult to handle
  ❖ Requires excellent vacuum $p < 10^{-6}$ mbar
  ❖ Subject to radiation damage (especially in an intense neutron field)???

○ Diamond detectors (p/sCVDD):
  ☒ New detector material
  ☒ Relatively few experimental results
  ❖ Difficult to produce (artificial) single-crystal diamonds
  ❖ Pulse height stability of pCVDD difficult to predict and to maintain with HIPs
  ✓ Fast response and low noise, mechanically stable -> easy to handle
  ✓ Promising timing characteristics (with Ni-ion @ 30 MeV/u $\sigma_t \approx 30$ ps)
  ✓ Radiation hard
  ❖ Never tested with fission fragments ($0.5 \text{ MeV/u} < E_{FF} < 2 \text{ MeV/u}$)
Experimental set-up

$(v, E)$

- $^{252}\text{Cf}$
- pCVDD, 100 $\mu$m
- PIPS, 300 $\mu$m
- 225 mm

pCVDD material
- size: $1 \times 1$ cm$^2$
- thickness: 100 $\mu$m
pCVDD – pulse-height properties

triple $\alpha$-source

irradiated with a $^{90}\text{Sr}^{90}\text{Y}$ $\beta$-source (3MBq, 72h)
Pulse-height “analysis”

- CVD pulse height spectrum
  - no coincidence
  - coincidence with 7 PIPS

- PIPS pulse height spectrum
  - no coincidence
  - coincidence with 7 PIPS
pcCVDDDD - Intrinsic timing resolution

- 252Cf
- pcCVDDDD, 100 µm
- pcCVDDDD, 100 µm
- 95 mm

pcCVDDD material
- size: $1 \times 1 \text{ cm}^2$
- thickness: 100 µm
pcCVDDD - Intrinsic timing resolution
Determination of the timing resolution

- By means of a Monte-Carlo simulation
- Experimental fission-fragment distribution
  - Post-neutron fragment yield
  - Post-neutron fragment kinetic energy
- Geometry of the detector set-up
- Variation of the time-resolution parameter until reproduction of the measured time distribution
pcCVD-DD - Intrinsic timing resolution

- Timing resolution very good but worse than expected from HI experiments
- Don’t forget! Here, we have a largely mixed particle beam in A and $E_{\text{kin}}$

$\tau_{\text{int}} < 300 \text{ ps}$
Pulse height stability against radiation damage up to a fission-fragment dose of at least $2 \times 10^9$

Including an $\alpha$-particle dose of $6.5 \times 10^{10}$ and a fast neutron dose of about $7.5 \times 10^9$
VERDI - the timing resolution

\((v, E)\)

\(^{252}\text{Cf}\)

\(\text{pCVDD, 100 }\mu\text{m}\)

330 mm

\(\text{PIPS, 300 }\mu\text{m}\)

### pCVDDD material
- size: \(1 \times 1\text{ cm}^2\)
- thickness: 100 \(\mu\text{m}\)

### various PIPS detectors
- ORTEC 900 mm\(^2\)
- CANBERRA (same specs.)
- Eurisys (25 mm\(^2\))
- CANBERRA (450 mm\(^2\))
VERDI - the timing resolution

Eurisys 25 mm$^2$

- exp. data
- $\tau = 600$ ps
- $\tau = 400$ ps

Yield vs. TOF (ns)
VERDI – data analysis

- Channel-to-time conversion making use of published $^{252}\text{Cf}$ mean-velocity data
- Pulse-height defect correction applied (Schmitt calibration)
VERDI – FF distributions

Eurisys 25 mm$^2$

normalized yield (%)

A (amu)

TOF
Lohengrin
from 2E
VERDI – FF distribution

Canberra “t-PIPS” 450 mm²

- 2E: post-neutron
- \(^{251}\)Cf\(n_{th},f\): Lohengrin
- \(^{252}\)Cf\(E_2\): VERDI

Preliminary results
Artificial diamonds have a timing resolution $\tau < 300$ ps for a mixed low-energy heavy-ion beam (= FF)

pCVDD detectors may be used for fission-fragment timing

radiation hardness of the pCVDD start trigger proven

Fission-fragment timing resolution of the ($\nu, E$) fission-fragment spectrometer $\tau < 600$ ps

Very much competitive with MCP detectors

Post-neutron mass resolution @ flight path $L = 50$ cm of $\Delta A = 2.2 - 2.8$ achieved
Future improvements

- Fission-fragment timing resolution $\tau < 200$ ps
- VERDI with mass resolution $\Delta A \approx 1.5$ possible
  - higher electric fields, $E_{CVDD} > 2V/\mu m$, to compensate for plasma delay
  - Segmented electrodes to decrease capacitance
  - faster electronics and “cabling”
  - includes work on timing characteristics of large-scale energy detectors

- Work on a fast radiation-hard transmission trigger device (possibly with energy resolution)

- VERDI will allow the consistent measurement of pre- and post neutron fission fragment data
- Prompt neutron emission data $Y(A^*, TKE; TXE)$
✓ Fission fragment spectrometry in the presence of a high alpha activity (MA: $^{241,243}\text{Am}$, $^{243,245}\text{Cm}$, but also $^{239}\text{Pu}$)

✓ High resolution neutron-induced cross-section measurements for MA

✓ Correlated prompt particle emission data (neutron and $\gamma$-ray spectra as well as multiplicity data)

✓ …
Lanthanum halide detector + pCVDDDD

ProjectionX of biny=[573,636]

ProjectionY of binx=[80,83]

Prompt fission γ-rays

Prompt fission neutrons

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The near future

First experiment @ KFKI beginning 2010 (EFNUDAT)

- $(\nu, E)$ experiment: $^{235}\text{U}(n_{\text{th}}, f) \Rightarrow Y(A, E_k)$
- probably with a $1 \times 1 \text{ cm}^2$ 4-fold segmented pCVD diamond transmission detector
- $\Phi_{n,\text{th}} \approx 5 \times 10^7/\text{s/cm}^2$: $c_{\text{th}} > 2 \text{ FF/s or } 10^6 \text{ FF/(120 h) per detector}$
- prompt fission $\gamma$-rays and neutron spectral using the pCVD detector as fission-trigger

pCVD diamond transmission detector

- under investigation
- thickness around $5 \mu\text{m}$, 8-fold segmented
- first (weak) $\alpha$-particle signals
- extremely difficult to get electrical contact (now glued)
- tests with fission fragments soon 😊
Nothing without a good team!

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Motivation

$^{238}\text{U} \ (n, f) \ @ \ E_n = 0.9 \ - \ 2 \ \text{MeV}$

$E^* \approx 5.8 \ \text{MeV}$

$E^* \approx 6.1 \ \text{MeV}$

E. Birgersson et al., Nucl. Phys. A817 (2009) 1-34