Development of a

Gaseous Proton-Recoil Detector

for neutron flux measurements between 0.2 and 2 MeV neutron energy

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I- Context and motivations

Cross section measurement

$^{242}\text{Pu}(n,f)$ measurement in the $[200 \text{ keV} ; 2 \text{ MeV}]$ energy range

Strong discrepancies $\exp./\exp.$ and $\exp./\text{databases}$

$\Delta=10\%$

$\Delta=10-20\%$
I- Context and motivations

Neutron flux measurement

Useful to normalize the cross section measurement (as well as for neutron beam line characterization, or dosimetry investigations...)

Usually, standard reactions are used: $^{235}\text{U}(n,f)$, $^{238}\text{U}(n,f)$, $^{237}\text{Np}(n,f)$

These standards are known with an accuracy of few % (from 0.5% to 10%)

An independent measurement

Evaluators require independent measurements

$^1\text{H}(n,p)$ reaction is a primary standard known with an accuracy around 0.2% in the MeV region

Especially, its application and detection are completely different from the other standards (e.g. recoil proton detection VS fission fragments detection)

A real improvement in term of independence
I- Context and motivations

Principle

**Experimental setup:**

- Neutrons ($E_n$) interact with a H-rich foil.
- Recoil protons ($E_p$) are generated.
- These protons are detected by a Si detector.

**Usual background:**

The Si detector may see other signals which have to be subtracted.

- **Need for a background measurement** (masking H-rich foil).
- To obtain a precise neutron flux ($\Delta N_{proton} \sim 1\%$), the background has to be small enough.

**Si spectrum after usual background subtraction:**

Proton peak ($N_{proton}$) at $E_p \sim E_n$.

**Well defined efficiency:**

Properly defined efficiency for the Si spectrum after usual background subtraction.
II- Issue at low energy

A tremendous background

At low energy, the background is hundred times higher than the proton peak

Non-ideal background subtraction

Remaining background

Impossible to determine \( N_{\text{proton}} \) better than 1% below 1 MeV

\[ E_n = 1.1 \text{MeV} \]
\[ E_n = 0.9 \text{MeV} \]
\[ E_n = 0.7 \text{MeV} \]
\[ E_n = 0.5 \text{MeV} \]

\( E_p \) (keV)

Counts/20keV

II- Issue at low energy

Background source

An experiment was carried out @AIFIRA to investigate this background:

- present as soon as the beam is ON
- present even when the Si detector is masked

Electrons less 'MeV/µm' but:
- whole Si depth used
- possible tangent tracks
- more multiple events

Very high signal at few 100 keV (quickly decreasing with E)

Emitted by gamma-ray interaction

\( e^- \) flux for a 1 MeV gamma-ray source (MCNP simulations)
II- Issue at low energy

Background source

An experiment was carried out @AIFIRA to investigate this background:

- present as soon as the beam is ON
- present even when the Si detector is masked

electrons
less 'MeV/μm' but:
- whole Si depth used
- possible tangent tracks
- more multiple events

Very high signal at few 100 keV (quickly decreasing with E)

Emitted by gamma-ray interaction

These gamma-rays are mainly produced by \((n,\gamma)\)
reaction on the neutron source material

They cannot be avoided
Main features

Low sensitivity to electrons: thickness adapted to proton range

Thinner Si detectors:
- need to be changed for each energy
- sensitive to irradiation
- more difficult to calibrate

Gaseous detector:
- gas pressure adapted to proton range
- much more complex

Background events rejection
- segmented detector to perform track analysis

Well defined efficiency
- a collimator is placed inside the detector => two chambers
100% efficiency required for good tracks ("no missed event")
III- A new detector, phase I

The Gaseous Proton Recoil Detector (GPRD)

- Designed with track calculations
  - (nbr e\textsuperscript{-} generated, different E\textsubscript{n}, different P\textsubscript{gas})

Constraint:
- As low material as possible to avoid interference with cross section measurement (e.g. fission)
III- A new detector, phase I

The Gaseous Proton Recoil Detector (GPRD)

Segmented detector (CEA/Irfu)

64 pads divided in two chambers: $\Delta E$-$E$

smaller pads in $\Delta E$ region (lower e- generation)

well defined efficiency (collimated sample)

Picture of the GPRD prototype (test experiment)

rotating sample disk

collimators

divided in two chambers:

$\Delta E$-$E$

$\Delta E$ region
III- A new detector, phase I

Energy calibration

- signal amplitude:

\[ E_{\text{proton}} = \sum_{\text{pad } i} E_{\text{deposited}}^i \]

\[ E_{\text{deposited}}^i = \frac{A^i}{\varepsilon_{\text{collection}}^i \eta_{\text{gain}}^i} \]

Due to \( \varepsilon_{\text{collection}} \), it is very hard to determine the proton energy via the signal amplitude.

\[ f(\text{exp.conditions,xyz}) \]

\[ f(\text{gap, gas, U}) \]
Energy calibration

- track length:

obtained thanks to the segmentation $\rightarrow$ proton energy

Issue: smooth end-of-track $\rightarrow$ energy deposition reconstruction (thanks to constant $\eta_{\text{gain}}$, despite $\varepsilon_{\text{collection}}$)

can we see this?

Issue: no information on the z-axis $\rightarrow$ very poor energy resolution
III- A new detector, phase I

Efficiency

- detector dead time:
  a high counting rate could lead to missed events
    . the recoil proton counting rate is usually quite low
    . OK if there is not a lot of background events

$$\varepsilon = \varepsilon_{\text{geom}}(E_n) \times \varepsilon_{\text{intr.}}$$

Calculation (simulation)

100 % ? not yet proven
III- A new detector, phase I

Test experiment on the AIFIRA facility in 2016

- irradiation with neutrons ($E_n$ down to 300 keV)
- same conditions than previous experiments (distance, reaction)

Validations

- track measurement

« straight » tracks using the whole length of the GPRD pads amplitudes

track for $E_n = 1$ MeV
Test experiment on the AIFIRA facility in 2016

- irradiation with neutrons ($E_n$ down to 300 keV)
- same conditions than previous experiments (distance, reaction)

Validations

- track measurement
- very low sensitivity to e- or $\gamma$
  
  test without H-film *gives no signal*
  (each pad is not sensitive enough to see signal from background electrons)

only few cosmic rays seen
III- A new detector, phase I

Test experiment on the AIFIRA facility in 2016

- irradiation with neutrons ($E_n$ down to 300 keV)
- same conditions than previous experiments (distance, reaction)

Validations

- track measurement ✔️
- very low sensitivity to e- or γ ✔️
- discrimination between direct and scattered neutrons ✔️
  shorter “$\Delta E-E$” tracks rejected
  (protons from neutrons with lower energy / higher angle)
Test experiment on the AIFIRA facility in 2016

- irradiation with neutrons ($E_n$ down to 300 keV)
- same conditions than previous experiments (distance, reaction)

Validations

- track measurement ✓
- very low sensitivity to e- or $\gamma$ ✓
- discrimination between direct and scattered neutrons ✓
- low detection energy limit: 300 keV (at least) ✓

track for $E_n = 300$ keV

no test carried out below 300 keV
III- A new detector, phase I

Test experiment on the AIFIRA facility in 2016

- irradiation with neutrons ($E_n$ down to 300 keV)
- same conditions than previous experiments (distance, reaction)

Validations

- track measurement ✓
- very low sensitivity to $\text{e}^-$ or $\gamma$ ✓
- discrimination between direct and scattered neutrons ✓
- low detection energy limit: 300 keV (at least) ✓
- general functioning (electronics, acquisition, gas regulation, rotating disk...) ✓
- $\varepsilon_{\text{intr}} = 100\%$ not proven ❌

need a quantitative and accurate experiment
III- A new detector, phase I

**Issues**

- **Static sparks**
  
  $\text{CF}_4$ gas at few 10 mbars $\Rightarrow$ Paschen regime
  $\Rightarrow$ drop of the breakdown voltage

  $\Rightarrow$ removal of some conductive pieces

  hence the adhesive!

- **Non homogeneous electric field**

  Weak signal on the side pads
  + perturbation due to the collimator

  $\Rightarrow$ future addition of a field cage to constraint the electric field
III- A new detector, phase I

Issues

- Signal loss after few minutes of irradiation

Charge accumulation on insulators (from e- coming « from » the beam) => electric field distortion

future addition of a field cage to constraint the electric field

grounding some mechanical elements reduce the issue
Electric field simulations

With the OPERA code (ex-Tosca)

collimators
micromegas detector
cathode
sample disk
IV- A new detector, phase II

Electric field simulations

With the OPERA code (ex-Tosca)

Equipotential lines:

- collimators
- ground ring (ground)
- macor structure
- sample disk
- micromegas detector (-500V)
- motor axis (ground)
- cathode (-2000V)

Electric field distortion!

top view of the GPRD

aluminum structure (ground)
Electric field simulations

With the OPERA code (ex-Tosca)

Equipotential lines:

much better electric field
**IV- A new detector, phase II**

**Electric field simulations**

*With the OPERA code (ex-Tosca)*

*A static electric charge can be added*

*strong electric field distortion!*

*top view of the GPRD*

*sample disk (electric charge -2nC)*
IV- A new detector, phase II

Electric field simulations

With the OPERA code (ex-Tosca)

A static electric charge can be added

sample disk (electric charge -2nC)

weak electric field distortion

top view of the GPRD
IV- A new detector, phase II

A different gas

With very good insulating properties: 70% N$_2$ – 30% CO$_2$

- used in accelerator tank (as is SF$_6$)
- very cheap

Much slower than CF$_4$:

no background events
=> a fast gas is not mandatory anymore

![Graph showing drift velocity vs. E/P (V/cm/torr) for different pressures and voltages for P10, CF4, and Aligal12 gases.](image)
Test experiments on the AIFIRA facility in 2018

- irradiation with neutrons ($E_n$ down to 200 keV)
- same conditions than usual experiments (distance, reaction)

Validations

- good static electric field behavior
  no more electron leakage on the side pads (except the last raw)
Test experiments on the AIFIRA facility in 2018

- irradiation with neutrons ($E_n$ down to 200 keV)
- same conditions than usual experiments (distance, reaction)

Validations

- good static electric field behavior
- good electric field behavior under irradiation

no loss of signal amplitude with irradiation!
Test experiments on the AIFIRA facility in 2018

- irradiation with neutrons ($E_n$ down to 200 keV)
- same conditions than usual experiments (distance, reaction)

Validations

- good static electric field behavior
- good electric field behavior under irradiation
- 3D tracks reconstruction

lower drift velocity => significant time difference depending on z-axis

improvement of $E_{res}$ via track length determination
Test experiments on the AIFIRA facility in 2018

- irradiation with neutrons ($E_n$ down to 200 keV)
- same conditions than usual experiments (distance, reaction)

Validations

- good static electric field behavior
- good electric field behavior under irradiation
- 3D tracks reconstruction
- low detection energy limit: 200 keV (at least)

track for $E_n = 200$ keV

limitation due to the
H-rich sample thickness
(0.5µm max at 200keV)
Test experiments on the AIFIRA facility in 2018

- irradiation with neutrons ($E_n$ down to 200 keV)
- same conditions than usual experiments (distance, reaction)

Validations

- good static electric field behavior ✓
- good electric field behavior under irradiation ✓
- 3D tracks reconstruction ✓
- low detection energy limit: 200 keV (at least) ✓
- $\varepsilon_{\text{intr}} = 100\%$ not proven ✗

need a quantitative and accurate experiment
Next experiment

**Goals**
- better understanding of the detector
- prove $\varepsilon_{\text{intr}} = 100\%$
- determine the detector rate limit

**Direct proton beam experiment**

A new chamber has been designed:
- direct proton micro beam
  (few p/s to few 10 p/s)
- GPRD shift in (x;y)
  to irradiate different parts
- Si detector
  to monitor the counting rate
Conclusion

A difficult energy range for recoil proton
- very high background due to $n \rightarrow \gamma \rightarrow e^-$
- prevent an accurate counting of recoil protons

The Gaseous Proton Recoil Detector
- built in 2016
- designed for a low sensitivity to $\gamma/e^-$ background
- test experiments @AIFIRA facility:
  - good behaviour under irradiation
  - validation of the low sensitivity to background
  - track reconstruction
  - low energy limit of 200 keV (limited by the thinness of the H-film)
- a direct proton experiment planned to investigate the efficiency

Perspectives: The GPRD will be completed and used to measure the $^{242}\text{Pu}(n,f)$ cross section below 1 MeV (submitted to EURATOM WP2018)
Thank you for your attention