Measurement of the capture cross section of $^{244}\text{Cm} \& ^{246}\text{Cm}$

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Motivation

Neutron Capture Cross Sections of minor actinides (MAs) and long-lived fission products (LLFPs) are important.

- Improving the performance and safety of actual reactors.
- Designing new types of reactors, for reducing the high-level radioactive waste (transmutation).

The reported uncertainties of C.S. libraries are often questionable.

Especially, $^{244}$Cm and $^{246}$Cm are very important:

- Share nearly 40-50% of the total actinide decay heat in spent reactor fuels even after three years of cooling.
- $^{244}$Cm is one of the main neutron emitters in the irradiated nuclear fuel (fuel safety).
- Cm isotopes open the path to the production of higher Z elements: Bk, Cf…
- Both capture and fission cross sections (transmutation) are known poorly.
- Only two previous measurements available.
Only 2 sets of previous data

Experiment by Moore et al.

- 1969 Using underground nuclear explosion
- Moxon-Rae detectors
- Accuracy questionable due to systematic uncertainties
- No data under 20eV

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- 2010 at J-PARC
- Two cluster-Ge detectors
- Above 100 eV, the measurement required severe dead time corrections (up to 90%)
- Resonance analysis up to 30 eV


Measurement at n_TOF
Collaboration between CIEMAT, JAEA and n_TOF

~1 mg $^{244}\text{Cm}$ and $^{246}\text{Cm}$ samples with high activity (~1 GBq)
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$\text{C}_6\text{D}_6$ in EAR2
TED
High intensity / 20m flight path
Worse RF

TAC in EAR1
TAC
Lower intensity / 185m flight
Better RF
Information EM cascade
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Measure the Cross Sections of $^{244}$Cm and $^{246}$Cm for improving the uncertainty assessment and extending the energy range
Measurement at n_TOF
Collaboration between CIEMAT, JAEA and n_TOF

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Measure the Cross Sections of \(^{244}\)Cm and \(^{246}\)Cm for improving the uncertainty assessment and extending the energy range

Measurement during May-September 2017
Relative measurement to \(^{240}\)Pu(n,\(\gamma\))
## Samples

<table>
<thead>
<tr>
<th>Element</th>
<th>Two $^{244}$Cm sample (%)</th>
<th>$^{246}$Cm sample (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{244}$Cm</td>
<td>60.6±1.1 (~0.80 mg)</td>
<td>20.3±0.5 (~0.38 mg)</td>
</tr>
<tr>
<td>$^{245}$Cm</td>
<td>2.38±0.30 (~0.02 mg)</td>
<td>1.03±0.29 (~0.02 mg)</td>
</tr>
<tr>
<td>$^{246}$Cm</td>
<td>6.35±0.55 (~0.08 mg)</td>
<td>57.7±1.5 (~1.10 mg)</td>
</tr>
<tr>
<td>$^{247}$Cm</td>
<td>-----</td>
<td>2.8±0.4 (~0.05 mg)</td>
</tr>
<tr>
<td>$^{248}$Cm</td>
<td>-----</td>
<td>8.8±0.2 (~0.17 mg)</td>
</tr>
<tr>
<td>$^{240}$Pu</td>
<td>31.1±0.6 (~0.40 mg)</td>
<td>9.30±0.15 (~0.17 mg)</td>
</tr>
</tbody>
</table>

**Diagram:**
- Mylar
- Kapton
- Al Ring
- 9 cm
- 0.5 mm
- 5 mm
- 1.2 mm

**Image:**
- Circular sample with Cm notation.
Neutron Capture measurement techniques

\[ E_c = S_n + E_n \]
Neutron Capture measurement techniques

TED
(Total Energy Detector)

I.) Low Efficiency Detectors:

II.) Efficiency to detect a γ-ray is proportional to its energy

III.) Proportionality fulfilled with Weighting factors

$$\varepsilon_c = \sum_{i=1}^{\varepsilon_{\gamma i}} = k \sum_{i=1}^{E_{\gamma i}} = kE_c$$

The detection efficiency is proportional to $$E_c$$

J.Lerendegui (U.S.) Private communication
Neutron Capture measurement techniques

TED (Total Energy Detector)

I.) Low Efficiency Detectors:

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\[ \varepsilon_c = \sum_{i=1}^{\sigma_\gamma} \varepsilon_{\gamma_i} = k \sum_{i=1}^{\sigma_\gamma} E_{\gamma_i} = k E_c \]

The detection efficiency is proportional to \( E_c \)

E\(_C\) = \( S_n + E_n \)

TAC (Total Absorption Calorimeter)

If intrinsic and angular efficiencies are large:

I.) Total efficiency of the cascade : \( 4\pi \)

II.) Peak efficiency

The detection efficiency is constant \( \approx 1 \)

J.Lerendegui (U.S.) Private communication
**C₆D₆ Setup EAR2 (~20 m)**

- Three detectors
  - Efficiency proportional to energy ($\varepsilon_{\gamma i} E_{\gamma i}$) achieved using PHWT.
  - Good time resolution (~1ns).
**C$_6$D$_6$ Setup EAR2 ($\sim 20$ m)**

- Three detectors
  - Efficiency proportional to energy ($\varepsilon_{\gamma i} \ E_{\gamma i}$) achieved using PHWT.
  - Good time resolution ($\sim 1$ns).

- Experiment
  - 3 months.
  - $8 \cdot 10^{18}$ protons of 20 GeV/c.
  - $\sim 50\%$ of the beam measuring $^{244}$Cm and $^{246}$Cm rest dummy measurements and check.
C$_6$D$_6$ Setup EAR2 ($\sim$20 m)

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  - Efficiency proportional to energy ($\varepsilon_{\gamma i} E_{\gamma i}$) achieved using PHWT.
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- Experiment
  - 3 months.
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- Analysis
  - Precise background subtraction.
  - Energy calibration ($^{133}$Ba, $^{137}$Cs, $^{60}$Co, $^{88}$Y, AmBe and CmC).
  - Gain drifts (12 sets)
$^{244}$Cm Experimental results EAR2

Counts

$10^5$

$10^4$

$10^{-2}$ $10^{-1}$ 1 $10$ $10^2$

Neutron energy (eV)

Cm
Dummy
Empty
Cm activity
Total bkg.
$^{246}$Cm Experimental results EAR2

![Graph showing neutron energy distribution for different conditions: Cm, Dummy, Empty, Cm activity, and Total bkg.](image-url)
Geant4 Simulations
Geant4 Simulations

![Graph showing counts vs. energy deposition](image)

- **MC**
- **Exp-Background**

Y-88
Geant4 Simulations

Comparing Cascade Cm244

- Experimental
- MC Simulated

Counts/7e12 protons

E_{dep}(MeV)

Cascade Simulation for WF correction
Preliminary capture yields

Blue → Experimental Yield

Other colors → Background + JEFF 3.3

Normalizing to $^{240}$Pu Cross Section

$^{244}$Cm Bins per decade

- Total Sammy Yield
- Experimental Yield
- Pu-$^{240}$ (n,γ)
- Cm-$^{244}$ (n,γ)
- Cm-$^{246}$ (n,γ)
- Cm-$^{244}$ (n,f)
- Cm-$^{245}$ (n,f)
Preliminary capture yields

Blue → Experimental Yield
Other colors →
Background + JEFF 3.3

Normalizing to $^{240}$Pu Cross Section

JEFF 3.3 C.S in $^{244}$Cm and $^{246}$Cm (1eV to 1keV) is taken from JENDL 4.0

Captured Yield + bkg $^{244}$Cm Bins per decade
Capture Yield+bkg $^{244}$Cm Bins per decade 3000

- Total Sammy Yield
- Experimental Yield
- Pu-240 (n,γ)
- Cm-244 (n,γ)
- Cm-246 (n,γ)
- Cm-244 (n,f)
- Cm-245 (n,f)
Capture Yield + bkg $^{246}$Cm Bins per decade 3000

E$_n$ (eV)

Capture Yield + bkg

- Total Sammy Yield
- Experimental Yield
- Pu-240 (n,γ)
- Cm-244 (n,γ)
- Cm-246 (n,γ)
- Cm-244 (n,f)
- Cm-245 (n,f)
- Cm-247 (n,f)
- Cm-248 (n,γ)
- Am-243 (n,γ)
TAC Setup EAR1 (~185m)

- TAC (Total Absorption Calorimeter).
  - Sphere of 40 BaF₂ crystals, 95% solid angle.
  - Detecting almost all the gammas in the cascade.
TAC Setup EAR1 (~185m)

- TAC (Total Absorption Calorimeter).
  - Sphere of 40 BaF$_2$ crystals, 95% solid angle.
  - Detecting almost all the gammas in the cascade.

- Experiment
  - 2 weeks.
  - $5 \cdot 10^{17}$ protons of 20 GeV/c.

- Analysis
  - Coincidence between the 40 detectors. Reject background.
  - Montecarlo simulations with Geant4.
$^{244}$Cm Experimental results EAR1 TAC

![Graph showing neutron energy distribution with different count levels for Cm, Dummy, Cm activity, Env. bkg., and Total bkg.](image-url)
EM cascades TAC

- Background subtracted
- Different multiplicities
- Normalization

First Resonance Pu$^{240}$, Neutron Energy 1 to 1.1 eV

First Resonance Cm$^{244}$, Neutron Energy 7.5 to 7.7 eV

~300000 counts
~60000 counts
Summary and conclusions

- Only 2 previous difficult measurements of $^{244}$Cm and $^{246}$Cm.

- ~1 mg samples with high activity (~1 GBq) provided by JAEA.

- Radiative capture cross section of $^{244}$Cm and $^{246}$Cm were successfully measured at n_TOF in both areas with complementary set ups:
  - EAR2 with C$_6$D$_6$ (TED).
  - EAR1 with TAC.

- Preliminary results are promising and we expect to reach the proposed goals with a precise analysis.
BACKUP SLIDES
Motivation
The n_TOF Facility at CERN: a Google view
The n_TOF lead spallation target

Higher Neutron Flux

PS Protons (20 GeV/c)

Neutrons (meV to ~100 MeV)

Pb

Neutrons (meV to GeV)

185 m

tof

Better Energy Resolution

EAR-1

Graph showing neutron flux vs. neutron energy (eV) for EAR1 and EAR2.
Neutrons per Pulse at n_TOF

Experimental neutron fluence per $7 \times 10^{12} p^+$
Neutron Capture measurement techniques

\[ E_c = S_n + E_n \]

TED (Total Energy Detector)
Total efficiency depends on \( E_c \) and not on the decay path

\[ i=1 \varepsilon_{\gamma_i} \]

TAC (Absorption Calorimeter)

\[ \sigma_\gamma \]

The gammas are ideally detected.

\[ E_c = \varepsilon^p_c = 1 \]

The proportionality between efficiency and \( \gamma \)-ray energy is obtained by software (WP).
Preliminary WF Det1

\[ \sum_i W_i R_{ij} / E_j \]

![Graph showing energy (MeV) vs. weight](image)

![Graph showing energy (MeV) vs. weight](image)
Energy calibrations

- 6 sources used: $^{133}\text{Ba}, ^{137}\text{Cs}, ^{60}\text{Co}, ^{88}\text{Y}, \text{AmBe}, \text{CmC}$
- Fitting MC simulation with $\chi^2$

**Calibration Detector 1**

$$f(x) = \begin{cases} ax^2 + bx + c & x < x_0 \\ dx + c & x \geq x_0 \end{cases}$$
Energy resolution

- 6 sources used (\(^{133}\)Ba, \(^{137}\)Cs, \(^{60}\)Co, \(^{88}\)Y, Ambe, CmC)
- Fitting MC simulation with \(\chi^2\) method varying gain and

\[
\sigma^2 = b_0 E + b_1 E^2
\]

\textbf{results01/2/Data2Det1.txt}
Gain Drifts

- 10 calibration measurements
- Source always in the same position.
MC Simulations Source Response

Cs Det1

Y_12 Det1

Ba Det1

Co Det1
CALIBRATIONS

red:exp -- green:MC -- blue:fit region

red:exp -- green:MC -- blue:fit region

red:exp -- green:MC -- blue:fit region

red:exp -- green:MC -- blue:fit region

red:exp -- green:MC -- blue:fit region

red:exp -- green:MC -- blue:fit region
Alpha/gamma discrimination and energy and time calibration

- Alpha discrimination
- Calibrations, Gaussian fitting
- Gain drift correction. Using alpha spectra

Two techniques:
- Gaussian fit of last peak
- $\chi^2$–Method using reference run