NArCoS project for nuclear physics and applications

PAGANO EMANUELE VINCENZO (1)

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Project’s motivations

The advent of the new facility for Radioactive Ion Beams (RIBs) in particular for the n-rich ones

“The RIBs are an important opportunity”

(C. Horovitz)
IDEA

To realize a prototype of detector able to detect at the same time charged particles and neutrons with high energy and angular resolution for reaction studies and applications

- Candidate: The plastic scintillator EJ276-Green Type (ex EJ299-33) \((3\times3\times3\text{cm}^3)\)
- 1 cluster: 4 consecutively cubes -> \(3\times3\times12\text{ cm}^3\)
- Reading the light signal: Si-PD or Si-PM and digitalization
- Modular, reconfigurable (in mechanic and electronic)
- Discrimination of n/γ from PSD (but also light charged particles)
- Energy measurement from ToF \((∆t≤1 \text{ ns with L_{ToF}}≈1÷1.5\text{m})\)
  TOF measured using the RF of the CS or with an ancillary MCP (low intensity exotic beams)

*Si incrocia l’info ampiezza-PSD e info da fasci di calibrazione (n,CP)*
To realize a prototype of detector able to detect at the same time charged particles and neutrons with high energy and angular resolution for reaction studies and applications

- Candidate: The plastic scintillator EJ276-Green Type (ex EJ299-33) (3x3x3 cm$^3$)
- 1 cluster: 4 consecutively cubes $\rightarrow$ 3x3x12 cm$^3$
- Reading the light signal: Si-PD or Si-PM and digitalization
- Modular, reconfigurable (in mechanic and electronic)
- Discrimination of n/γ from PSD (but also light charged particles)
- Energy measurement from ToF ($\Delta t \leq 1$ ns with $L_{ToF} \approx 1 \div 1.5$ m)

TOF measured using the RF of the CS or with an ancillary MCP (low intensity exotic beams)
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- Energy measurement from ToF (Δt≤1 ns with L_TOF≈1÷1.5m)

TOF measured using the RF of the CS or with an ancillary MCP (low intensity exotic beams)

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TOF measured using the RF of the CS or with an ancillary MCP (low intensity exotic beams)

*Si incrocia l’info ampiezza-PSD e info da fasci di calibrazione (n,CP)
Just few numbers

- Time of flight: \( L = 100 \text{ cm}; \ \Delta T = 1 \text{ ns} \)
- DSSSD 32x32
  - Width: 300 \( \mu \text{m} \)
- NArCoS: \( \approx 12 \text{ cm} \)
- Solid angle: \( \approx 14 \text{ msr} (0.12\%) \)
- Angular resolution DSSSD: \( 0.2^\circ \)
- Angular resolution NArCoS: \( 2^\circ \)
- \( \theta \approx 7.5^\circ \)
- \( L_{\text{DSSSD}} = 50 \text{ cm} \)
- \( L_{\text{NArCoS}} = 100 \text{ cm} \)

\[ \frac{\Delta T}{T} (\Delta T = 1 \text{ ns}) \text{ (100 cm)} \]

- \( p \) (6 MeV Th)
- \( d \) (8 MeV Th)
- \( t \) (10 MeV Th)
- \( \alpha \) (25 MeV Th)

\*the mechanical structure will have the possibility of an angular movement.
Just few numbers

Time of flight

\[ L = 100 \text{ cm}; \Delta T = 1 \text{ ns} \]

DSSSD 32x32

300 \text{ \mu m}

\[ \text{NArCoS} \approx 12 \text{ cm} \]

\[ T_{\text{NArCoS}} = 100 \text{ cm} \]

\[ L_{\text{DSSSD}} = 50 \text{ cm} \]

\[ L_{\text{NArCoS}} = 100 \text{ cm} \]

Solid angle = 14 msr (0.12\%)

Angular resolution DSSSD = 0.2°

Angular resolution NArCoS = 2°

\[ \Delta T/T (\Delta T = 1 \text{ ns}) (100 \text{ cm}) \]

- \( p \) (6 MeV Th)
- \( d \) (8 MeV Th)
- \( t \) (10 MeV Th)
- \( \alpha \) (25 MeV Th)

\[ \text{Energy (MeV)} \]

*the mechanical structure will have the possibility of an angular movement.

\*\*The Fast Timing Application for Nuclear Physics and Medical Application - Acireale, Italy - 5 September 2019\*\*
Just few numbers

Time of flight

$L=100 \text{ cm} ; \Delta T=1 \text{ ns}$

DSSSD 32x32

300 $\mu m$

NArCoS

$\approx 12 \text{ cm}$

Solid angle = 14 msr (0.12%)
Angular resolution DSSSD = 0.2°
Angular resolution NArCos = 2°

$L_{\text{DSSSD}}=50 \text{ cm}$

$L_{\text{NArCoS}}=100 \text{ cm}$

$\theta=7.5°$

$\Delta T/T (\Delta T=1 \text{ ns}) (100 \text{ cm})$

$\Delta E/E (\Delta T=1 \text{ ns}) (100 \text{ cm})$

*the mechanical structure will have the possibility of an angular movimentation

E. V. Pagano. LNS-INFN

FATA2019 Fast Timing Application for Nuclear Physics and Medical Application - Acireale, Italy - 5 September 2019
Just few numbers

Time of flight

L=100 cm; ΔT=1 ns

DSSSD 32x32
300 μm

NArCoS
≈ 12 cm

T
θ=7.5°

L_{DSSSD}=50 cm

L_{NArCoS}=100 cm

Solid angle = 14 msr (0.12%)
Angular resolution DSSSD = 0.2°
Angular resolution NArCos = 2°

*EFF* ≈ 25%
For one cluster

*the mechanical structure will have the possibility of an angular movimentation*

ΔT/T (ΔT=1ns) (100 cm)

ΔE/E (ΔT=1ns) (100 cm)
Just few numbers

Time of flight
L=100 cm; ΔT=1 ns

DSSSD 32x32

300 μm

θ≈7.5°

L_{DSSSD}=50 cm

L_{NArCoS}=100 cm

≈ 12 cm

Solid angle = 14 msr (0.12%)
Angular resolution DSSSD = 0.2°
Angular resolution NArCoS = 2°

<EFF>=25% For one cluster

For one cluster

L=100 cm; ΔT=1 ns

Energy (MeV)

0 5 10 15 20 25 30 35 40 45 50 55 60
0 5 10 15 20 25 30 35 40 45 50

Energy (MeV)

0 5 10 15 20 25 30 35 40 45 50 55 60
0 2 4 6 8 10 12 14 16 18 20 22

ΔM/M (ΔT=1 ns) (100 cm)

ΔE/E (ΔT=1 ns) (100 cm)

p (6 MeV Th)
d (8 MeV Th)
t (10 MeV Th)
α (25 MeV Th)

*the mechanical structure will have the possibility of an angular movimentation

E. V. Pagano. LNS-INFN

FATA2019 Fast Timing Application for Nuclear Physics and Medical Application - Acireale, Italy- 5 September 2019
Just few numbers

Time of flight

$L = 100 \text{ cm}; \Delta T = 1 \text{ ns}$

DSSSD 32x32

300 μm

NArCoS

$\approx 12 \text{ cm}$

Solid angle $= 14 \text{ msr (0.12\%)}$
Angular resolution DSSSD $= 0.2^\circ$
Angular resolution NArCos $= 2^\circ$

$\langle \text{EFF} \rangle \approx 25\%$

For one cluster

$\Delta M / M \ (\Delta T = 1 \text{ ns}) (100 \text{ cm})$

$\Delta E / E \ (\Delta T = 1 \text{ ns}) (100 \text{ cm})$

$p$ (6 MeV Th)
$d$ (8 MeV Th)
t (10 MeV Th)
$\alpha$ (25 MeV Th)

*the mechanical structure will have the possibility of an angular movimentation
Just few numbers

Time of flight

$L = 100 \text{ cm}; \Delta T = 1 \text{ ns}$

DSSSD 32x32
300 $\mu$m

$\theta \approx 7.5^\circ$

$L_{DSSSD} = 50 \text{ cm}$

$L_{NArCoS} = 100 \text{ cm}$

$\text{NArCoS} \approx 12 \text{ cm}$

Solid angle $= 14 \text{ msr} (0.12\%)$
Angular resolution DSSSD $= 0.2^\circ$
Angular resolution NArCos $= 2^\circ$

$\Delta E/E \ (\Delta T = 1\text{ ns}) \ (100 \text{ cm})$

$\Delta M/M \ (\Delta T = 1\text{ ns}) \ (100 \text{ cm})$

For one cluster

$<\text{EFF}> \approx 25\%$

*the mechanical structure will have the possibility of an angular movimentation

Energy (MeV)
**Just few numbers**

Time of flight

$L = 150 \text{ cm}; \Delta T = 0.5 \text{ ns}$

- **DSSSD 32x32**
  - Solid angle $\approx 7 \text{ msr (0.07\%)}$
  - Angular resolution DSSSD $= 0.15^\circ$

- **NArCoS**
  - Angular resolution NArCoS $= 1.25^\circ$

- $\theta \approx 5^\circ$

- $\approx 12 \text{ cm}$

- Angular resolution $\approx 0.15^\circ$

For one cluster $<\text{EFF}> \approx 25\%$

---

**Energy vs. Time of Flight**

- $L = 150 \text{ cm}$
- $\Delta T = 0.5 \text{ ns}$

*the mechanical structure will have the possibility of an angular movement*
Just few numbers

Time of flight

$L = 150 \text{ cm}; \Delta T = 0.5 \text{ ns}$

$\theta = 5^\circ$

$\Delta T / T (\Delta T = 0.5 \text{ ns}) (150 \text{ cm})$

Energy (MeV)

- $p$ (6 MeV Th)
- $d$ (8 MeV Th)
- $t$ (10 MeV Th)
- $\alpha$ (25 MeV Th)

Solid angle = 7 msr (0.07%)
Angular resolution DSSSD = 0.15°
Angular resolution NArCos = 1.25°

$<\text{EFF}> \approx 25\%$

For one cluster

$*$the mechanical structure will have the possibility of an angular movimentation
**Just few numbers**

- **Time of flight**
  - $L = 150 \text{ cm}$; $\Delta T = 0.5 \text{ ns}$

- **DSSSD 32x32**
  - 300 $\mu$m

- **NArCoS**
  - $\approx 12 \text{ cm}$

- **Solid angle**
  - $\approx 7 \text{ msr (0.07\%)}$
  - Angular resolution DSSSD $\approx 0.15^\circ$
  - Angular resolution NArCos $\approx 1.25^\circ$

- **<EFF>$$\approx 25\%$$
  - For one cluster

- **Energy vs. Time of Flight**
  - $\Delta T / T$ ($\Delta T = 0.5 \text{ ns}$) ($150 \text{ cm}$)

- **Energy vs. Energy Resolution**
  - $\Delta E / E$ ($\Delta T = 0.5 \text{ ns}$) ($150 \text{ cm}$)

*The mechanical structure will have the possibility of an angular movimentation*
Just few numbers

- Time of flight: $L = 150 \text{ cm}; \Delta T = 0.5 \text{ ns}$
- Solid angle: $\approx 7 \text{ msr (0.07\%)}$
- Angular resolution DSSSD: $0.15^\circ$
- Angular resolution NArCos: $1.25^\circ$
- $\langle\text{EFF}\rangle \approx 25\%$

For one cluster

*The mechanical structure will have the possibility of an angular movement.
Just few numbers

Time of flight

\[ L = \text{150 cm; } \Delta T = \text{0.5 ns} \]

DSSSD 32x32

300 \( \mu \)m

NArCoS

\[ \approx \text{12 cm} \]

Solid angle \( \approx \text{7 msr (0.07\%)} \)

Angular resolution DSSSD \( \approx \text{0.15°} \)

Angular resolution NArCos \( \approx \text{1.25°} \)

\[ \text{Angular resolution } \Delta T = \text{0.5 ns} \]

\[ \text{Time of flight} \]

\[ \text{For one cluster} \]

\[ \text{<EFF>\approx25\%} \]

\[ \text{*the mechanical structure will have the possibility of an angular movimentation} \]
Just few numbers

Time of flight

\[ L = 150 \text{ cm}; \Delta T = 0.5 \text{ ns} \]

DSSSD 32x32

\[ 300 \mu m \]

NArCoS \approx 12 \text{ cm}

Solid angle \approx 7 \text{ msr (0.07\%)}

Angular resolution DSSSD = 0.15°

Angular resolution NArCos = 1.25°

\[ \theta = 5^\circ \]

\[ L_{\text{DSSSD}} = 75 \text{ cm} \]

\[ L_{\text{NArCoS}} = 150 \text{ cm} \]

\[ \Delta \frac{M}{M} (\Delta T = 0.5 \text{ ns}) \quad (150 \text{ cm}) \]

\[ \Delta \frac{E}{E} (\Delta T = 0.5 \text{ ns}) \quad (150 \text{ cm}) \]

\*the mechanical structure will have the possibility of an angular movimentation
Just few numbers

Time of flight

$L=150 \text{ cm}; \Delta T=0.5 \text{ ns}$

Solid angle $\approx 7 \text{ msr (0.07\%)}$
Angular resolution DSSSD $= 0.15^\circ$
Angular resolution NArCos $= 1.25^\circ$

Effective $(<\text{EFF}>\approx 25\%)$
For one cluster

The mechanical structure will have the possibility of an angular movement

\[ \frac{\Delta M}{M} (\Delta T= 0.5 \text{ ns}) \ (150 \text{ cm}) \]

\[ \frac{\Delta E}{E} (\Delta T=0.5\text{ns}) \ (150 \text{ cm}) \ (\Delta L=1.5\text{cm}) \]

$1^\circ$ Step
$2^\circ$ Step
$3^\circ$ Step
$4^\circ$ Step

$E. V. \ Pagano. \ LNS-INFN$
What about the neutron detection efficiency?

GEANT 4 simulation in order to estimate the neutron detection efficiency

Mean value for one detection cell (3x3x3 cm$^3$) $\approx 9\%$

Mean value for one detection cluster (3x3x12 cm$^3$) $\approx 25\%$
L'EJ276
(ex EJ-299-33)

N. P. Hawkes et al., NIM A729 (2013) 522
S.A. Pozzi et al., NIM A723 (2013) 19
E. V. Pagano et al. NIM A 889 (2018) 83-88
E. V. Pagano et al. NIM A 905 (2018) 47-52
L’EJ276
(ex EJ-299-33)

FATA2019 Fast Timing Application for Nuclear Physics and Medical Application - Acireale, Italy - 5 September 2019
L’EJ276
(ex EJ-299-33)

1.096

E. V. Pagano. LNS-INFN

FATA2019 Fast Timing Application for Nuclear Physics and Medical Application – Acireale, Italy - 5 September 2019

<table>
<thead>
<tr>
<th>PROPERTIES</th>
<th>EJ-276</th>
<th>EJ-276G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Output (% Anthracene)</td>
<td>56</td>
<td>52</td>
</tr>
<tr>
<td>Scintillation Efficiency (photons/1 MeV e⁻)</td>
<td>8,600</td>
<td>8000</td>
</tr>
<tr>
<td>Wavelength of Maximum Emission (nm)</td>
<td>425</td>
<td>490</td>
</tr>
<tr>
<td>No. of H Atoms per cm³ (x10^{22})</td>
<td>4.53</td>
<td>4.53</td>
</tr>
<tr>
<td>No. of C Atoms per cm³ (x10^{22})</td>
<td>4.89</td>
<td>4.89</td>
</tr>
<tr>
<td>No. of Electrons per cm³ (x10^{23})</td>
<td>3.52</td>
<td>3.52</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>1.096</td>
<td>1.096</td>
</tr>
<tr>
<td>Approx. Mean Decay Times of First 3 Components (ns)</td>
<td>13, 35, 270</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>13, 59, 460</td>
<td>—</td>
</tr>
</tbody>
</table>

EJ-276 & EJ-276G EMISSION SPECTRUM

AMPLITUDE

WAVELENGTH (nm)
L’EJ276
(ex EJ-299-33)

FATA2019 Fast Timing Application for Nuclear Physics and Medical Application – Acireale, Italy – 5 September 2019
Si PIN photodiode
S3204/S3584 series

Large area sensors for scintillation detection

S3204/S3584 series are large area Si PIN photodiodes having an epoxy resin window. These photodiodes are also available without window.
L’EJ276
(ex EJ-299-33)

S3204/S3584 series are large area Si PIN photodiodes having an epoxy resin window. These photodiodes are also available without window.
Test using radioactive sources @ LNS

Dimension: 3x3x3 cm³

$\langle \text{neutron EFF} \rangle \ (\text{GEANT4}) \approx 9\%$

Read by PM tube: EMI-9544QA

High Voltage: 1500-1700 V
Test using radioactive sources @ LNS

Dimension: 3x3x3 cm³

<neutron EFF> (GEANT4) ≈ 9%

Read by PM tube: EMI-9544QA

High Voltage: 1500-1700 V
Test using radioactive sources @ LNS

Dimention: 3x3x3 cm3
<neutron EFF> (GEANT4) ≈ 9%
Read by PM tube: EMI-9544QA
High Voltage: 1500-1700 V

Like in ARGOS detector

PM -EMI 9954QA
Like in ARGOS detector

G. Lanzanò, et al., NIM A 312, 3, (1992), 515-520
Test using radioactive sources @ LNS

Sources:
1) \( \gamma^{60}Co \)
2) \( \alpha^{241}Am \)
3) \( \alpha^{232}Th \)
4) \( n e \gamma AmBe \)

Dimention: 3x3x3 cm³
\(<\text{neutron EFF}> (\text{GEANT4}) \approx 9\%\)
Read by PM tube: EMI-9544QA
High Voltage: 1500-1700 V
Some results: the digitalized signal

Signal acquired and digitalized by using the GET system
(General Electronic for TPC)
Sampling frequency: 100 MHz

Some results: A few of spectra

E. V. Pagano et al. NIM A 889 (2018) 83-88
Some results: A few of spectra

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E. V. Pagano et al. NIM A 889 (2018) 83-88
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E. V. Pagano et al. NIM A 889 (2018) 83-88

Detection threshold \( \approx 0.7 \) MeV

Discrimination threshold \( \approx 1.5 \) MeV \((\text{FOM}_{\text{PSD}}=0.43)\)

\[
L_{\text{out}} = A \cdot E_{\text{dep}} - B \cdot (1 - e^{-C \cdot E_{\text{dep}}})
\]

\( A = 0.8 \) MeV\cdot MeV\(^{-1}\);

\( B = 3.9 \) MeV\( \cdot \) MeV\(^{-1}\);

\( C = 0.19 \) MeV\(^{-1}\);

C. C. Lawrence et al., NIM A759 (2014) 16
Some results: A few of spectra

E. V. Pagano et al. NIM A 889 (2018) 83-88

Some results: A few of spectra

- A few of spectra

- $5.4 \text{ MeV} \leq E_{\alpha} \leq 6.8 \text{ MeV}$

- $E_{\alpha} \approx 8.7 \text{ MeV}$

- $240 \text{ KeV} \leq E_{\gamma} \leq 2600 \text{ KeV}$

Plastic energy intrinsic resolution for Alpha particles:

$(E_{\alpha})$ of 8.7 MeV $\approx 15\%$
Some results: A few of spectra

Thorium + AmBe

- Slow Component (arb units)
- Fast Component (keVee)

α, n, γ
The latest results: tests in high background condition
The test was done during the Barrier experiment @ LNS $^{24}\text{Mg}+^{90,92}\text{Zr}$ @ 71.5MeV < E < 81 MeV

E. V. Pagano et al. NIM A 905 (2018) 47-52
The latest results: tests in high background condition
The test was done during the Barrier experiment @ LNS $^{24}\text{Mg}^{90,92}\text{Zr} @ 71.5\text{MeV} < E < 81 \text{MeV}$

E. V. Pagano et al. NIM A 905 (2018) 47-52

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The latest results: tests in high background condition

The test was done during the Barrier experiment @ LNS $^{24}\text{Mg}+^{90,92}\text{Zr}$ @ 71.5 MeV $< E < 81$ MeV
The latest results: tests in high background condition
The test was done during the Barrier experiment @ LNS $^{24}\text{Mg} + ^{90,92}\text{Zr} @ 71.5\text{MeV} < E < 81\text{ MeV} $

E. V. Pagano et al. NIM A 905 (2018) 47-52

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The graph shows the pulse amplitude over time with a distinction between fast and slow components. The decay time spectrum is also depicted, with different colors representing $Z=2$ and $Z=1$ elements. The yield as a function of decay time is presented for $Z=1$ and $Z=2$ elements. The figure also includes a total component slice at 3.7 - 4.2 MeVee and another slice at 0.5 - 1.0 MeVee with a FOM of 0.52.
Purposes of the project

Energy of interest: $5 \leq E \leq 100$ AMeV (having particular attention to the Fermi regime)

Nuclear fundamental physics

- Intensity interferometry (HBT effect)
  - n-n, n-p, n-LCP, n-IMF, n-TLF, n-PLF
- Studies related to the nuclear symmetry energy (EOS) and its dependence to the nuclear density
- Neutron stars (nuclear astrophysics)
- Reaction mechanism
- Reaction times
- Clustering
- Validation of nuclear dynamics model (BUU,QMD)
- Measurements of the neutron signal in the n-rich RIBs (SPES, SPIRAL2, FRIB, FAIR)

Some applications

- Radioprotection
- Measurement of neutron flux (single measurement, cross section)
- Validation of MC based code (GEAN4, MCNPX)
- Homeland security
Correlation functions

$$1 + R(q) = \frac{C_{\text{Corr}}(q)}{C_{\text{Uncorr}}(q)}$$

Intensity interferometry (HBT effect)

Space-time characterization of the emitting source
Purposes of the project: a few example for the fundamental nuclear physics

Intensity interferometry (HBT effect)

$1 + R(q) = \frac{C_{\text{Corr}}(q)}{Y_{\text{Uncor}}(q)}$

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FIG. 3. Angle-integrated correlation functions for two cuts on the total neutron pair momentum in the compound nucleus frame. The solid and dashed curves are results of theoretical calculations with the indicated emission time scales.
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N. Colonna et al., PRL 75, 23 (1995) 4190-4193

R. Ghetti et al., PRL 87, 10 (2001)

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Correlation functions

$$1 + R(q) = C \frac{Y_{\text{Corr}}(q)}{Y_{\text{Uncor}}(q)}$$

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\[ \varphi(q) = C_Y Y_{\text{unc}}(q) \]

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\[ S(\rho) = C_K (\rho / \rho_0)^2 + C_p (\rho / \rho_0)^\gamma \]

52Ca + 48Ca E/A = 80MeV

Central collision

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**Validation of Monte Carlo codes**

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**Neutron Camera**

Possible device for homeland security and health safety to be installed in airports, ports, etc...
Conclusions and perspective

The results carried out so far are with EJ276 coupled by PM are encouraging. It seems possible to build a versatile and modular detector for neutrons and light charged particles with high angular and energy resolution, read by using silicon technology and signal digitalization. The studies of the background and of the cross-talk problems and theirs influence on the experimental results are going on using the GEANT4 software.

The studies on the timing properties of the EJ-276 green version and its PSD capability, performed by using silicon technology (PD, or SIMP) are going on.

FIRST RESULT ON EJ276 green coupled with PD *

Preliminary results during Hoyle exp. @ LNS July 2019.

α + Au total energy beam 64 MeV

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\[ \begin{array}{|c|c|c|c|}
\hline
Yields (a. u.) & E (a. u.) & \text{Rise Time (a. u.)} \\
\hline
50 & 1000 & 2000 \\
200 & 1200 & 600 \\
300 & 1400 & 300 \\
400 & 1600 & 400 \\
\hline
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Thank you for the attention