Position-Sensitive Coincidence Detection of Two and Three Particle Nuclear Reactions

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Research carried out in frame of the Medipix Collaboration
2.5 MeV VdG at IEAP CTU in Prague

E = 0.3 – 2.5 MeV; I = 0.5-50 µA
p,d,\(^4\)He; \(^3\)He (future)
n (monochromatic 14-16 MeV, 4-5 MeV, 40-60 keV (future)
Outline

- Motivation, studied reactions/channels/resonances
  - Discrepancies in experimental (and theoretical) information of reaction $p + {^{11}}B$

- Instrumentation
  - VdG accelerators
    - Tandem VdG KINR Kiev
    - 0.3 - 2.5 MeV IEAP CTU Prague
  - Hybrid semiconductor pixel detector Timepix
  - Readout electronics,
  - integrated analog signal module
  - coinc/sync unit

- Position- and spectral-sensitive coincidence detection:
  - 2-particle reactions
  - 3-particle reactions

- Tests and studied reactions/sources:
  - $p + {^{11}}B$: $^{11}B(p,\alpha)^{8}Be \rightarrow 2\alpha$
  - $p + CH_4$: $(p,p)$
  - $^{226}Ra$: $\alpha$'s
Motivation I: \( p + ^{11}\text{B} \rightarrow ^{11}\text{B}(p,\alpha)^{8}\text{Be} \rightarrow 2\alpha \)

- Low energy reaction \( p+11\text{B} \rightarrow \)
  - charge particle induced **thermonuclear rates**
  - possible **aneutronic fusion reaction** as fuel for
    - space rocket propulsion
    - fusion reactors
- Measurement of angular and energy correlations
  - correct assignments of **reaction/resonance quantum numbers**
- Measurement of angular distributions
  - spectral and angular distribution of reaction products \( \rightarrow \) cross sections, spectroscopic factors, resonance characteristics, etc.,
  - **interference phenomena**, (transition from destructive to constructive phase etc.) \( \rightarrow \) shed light on aspects of reaction mechanism which are hard to be studied with traditional scattering experiments
  - information on yields, **directional information** (! for fusion & rocket purposes)
- Constructed a modular and configurable setup based on the semiconductor pixel detector Timepix and single silicon diode detectors for complete kinematics studies of three-, and four-particle final state reactions
- Experiments @ selected energies (**resonances**: 0.67 MeV, 2.64 MeV):
  - 5 MeV Tandem VdG, KINR Kiev (2012 tests, 2-3Q 2013 measurements)
  - 300 keV – 2.5 MeV VdG, IEAP CTU Prague (3-4Q, 2013)
  - 100 – 300 keV: … (future)
3x $\alpha$-particle nuclear reaction:
Renewed interest in aneutronic fusion fuel

Suggested at the **IEEE Symposium (2011) on Fusion Engineering** by **John J. Chapman**, a physicist and electronics engineer at **NASA's Langley Research Center** in VA, **aneutronic fusion** could improve space propulsion significantly. The new propulsion method is based on boron fuel rather than deuterium and tritium, the typical fuel for nuclear fusion.
3x $\alpha$-particle nuclear reaction: Novel fusion ion rocket propulsion

Advanced Fusion Reactors for Space Propulsion and Power Systems
John J. Chapman, NASA, Langley Research Center

Advanced clean fusion ion engine system uses scientifically proven concepts to offer a unique solution to space applications. Abundantly available, Boron-11 fuel undergoes transmutation via a pulsed p-B11 plasma process to produce thrust in a novel & efficient fashion. Nuclear gain enables a dramatic performance increase as compared to existing ionic propulsion and power technology. Efficiency improvements are due to delivery of high velocity ions from plasma to exhaust while eliminating the customary radioactive isotopes as fuel stocks and reaction by-products.
Motivation II: Timepix for true coincident detection for elemental analysis

- This method of detection of two products of two-particle reactions in true coincidences by applying Timepix detectors provides valuable approach for element analysis in thin (nano-, micro-meter scale) foils.
  - e.g. content and spatial distribution with high sensitivity and high spatial resolution of tritium in $T$ samples and $T$ targets

- True coincidence method allows for to enhance separation of rare admixtures by few orders of magnitude in comparison with traditional Rutherford back-scattering method.

- Scanning by micro-beam over the sample under the study one should be able to map the admixture position with a position resolution of the Timepix detector (10-20 $\mu$m).
The $^{11}\text{B}(p,\alpha)^{8}\text{Be} \rightarrow \alpha + \alpha$ and the $^{11}\text{B}(\alpha,\alpha)^{11}\text{B}$ Reactions at Energies Below 5.4 MeV

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Abstract Measurements of the absolute cross section and angular distributions for the $^{11}\text{B}(p,\alpha)^{8}\text{Be} \rightarrow \alpha + \alpha$ and the $^{11}\text{B}(\alpha,\alpha)^{11}\text{B}$ reactions have been performed from 0.15 to 3.8 MeV for the $^{11}\text{B}(p,\alpha)$ study and from 2 to 5.4 MeV for the $^{11}\text{B}(\alpha,\alpha)$ reaction. The absolute cross sections are presented in terms of the total number of $\alpha$-particles detected in order to avoid uncertainties due to ambiguities in the number of alpha particles emitted in the reaction at a particular energy. The angular distributions of the

Keywords Low energy nuclear physics · Aneutronic fusion · Fusion · Triple alpha · Energy production · $^{11}\text{B}$ · Alpha · Proton fusion · Alpha elastic scattering · Cross section · Angular distribution

Introduction

As previously discussed [1], the history of the study of the
Jine clanky + motivace
$^{12}$C: Energy levels
\[ ^8\text{Be: Energy levels} \]

\[
\begin{align*}
18.9122 & \quad ^9\text{Be} + ^3\text{He} - \alpha \\
18.8997 & \quad ^7\text{Be} + n \\
17.8198 & \quad ^{10}\text{B} + d - \alpha \\
16.7874 & \quad ^6\text{Li} + ^3\text{He} - p \\
16.0052 & \quad ^8\text{Li} \\
15.0306 & \quad ^7\text{Li} + d - n \\
16.626 & \quad 15.922 \\
17.2551 & \quad 16.6751 \\
16.0236 & \quad ^7\text{Be} + d - p \\
8.590 & \quad ^{11}\text{B} + p - \alpha \\
4.5918 & \quad ^9\text{Be} + d - t \\
4.571 & \quad ^{11}\text{B} + ^3\text{He} - ^6\text{Li} \\
0.2305 & \quad ^{10}\text{B} + n - t \\
-1.5657 & \quad ^5\text{Li} - \alpha - d \\
-1.6654 & \quad ^5\text{Be} + \gamma - n \\
0.5592 & \quad ^9\text{Be} + p - d \\
-0.5332 & \quad ^{10}\text{B} + p - ^3\text{He} \\
0.0042 & \quad ^{10}\text{Be} + p - t \\
\end{align*}
\]
3-particle reaction: $^{11}\text{B}(p,\alpha)^8\text{Be} \rightarrow 2\alpha$

Comparison of the two-step reaction simulation with data at $\theta_{\text{lab}} = 90^\circ$ and $E_p = 2.64$ MeV. The sharp peak at 7.26 MeV corresponds to the $\alpha_0$ channel.
3-particle reaction: $^{11}\text{B}(p,\alpha)^8\text{Be} \rightarrow 2\alpha$

Comparison of the two-step reaction simulation using $\ell = 1$ with data at $\theta_{\alpha}^{\text{lab}} = 90^\circ$ and $E_p = 0.675$ MeV.

Comparison of the two-step simulation using $\ell = 3$ with data at $\theta_{\alpha}^{\text{lab}} = 90^\circ$ and $E_p = 0.675$ MeV.

3-particle reaction: $^{11}\text{B}(p,\alpha)^8\text{Be} \rightarrow 2\alpha$

Coincidence spectra for $E_p = 0.675$ MeV (top) and 2.64 MeV (bottom) at the same lab $\alpha-\alpha$ opening angle of 150°. The spectra have been normalized so that the maximum in the $z$ direction is 1.0. The vertical and horizontal slices in the lower figure removed the elastic events.
Interference phenomena

Reaction: \( p + ^{11}B \rightarrow \alpha + ^{8}Be \rightarrow \alpha_1 + \alpha_2 + \alpha_3 \)

- Kinematical curve: \( E_2(E_1) \)
- \(^{8}Be^* (3.0\ MeV)\)
- \( E_p = 2.65\ MeV \)
- \( \Theta_1 = 45^\circ \)
- \( \Theta_2 = 120^\circ \)
- \( \phi_1 - \phi_2 = 0^\circ \)

\( E_x (^{8}Be) = E_{rel} + E_{th} \)
KINR Kiev
5 MeV Tandem VdG
KINR Kiev
Ion beam, chamber, team, setup
Hybrid semiconductor pixel detector Timepix: per-pixel E, t sensitivity

- Single particle counting (no dark current)
- Per-pixel energy and time sensitivity
- Hybrid technology allows the use of different semiconductor sensors (e.g., Si, CdTe, GaAs) and sensor thickness.
- Pulse processing electronics provides simultaneously fast and noise free images.
- Integrated readout interface: online visualization, trigger in/out.

Pixelman SW tool: control & online visualization [J. Jakubek, D. Turecek]
Timepix [TOT] @ focal plane
Position & Energy

Sao Paulo Pelletron VdG
24 MeV $^9$Be onto $^7$Li target → reaction products

E = 24.4 MeV
A = 137 px
C = 921 keV

E = 30.7 MeV
A = 147 px
C = 365 keV

E = 23.8 MeV
A = 142 px
C = 861 keV

E = 5.0 MeV
A = 52 px
C = 1.3 MeV

E = 23.8 MeV
A = 392 px
C = 332 keV

E = 5.6 MeV
A = 71 px
C = 362 keV

E = 9.5 MeV
A = 62 px
C = 116 keV

E = 3.5 MeV
A = 66 px
C = 118 keV

E = 20.8 MeV
A = 141 px
C = 525 keV

E = 20.8 MeV
A = 110 px
C = 380 keV

E = 11.8 MeV
A = 110 px
C = 525 keV

23.8 MeV

5.6 MeV

3.5 MeV

20.8 MeV
Timepix + KINR VdG Kiev: 2- and 3- particle reactions

\[ ^1H(p,p)^1H \quad E_p = 2.65 \text{ MeV} \]

\[ ^{11}B(p,\alpha)^8\text{Be} \rightarrow 2\alpha \quad E_p = 2.65 \text{ MeV} \]
Timepix + FITPix R/O interface + Pixelman SW: Position– and energy– sensitive detection

α’s from $^{226}$Ra in vacuum, KINR Kiev
VdG - 7.5.2013

Spatial distribution of event position

$1^{st}$ frame: Fri May 17 18:29:22
Last frame: Fri May 17 18:43:03
Total # of frames acquired in 14 min total measuring time = 6 k. Total 17.7 k events with single filter condition (cluster area < 4 px). Acquisition time in the px detector (shutter time) = 0.1 s.
Partial distributions – according to energy range (as indicated by green curve).

A > 40 px
Cal
9.7 k events

A > 106 px
Cal
2.0 k events
Partial distributions – according to energy range (as indicated by green curve).

9.7 k events

A > 40 px

Corrected for per-pixel ToT saturation/distortion

4601 keV

4784 keV

5489 keV

7687 keV
Partial distributions – according to energy range (as indicated by green curve).

5.0 MeV < E < 5.5 MeV
CAL
2.6 k events

Integrated over many frames
Partial distributions – according to energy range (as indicated by green curve)

7.8 MeV < E < 8.6 MeV
CAL
2.0 k events
2.65 MeV p + CH₄: p + p elastic scattering

- Si diode (trigger) + 1x Timepix
tests, long data taken

- 2x Timepix in coincidence, sync DAQ
tests, more data

- 3x Timepix in coincidence, sync DAQ
future
2.65 MeV $p + CH_4$: $p + p$ elastic scattering
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2.65 MeV $p + \text{CH}_4$: $p + p$ elastic scattering
2.65 MeV $p + CH_4$: $p + p$ elastic scattering
2.65 MeV p + CH₄: p + p elastic scattering

Geometry & vertex reconstruction: plane of the event pair

4 event pairs
2.65 MeV $p + CH_4$: $p + p$ elastic scattering

Geometry & vertex reconstruction: plane of the event pair

100 event pairs
2.65 MeV $p + CH_4$: $p + p$ elastic scattering

Distribution of angles

- $p+p$: X-plane projection
- $p+p$: plane of particles
2.65 MeV p + CH$_4$: p + p elastic scattering

Geometry & vertex reconstruction: plane of the detectors

100 event pairs
2.65 MeV p + $^{11}$B: $^{11}$B(p,$\alpha$)$^8$Be $\rightarrow$ 2$\alpha$

Si diode + Timepix: setups

- Si diode (trigger) + 1x Timepix
tests, long data taken

- 2x Timepix in coincidence, sync DAQ
tests, more data

- 3x Timepix in coincidence, sync DAQ
future
Correlation: on-line
Si diode & Timepix analog signal
Correlation: off-line
Si diode & Timepix pixelated signal

Coincidence between Si-diode (45°) and TimePix (120°) in $^{11}\text{B} + p \rightarrow 3\alpha$ reaction.
Processed files: D00.028-D00.034
2.65 MeV p + $^{11}$B: $^{11}$B(p,α)$^{8}$Be → 2α

Si diode (trigger) + Timepix

Spatial distribution

Energy spectra

1065 events

577 events

284 events
2.65 MeV $p + ^{11}\text{B}$: $^{11}\text{B}(p,\alpha)^{8}\text{Be} \rightarrow 2\alpha$

2x Timepix in sync
2.65 MeV p + $^{11}\text{B}$: $^{11}\text{B}(p,\alpha)^{8}\text{Be} \rightarrow 2\alpha$

2x Timepix in sync
2.65 MeV p + $^{11}$B: $^{11}$B(p,α)$^8$Be → 2α

2x Timepix in sync
2.65 MeV p + $^{11}$B: $^{11}$B(p,α)$^{8}$Be → 2α

2x Timepix in sync
2.65 MeV p + $^{11}$B: $^{11}$B(p,α)$^{8}$Be → 2α
Si diode (trigger) + Timepix

In 1 k f’s, each 0.3 ms → total measuring t = 300 ms, found 393 pairs.
2.65 MeV p + $^{11}$B: $^{11}$B(p,α)$^{8}$Be → 2α

2x Timepix in sync

Geometry & vertex reconstruction: plane of the detectors

80 pairs
2.65 MeV $p + ^{11}B$: $^{11}B(p,\alpha)^8Be \rightarrow 2\alpha$

2x Timepix in sync

Geometry & vertex reconstruction: plane of the detectors

390 pairs

Further analysis and work in progress
Conclusions

- The granularity and per-pixel energy/time sensitivity of Timepix allows performing spatial- and time-correlated detection of reaction products with high spatial and time resolution and enhanced signal-to-noise resolving power.
- Constructed a modular and configurable setup based on the semiconductor pixel detector Timepix and single silicon diode detectors for complete kinematics studies of three-, and four-particle final state reactions.
- Instrumentation
  - Developed, configured, calibrated
  - Tested, demonstration of proof-of-principle
- Tests & experiments
  - Tests and proof-of-principle measurements done
  - Long measurements started
- Extension at
  - other resonances
  - Lower p energies (100 keV – 300 keV)

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