FIRST MEASUREMENT WITH TROJAN HORSE METHOD USING RADIOACTIVE ION BEAM

$^{18}\text{F} + p \rightarrow ^{15}\text{O} + \alpha \ @ \ CRIB$

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Summary

- Astrophysical motivations & State of Art
- Indirect measurement by Trojan Horse Method
- Experimental set-up → new apparatus for RIB application
- Data Analysis and preliminary results
Astrophysical motivations

- Gamma-ray emission of energy 511keV from novae is dominated by the positron annihilation following the $\beta^+$ decay of unstable nuclei
- $^{18}\text{F}$ is especially important because
  - It is produced relatively abundantly
  - Its lifetime of $\sim 158$ min is well matched to the timescale for nova ejecta to become transparent to $\gamma$-ray emission
- The $^{18}\text{F}(p,\alpha)^{15}\text{O}$ reaction influence the $^{15}\text{O}$ production considered as a key isotope for the escape from the hot-CNO cycle to the $\text{rp}$-process

\[ ^{18}\text{F}(p,\alpha)^{15}\text{O} \]

S(E) dominated by several resonances of $^{19}\text{Ne}$
State of Art

Many experiments performed using 18F beam @ ARGONNE - ATLAS LLN ORNL TRIUMF GANIL- SPIRAL RIKEN – CRIB TAMU

Direct measurements → thick target method
Indirect measurement → (d,p) (d,n) stripping reaction

Most recent references:

D. J. Mountford et al PHYSICAL REVIEW C 85, 022801(R) (2012)
“Resonances in 19Ne with relevance to the astrophysically important 18F( p,α)15O reaction.”

A. S. Adekola et al. PHYSICAL REVIEW C 83, 052801(R) (2011)
“First proton-transfer study of 18F + p resonances relevant for novae”

C. E. Beer et al. PHYSICAL REVIEW C 83, 042801(R) (2011)
“Direct measurement of the 18F( p,α)15O reaction at nova temperatures”
New measurement @ CRIB by using the Trojan Horse Method

\[ A \ (x+s) + B \rightarrow C + D + S \]

\[ B + x \rightarrow C + D \]

\[ E_{BA} > E_C \]

\[ E_{BA} = A-B \text{ relative energy} \]

\[ E_C = A-B \text{ Coulomb Barrier} \]

\[ E_{Bx} = E_{CD} - Q^{2\text{Body}}_{\text{pcp}} \]

\[ ^{18}F + d \rightarrow ^{15}O + \alpha + n \]

\[ ^{18}F + p \rightarrow ^{15}O + \alpha \]

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TURNING THE IDEA INTO PRACTICE

Assuming the QF mechanism is dominant the process can be represented in Feynman diagrams

Three body reaction  \begin{align*}
\begin{array}{c}
A \\
\downarrow \ x \\
\downarrow C \\
B \\
\end{array}
\rightarrow
\begin{array}{c}
S \\
\downarrow \ x \\
\downarrow D \\
C \\
\end{array}
\end{align*}

Virtual decay  \begin{align*}
\begin{array}{c}
A \\
\downarrow \\
S \\
\end{array}
\end{align*}

Virtual reaction  \begin{align*}
\begin{array}{c}
x \\
\downarrow \\
C \\
\end{array}
\end{align*}

Half off-shell (astrophysical process)

In PWIA:

\[ \frac{d^3 \sigma}{d\Omega_C \; d\Omega_B \; dE_C} = K F \cdot |\Phi (P_s)|^2 \times \frac{d\sigma}{d\Omega} \]

Measured at high energy

Calculated e.g. Montecarlo

Deduced

Need direct data for normalization

\[ E_{Bx} = E_{CD} - Q^{2\text{body}} \]
“Plus” of the TH methods

1) Typical QF process cross sections (mbarn/sr) though measuring astrophysical ones

2) The TH cross sections is the purely NUCLEAR one: no Coulomb barrier effects

3) No electron screening effects: an INDEPENDENT piece of information can be obtained on the electron screening potential $U_e$ by comparison to direct data

4) Can be extended to use QFR for studying NEUTRON induced reactions (VNM Virtual Neutron Method)

“Minus” of the TH methods

1) Competition between QF and other reaction mechanisms: identification of the convenient kinematical conditions may need more than one experiment run

2) Some dependence on theoretical models

3) Need of direct data at higher energies for normalization

BEAM PRODUCTION

$^1^8$O$(p,n)^{1^8}$F

$^{18}$O$^+8$ @ 4.5-5 MeV/A from AVF cyclotron

gas target $^2$H

Double-achromatic magnetic separator

Scattering chamber

Wien filter

CRIB set-up

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### $^{18}$F beam development

<table>
<thead>
<tr>
<th>Year</th>
<th>BTU type</th>
<th>Prod. Target type</th>
<th>Peak intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>Beam dev</td>
<td>Room temp.</td>
<td>$\sim 10^5$</td>
</tr>
<tr>
<td>2007</td>
<td>Thick target experiment</td>
<td>Liquid N cooled</td>
<td>$5 \times 10^5$</td>
</tr>
<tr>
<td>2008</td>
<td>Trojan Horse experiment</td>
<td>Liquid N cooled</td>
<td>$&gt; 10^6$</td>
</tr>
</tbody>
</table>

Primary beam: $^{18}$O $^{8+}$, 4.5-5 MeVA

Production target: $\text{H}_2$

Production reaction: $^{18}$O(p,n)$^{18}$F

BEAM PURITY > 98%

$E_{\text{beam}} = 48.7$ MeV

$\sigma = 0.8$ MeV
EXPERIMENTAL SETUP

(Other than CRIB.....)

ASTRHO: Array of Silicons for TRojan HOrse

Beam @PPAC
2.4 \( \cdot 10^6 \) pps
48.7 ± 0.8 MeV

Beam track reconstruction
event by event

PPAC  MCP  CD2
In order to allow for the optimization of the two experiments ASTRHO and the DSSSD were hosted in a mechanical system that allowed for easy movement of the detector holder plates.
EXPERIMENTAL SETUP

How ASTRHO looks like in reality
(before PPAC explosion...)

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Beam track reconstruction event by event

xppc1

yppc1

xppc2

yppc2

xt

yt

y

θ_1

θ_2

BEAM TRACKER

PPAC

MCP

target

DSSiSD

DPSSD

BEAM TRACKER

x

y

z

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CUTS:

- Event multiplicity = 2
- $|T_2 - T_1| \leq 0$
- $E1 > 20$ MeV

Q-VALUE SPECTRUM

$^{18}F+d \rightarrow ^{15}N + \alpha + p \ @ \ q = 4.194$ MeV

$^{18}F+d \rightarrow ^{15}O + \alpha + n \ @ \ q = 0.658$ MeV

$^{18}F+d \rightarrow ^{18}O + p + p \ @ \ q = 0.213$ MeV

$^{18}F+d \rightarrow ^{18}F + p + n \ @ \ q = -2.225$ MeV
EVENT SELECTION

Red: $^{18}F + d \rightarrow ^{15}N + \alpha + p$
Black: $^{18}F + d \rightarrow ^{15}O + \alpha + n$
Blue: $^{18}F + d \rightarrow ^{18}F + p + n$
Green: $^{18}F + d \rightarrow ^{18}O + p + p$

“1”+“2”+“3”
CUTS:

- Event multiplicity = 2
- $|T_2 - T_1| \approx 0$
- $E_1 > 20$ MeV
- Correlation $E_{13} - E_{12}$
- Correlation $E_1 - \theta_1$

GOOD AGREEMENT with

- q-value expected position (0.658 MeV)
- and beam profile (exp. Sigma 0.8 MeV)
HINTS FOR QF MECHANISM

If the quasi-free mechanism is predominant

\[
\frac{d^3\sigma}{d\Omega_{^1S_0} d\Omega_{\alpha} dE_{\alpha}} \propto K F \left| \Phi(p_s) \right|^2 \cdot \frac{d\sigma^N}{d\Omega}
\]

Minimum of \( p_s \)

Counts

10<\( p_s <40 \) (MeV/c)

40<\( p_s <70 \) (MeV/c)

70<\( p_s <100 \) (MeV/c)

\( E_{^{15}O} \) (MeV)

Hulten function

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BARE NUCLEUS CROSS SECTION

FIRST TROJAN HORSE experiment with RIB !!!

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Conclusions and Perspective

- THM was successfully applied to radioactive ion beam induced reaction

- The beam is tracked event by event and the kinematical variables were consequently reconstructed

- The preliminary results showed the possibility to study the cross section of the $^{18}\text{F}(p,a)^{15}\text{O}$ reaction and extract complementary information on $S(E)$ factor → (work in progress)

- Increase statistic and confirm the results with a second experimental run

- Possibility to measure the $^{18}\text{F}(n,a)^{15}\text{N}$ reaction
BARE NUCLEUS CROSS SECTION

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Trojan Horse for Resonance Reactions

HALF OFF-SHELL

\[
\frac{d^2\sigma^{TH}}{d\Omega_{k_F} dE_{CC}} = \frac{1}{2\pi} \frac{\Gamma_{cc}(E_{cc})}{(E_{cc} - E_{Re_c})^2 + \frac{1}{4}\Gamma^2(E_{cc})} \times \frac{d\sigma_{(a+A\rightarrow s+F)}}{d\Omega_{k_F}},
\]

ON-SHELL

\[
\sigma_{(x+A\rightarrow c+C)}^{R} = \frac{\pi}{k_{xA}^2} \frac{\hat{j}_F}{\hat{j}_A \hat{j}_a} \frac{\Gamma_{cc}(E_{cc}) \Gamma_{xA}(E_{xA})}{(E_{cc} - E_{Re_c})^2 + \frac{1}{4}\Gamma^2(E_{cc})}.
\]

\[
\Gamma_{xA}(E_{xA}) = 2 P_l(E_{xA}, r_0) \gamma_{xA}^2,
\]

Penetrability

Independent from spectroscopic factor value
Collaborators


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T. Komatsubara, N. Iwata, T. Teranishini
CUTS

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