Experimental Study of Photodisintegration Cross Sections on $^3$He and $^4$He at Low Energies

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Outline

• $^3\text{He}(\gamma,pd) \sigma_{\text{tot}}$ between $E_\gamma = 7$ and 16 MeV

• $^4\text{He}(\gamma,pt) \sigma_{\text{tot}}$ between $E_\gamma = 22$ and 29.5 MeV

• $^4\text{He}(\gamma,^3\text{He})n \sigma_{\text{tot}}$ between $E_\gamma = 27 - 28$ MeV

• $^3\text{He}(n,n)^3\text{He} A_y(\theta)$ between $E_n = 1.6$ and 5.4 MeV
Quasi monoenergetic $\gamma$-ray flux on target: $>10^8$ s$^{-1}$

Tunable from 1 to 97 MeV
100% linear or circular polarization
Energy resolution determined by Collimation; no need for tagging

Vladimir Litvinenko (1992)
HI$\gamma$S Facility at TUNL
$^3\text{He}(\gamma,\text{pd})$

$Q = -5.49 \text{ MeV}$
$^{3}\text{He}(\gamma,p)^2\text{H}$

solid symbols: photons
open symbols: p-d capture
crosses: electrons

$\sigma$ (mb)

$E_\gamma$ (MeV)

Naito et al. (2006)
Skopik et al. (1979)
Ticcioni et al. (1973)
Matthews et al. (1973)
vanderWoude et al. (1971)
Kundu et al. (1971)
Belt et al. (1970)
Woelfli et al. (1966)
Fetisov et al. (1964)
Warren et al. (1963)
Griffiths et al. (1962)
~1.7 MeV $\gamma$-ray energy width

$10^4$ $\gamma$ rays per second

Shima et al., 2005
Time projection chamber as target as detector
We don’t have a time-projection chamber

We used $^3$He-Xe high-pressure gas scintillators instead

Xe admixture (~5 – 10%) is needed:

a) to increase light output, i.e., energy resolution
b) provide stopping power for the protons within scintillator volume (proton energies vary from 1.1 MeV at $E_\gamma=7$ MeV to 7.6 MeV at $E_\gamma=16$ MeV)
Construction

1 mm thick stainless steel

1 cm thick glass window

Glue Maxos glass window into cap
Araldit + Hardener
• MgO creates white film on gas cell walls
- Evaporate Diphenylstilbene (DPS) onto glass window and inside of gas cell
- DPS shifts the wavelength from 340 nm to 410 nm
• Fill cell with $^3$He (95%) and Xenon (5%)
  - (Xenon is also a wavelength shifter)
• Attach PMT to gas cell
• Pressure test cell bringing pressure to 1000 psi
• Response function is linear
• Light output is independent of particle type
• Energy resolution is energy dependent
• $^3$He-Xe gas scintillators have very good energy resolution (2-10%)
$^3$He and Xe pressures used for $^3$He($\gamma$,pd) experiment

- 42 psi Xe & 458 psi $^3$He at 6.96 and 7.93 MeV
- 148 psi Xe & 602 psi $^3$He at 8.78, 9.85, 10.85, 12.78 MeV
- 132 psi Xe & 528 psi $^3$He at 12 MeV
- 300 psi Xe & 450 psi $^3$He at 12.78 MeV
- 294 psi Xe & 442 psi $^3$He at 14, 15, 16 MeV
Edge Effects: Range of protons <1 cm
Photon Flux Determination

1) Move $^3$He - Xe gas scintillator out of the photon beam
2) Reduce $\gamma$-ray flux to a few kHz rate
3) Move NaI scintillator of known efficiency into photon beam
4) Take data to determine ratio of Plastic Scintillator Paddle and NaI detector counts
5) Move NaI detector out of the photon beam
6) Move $^3$He - Xe gas scintillator into the photon beam
7) Increase $\gamma$-ray flux to about 1 MHz
8) Take $^3$He($\gamma$,pd) data
9) Use Plastic Scintillator Paddle yield and 4) to determine $\gamma$-rays used in 8)
Statistical Uncertainty: <1%
Systematic Uncertainty: 4% (NaI detector efficiency)

Check on $\gamma$-ray flux via Compton scattering from a Cu plate into an off-axis HPGe detector at energies below 10 MeV

Check on $\gamma$-ray flux determination via activation: $^{197}\text{Au}(\gamma,n)^{196}\text{Au}$ between 12 and 16 MeV
$^3\text{He}(\gamma,p)^2\text{H}$

solid symbols: photons
open symbols: p-d capture
crosses: electrons

$E_\gamma$ (MeV) vs. $\sigma$ (mb)

Data from:
- Naito et al. (2006)
- Skopik et al. (1979)
- Ticcioni et al. (1973)
- Matthews et al. (1973)
- van der Woude et al. (1971)
- Kundu et al. (1971)
- Belt et al. (1970)
- Woelfli et al. (1966)
- Fetisov et al. (1964)
- Warren et al. (1963)
- Griffiths et al. (1962)
\[ ^3\text{He}(\gamma,p)^2\text{H} \]
Electromagnetic interactions of 4N systems

\[ \gamma + ^{4}\text{He} = ^{3}\text{H} + p \quad Q = -19.81 \text{ MeV} \]
\[ \gamma + ^{4}\text{He} = ^{3}\text{He} + n \quad Q = -20.58 \text{ MeV} \]
\[ \gamma + ^{4}\text{He} = d + d \quad Q = -23.85 \text{ MeV} \text{ (isospin forbidden)} \]
\[ \gamma + ^{4}\text{He} = d + n + p \quad Q = -26.07 \text{ MeV} \]
\[ \gamma + ^{4}\text{He} = n + p + n + p \quad Q = -28.30 \text{ MeV} \]
${}^4\text{He}(\gamma,pt)$

Now using $^4$He-Xe gas scintillators

<table>
<thead>
<tr>
<th>Photon Energy (MeV)</th>
<th>Xe (psi)</th>
<th>$^4$He (psi)</th>
<th>Proton Energies (MeV)</th>
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</thead>
<tbody>
<tr>
<td>22.0</td>
<td>50</td>
<td>700</td>
<td>1.3 - 1.9</td>
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<tr>
<td>22.5</td>
<td>50</td>
<td>700</td>
<td></td>
</tr>
<tr>
<td>23.0</td>
<td>150</td>
<td>605</td>
<td>1.9 – 2.8</td>
</tr>
<tr>
<td>23.5</td>
<td>150</td>
<td>605</td>
<td></td>
</tr>
<tr>
<td>24.0</td>
<td>150</td>
<td>605</td>
<td>2.6 – 3.6</td>
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<tr>
<td>24.5</td>
<td>200</td>
<td>400</td>
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</tr>
<tr>
<td>25.0</td>
<td>200</td>
<td>400</td>
<td>3.3 – 4.4</td>
</tr>
<tr>
<td>25.5</td>
<td>200</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>26.0</td>
<td>250</td>
<td>500</td>
<td>3.9 – 5.2</td>
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<td>26.5</td>
<td>250</td>
<td>500</td>
<td></td>
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<tr>
<td>27.0</td>
<td>250</td>
<td>500</td>
<td>4.6 – 6.1</td>
</tr>
<tr>
<td>27.5</td>
<td>250</td>
<td>500</td>
<td></td>
</tr>
<tr>
<td>28.0</td>
<td>350</td>
<td>400</td>
<td>5.3 – 6.9</td>
</tr>
<tr>
<td>28.5</td>
<td>350</td>
<td>400</td>
<td></td>
</tr>
<tr>
<td>29.0</td>
<td>350</td>
<td>400</td>
<td>6.0 – 7.7</td>
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<tr>
<td>29.5</td>
<td>350</td>
<td>400</td>
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</table>
### Photon-induced reaction thresholds (in MeV) on xenon isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Nat. Abundance (%)</th>
<th>(γ,p)</th>
<th>(γ,α)</th>
<th>(γ,n)</th>
<th>(γ,2n)</th>
<th>(γ,nα)</th>
</tr>
</thead>
<tbody>
<tr>
<td>128</td>
<td>1.92</td>
<td>8.17</td>
<td>1.77</td>
<td>9.61</td>
<td>16.84</td>
<td>11.19</td>
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<td>129</td>
<td>26.44</td>
<td>8.25</td>
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<td>6.91</td>
<td>16.52</td>
<td>8.68</td>
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<td>131</td>
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<td>2.55</td>
<td>6.61</td>
<td>15.87</td>
<td>8.85</td>
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<td>132</td>
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<td>3.66</td>
<td>7.99</td>
<td>14.44</td>
<td>11.73</td>
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</table>

### Photon-induced reaction thresholds (in MeV) on magnesium isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Nat. Abundance (%)</th>
<th>(γ,p)</th>
<th>(γ,α)</th>
<th>(γ,n)</th>
<th>(γ,2n)</th>
<th>(γ,nα)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24</td>
<td>78.99</td>
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<td>9.31</td>
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<td>25</td>
<td>10.00</td>
<td>12.06</td>
<td>9.89</td>
<td>7.33</td>
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<tr>
<td>26</td>
<td>11.01</td>
<td>14.15</td>
<td>10.61</td>
<td>11.09</td>
<td></td>
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</tbody>
</table>
Photon-induced reaction thresholds (in MeV) on oxygen isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Nat. Abundance (%)</th>
<th>(γ,p)</th>
<th>(γ,α)</th>
<th>(γ,n)</th>
<th>(γ,2n)</th>
<th>(γ,nα)</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>99.762</td>
<td>12.13</td>
<td>7.16</td>
<td>15.67</td>
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<tr>
<td>17</td>
<td>0.038</td>
<td>13.78</td>
<td>6.36</td>
<td>4.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>0.200</td>
<td>15.94</td>
<td>6.23</td>
<td>8.05</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Compton scattered electrons $E_\gamma = 22$ MeV

- $^4\text{He}$ (47.6 atm) + Xe (3.4 atm) Target
- $^4\text{He}(\gamma,p)^3\text{H}$

Compton scattered electrons $E_\gamma = 22$ MeV

- Xe (3.4 atm) Target

Compton scattered electrons $E_\gamma = 28$ MeV

- $^4\text{He}(\gamma,p)^3\text{H}$
- $^4\text{He}$ (27.2 atm) + Xe (23.8 atm) Target

Compton scattered electrons $E_\gamma = 28$ MeV

- Xe (23.8 atm) Target
\[ ^4\text{He}(\gamma,p)^3\text{H} \]

**Graph:**
- **Y-axis:** $\sigma$ (mb)
- **X-axis:** $E_\gamma$ (MeV)

- Blue triangles: Present data
- Green circle: T. Shima et al. (2005)
- Red line: S. Quaglioni et al.

The graph shows a plot of differential cross-section $\sigma$ versus photon energy $E_\gamma$. The data points and curves represent different sets of measurements and calculations for the reaction $^4\text{He}(\gamma,p)^3\text{H}$. The spread and precision of the data points are marked with error bars.
Circles: old data of Shima et al.
Dots: new data of Shima et al.

W. Horiuchi
Y. Suzuki
K. Arai

Solid: AV8'
Dashed: G3RS + 3NF (Tamagaki)
Dotted: LIT with Malfliet Tjon
$^4\text{He}(\gamma,^3\text{He})n$
MAX - lab at Lund, Sweden

$\sim 300 \text{ keV } \gamma$-ray energy width

$10^5 \gamma$ rays per second

$^4\text{He}(\gamma, n)^3\text{He}$

Neutron detectors

Bremsstrahlung tagging technique
$^4\text{He}(\gamma, ^3\text{He})n$ at $E_\gamma = 28$ MeV

$^4\text{He}(\gamma, pt)$ at 28 MeV
$^3\text{He}$ from $^4\text{He}(\gamma, ^3\text{He})n$

$(\gamma, x)$ on Xe, Mg and O

Tritons and partially stopped protons from $^4\text{He}(\gamma, \text{pt})$

Xenon only
Circles: old data of Shima et al.
Dots: new data of Shima et al.
Triangles: Nilsson et al.

W. Horiuchi
Y. Suzuki
K. Arai

Solid: AV8’ = 3NF
Dashed: G3RS + 3NF
Dotted: LIT Malfliet-Tjon
What's next?

${}^3\text{H}(\gamma,p)2n$
Di-neutron and the three-nucleon continuum observables

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We investigate how strongly a hypothetical $^1S_0$ bound state of two neutrons would affect observables in neutron-deuteron reactions. To that aim we extend our momentum-space scheme of solving the three-nucleon Faddeev equations and incorporate in addition to the deuteron also a $^1S_0$ di-neutron bound state. We discuss effects induced by a di-neutron on the angular distributions of the neutron-deuteron elastic scattering and deuteron breakup cross sections. A comparison to the available data for the neutron-deuteron total cross section and elastic scattering angular distributions cannot decisively exclude the possibility that two neutrons can form a $^1S_0$ bound state. However, strong modifications of the final-state-interaction peaks in the neutron-deuteron breakup reaction seem to disallow the existence of a di-neutron.

DOI: [10.1103/PhysRevC.85.064003](https://doi.org/10.1103/PhysRevC.85.064003)  
PACS number(s): 21.45.Bc, 25.10.+s, 25.40.Dn
TABLE I. The di-neutron binding energy $\epsilon_{nn}$, the nn scattering length $a_{nn}$, and the effective range parameter $r_{eff}$ for different factors $\lambda$ by which the nn $^1S_0$ component of the CD Bonn potential was multiplied.

<table>
<thead>
<tr>
<th>$\lambda$</th>
<th>$\epsilon_{nn}$ [MeV]</th>
<th>$a_{nn}$ [fm]</th>
<th>$r_{eff}$ [fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>–</td>
<td>-8.25</td>
<td>3.12</td>
</tr>
<tr>
<td>1.0</td>
<td>–</td>
<td>-18.80</td>
<td>2.82</td>
</tr>
<tr>
<td>1.19</td>
<td>-0.099</td>
<td>+21.69</td>
<td>2.39</td>
</tr>
<tr>
<td>1.21</td>
<td>-0.144</td>
<td>+18.22</td>
<td>2.35</td>
</tr>
<tr>
<td>1.3</td>
<td>-0.441</td>
<td>+10.95</td>
<td>2.20</td>
</tr>
<tr>
<td>1.4</td>
<td>-0.939</td>
<td>+7.87</td>
<td>2.07</td>
</tr>
</tbody>
</table>
Changing Topics:

\[ A_y(\theta) \text{ in } ^3\text{He}(n,n)^3\text{He} \]

and Comparison to \(^3\text{He}(p,p)^3\text{He}\) at Low Energies
FIG. 2 (color online). The differential cross section and proton analyzing power $A_y$ at 2.25, 4.0, and 5.54 MeV proton lab energy. Results including the Coulomb interaction obtained with potentials CD Bonn (solid curves), AV18 (dashed curves), INOY04 (dashed-dotted curves), and N3LO (dotted curves) are compared. The data are from Refs. [22,32,33].

A. Deltuva and A. Fonseca (Lisbon)
E_n=1.60 MeV

Data: ^3He(n,n)^3He
J.H. Esterline

Dashed blue: AV18
Solid orange: CD-Bonn
Dotted red: CD-Bonn + Δ
Dashed-dotted green: INOY04

Calculations:
A. Deltuva & A. Fonseca

E_n=2.26 MeV

E_n=3.14 MeV

E_n=4.05 MeV

E_n=5.54 MeV
Triangles: $^3$He(p,p)$^3$He
Circles: $^3$He(n,n)$^3$He

CD-Bonn     INOY04 (Doleschall)
A. Deltuva (Lisbon)
Acknowledgments

J.H. Esterline
M.W. Ahmed
A.S. Crowell
H.J. Karwowski
J.H. Kelley
R. Pywell
R. Raut
G. Rusev
S.C. Stave
A.P. Tonchev

and to all the theoreticians I had the pleasure to interact with.