Luminosity determination for the WASA-at-COSY experiment - analysis of the $dd \rightarrow ^3He n$ reaction

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Luminosity determination

Spectator model - $dd \rightarrow ppn_{sp}n_{sp}$ reaction

$dd \rightarrow ^{3}\text{He}n$

$L = \frac{N}{\sigma \epsilon}$

$N$-number of experimental events

$\sigma$-cross section for $dd \rightarrow ^{3}\text{He}n$ reaction

$\epsilon = \frac{A_{acc}}{A_{gen}}$-detection efficiency

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Simulation of $dd \rightarrow ^3He + n$ reaction

1. $p_{beam}$ is generated with uniform probability density distribution in the range of $p_{beam} \in (2.127, 2.422) \text{GeV/c}$.

2. The neutron and $^3\text{He}$ momentum vectors are simulated isotropically in the CM frame in spherical coordinates ($\cos \theta^*$ is generated with uniform probability density distribution in the range of -1 to 1 while $\phi^*$ in the range of $-\pi$ to $\pi$) and transformed into Cartesian coordinates.

3. Four-momenta of $^3\text{He}$ and neutron are calculated in the CM system.

4. The differential cross section $\frac{d\sigma(t-t_{\text{max}})}{dt} = \sum_{i=1}^{3} a_i e^{b_i(t-t_{\text{max}})}$ is calculated for each event for appropriate $p_{beam}$ and $\Delta t = (t - t_{\text{max}}) = 2 \cdot |\vec{p}_{beam}| \cdot |\vec{p}_{^3\text{He}}^*| \cdot (\cos \theta^* - 1)$ values.

5. Each event is saved with probability given by the cross section.

6. WASA Monte Carlo (simulation of the detection system response by geant) is carried out for generated events.
• $\sigma_{dd \rightarrow ^3He n}$ is a function of transferred momentum squared $t = (P_{^3He} - P_{beam})^2$ and beam energy $E_{beam}$

• t-spectra measured in experiment fitted with the sum of exponentials: $\frac{\sigma(t-t_{max})}{dt} = \sum_{i=1}^{3} a_i e^{b_i(t-t_{max})}$

• energy dependance of fit parameters was fitted with hyperbolical functions: $par_i(\sqrt{s_{dd}}) = \frac{p_i}{\sqrt{s_{dd}} - q_i} + r_i$

<table>
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<tr>
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<th>$p_i$</th>
<th>$q_i$</th>
<th>$r_i$</th>
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<td>$a_1$</td>
<td>11.64</td>
<td>4.05</td>
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<td>9.04</td>
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<tr>
<td>$a_3$</td>
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<td>4.08</td>
<td>1.24</td>
</tr>
<tr>
<td>$b_3$</td>
<td>0.78</td>
<td>3.92</td>
<td>9.04</td>
</tr>
</tbody>
</table>
Differential cross section $dd \rightarrow ^3He n$
Differential cross section $dd \rightarrow ^3\text{He} n$

$\frac{d\sigma}{dt} [\mu b/(GeV/c)^2]$

- $p_{\text{beam}} = 2.127$ GeV/c
- $p_{\text{beam}} = 2.334$ GeV/c
- $p_{\text{beam}} = 2.422$ GeV/c

$\sigma_{\text{tot}} [\mu b]$ vs $\sqrt{s_{dd}} [GeV]$
Luminosity determination

Spectator model - $dd \rightarrow ppp_{sp}n_{sp}$ reaction

$dd \rightarrow ^3He n$

FD

Forward Detector

COSY beam

Pellet Target

SCS

MDC

FPC

FWC

FTH

PSB

FRH

Absorber

Central Detector

FRH

$E_{kin, ^3He} [\text{GeV}]$

$\theta_{^3He} [\text{deg}]$

FRH4

FRH3

FRH2

FRH1

$\theta_n [\text{deg}]$

neutron in CD

$^3$He in FD
Analysis - conditions and cuts

Analysis was carried out for DATA and WMC after preselection. Conditions applied in analysis are following:

a) trigger 7 (at least 1 charged track in FD, track matching between FWC, FTH, FRH, high threshold for FWC),

b) no el_22 of FRH2 and el_1 of FRH3 ((those elements didn’t work properly during measurement, amplification was fluctuating, therefore we were not able to improve calibration for them),

c) one charged track in Forward Detector, $\theta_{3He} \in (3, 18)^{\circ}$, 0 or 1 neutral clusters in CD, no charged clusters in CD.
Luminosity determination

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\( ^3He \) identification in FD - DATA

![Graph showing data analysis for the WASA-at-COSY experiment](image)
$^3$He identification in FD - WMC

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Additional cut: $m_x(E_x) \, dd \rightarrow ^3\text{He}n$
Background rejection - DATA

The missing mass $m_x$ spectrum for $\cos \theta^* \in (0.96,0.98)$ and $Q \in (0,5)$ MeV
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## Luminosity calculation

1. The number of events for DATA after all cuts (background rejection) is saved to 2 dimensional histogram $\cos \theta^*$ vs. excess energy $Q$ (5 bins of $\cos \theta^*$ and 5 bins of $Q$).

2. Detection efficiency for WMC is calculated as the number of accepted events to the number of all generated events ($\epsilon = N_{acc}/N_{gen}$) and saved in 2 dimensional histogram.

3. The total cross section for each of $(\cos \theta^*, Q)_{i,j}$ bin was determined as:

$$\sigma_{toti,j} = \frac{d\sigma_{i,j}}{d(\cos \theta^*)} \cdot \Delta(\cos \theta^*),$$

where:

$$\frac{d\sigma_{i,j}}{d(\cos \theta^*)}$$

- differential cross section calculated for $\cos \theta^*$ and $Q$ values in the center of $(i,j)$-th bin:

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   \[ \sigma_{tot_{i,j}} = \frac{d\sigma_{i,j}}{d(cos\theta^*)} \cdot \Delta(cos\theta^*), \]
   where:
   \[ \frac{d\sigma_{i,j}}{d(cos\theta^*)} \] - differential cross section calculated for $cos\theta^*$ and $Q$ values in the center of $(i,j)$-th bin:
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$\in(Q, \cos \theta_{cm})$

$\cos \theta_{cm}$
0.98
0.97
0.96
0.95
0.94
0.93
0.92
0.91
0.9
0.89
0.88

$Q [\text{GeV}]$
-70
-60
-50
-40
-30
-20
-10
0
10
20
30

0.7
0.65
0.6
0.55
0.5
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3. $\sigma_{tot,i,j} = \frac{d\sigma_{i,j}}{d(\cos\theta^*)} \cdot \Delta(\cos\theta^*)$, where:
   - $\frac{d\sigma_{i,j}}{d(\cos\theta^*)}$ - differential cross section calculated for $\cos\theta^*$ and $Q$ values in the center of $(i,j)$-th bin
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The diagram shows the distribution of differential cross-section \( d\sigma/d\cos\theta_{cm}(Q,\cos\theta_{cm}) \) as a function of \( \cos\theta_{cm} \) and \( Q \) in GeV.
Luminosity is calculated for each bin as:

\[ L_{i,j} = \frac{N_{i,j}}{\epsilon_{i,j} \cdot \sigma_{tot_{i,j}}} \]

where:

- \( N_{i,j} \) - number of events in \((i,j)\)-th bin,
- \( \epsilon_{i,j} \) - detection efficiency in \((i,j)\)-th bin,
- \( \sigma_{tot_{i,j}} \) - total cross section for each of \((cos\theta^*,Q)_{i,j}\) bin (multiplied by 1000 in order to get \( L \) in \( nb^{-1} \)).

Luminosity for each \( cos\theta^* \) bin was calculated as a sum of luminosities for 5 \( Q \) bins:

\[ L_j = \sum_{i=1}^{5} L_{i,j} \]

The average integrated luminosity was calculated as a weighted average of the luminosities determined for individual \( cos\theta_{cm} \) intervals:

\[ L_{av} = \frac{\sum_{j=1}^{5} L_j \frac{1}{(\Delta L_j)^2}}{\sum_{j=1}^{5} \frac{1}{(\Delta L_j)^2}}, \quad \Delta L_{av} = \left( \sum_{j=1}^{5} \frac{1}{(\Delta L_j)^2} \right)^{-1/2} \]
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$\mathcal{L}(\cos \theta_{cm})$

$L_{av} = (1102 \pm 2) \text{ nb}^{-1}$