First High-Precision Measurement of the Isovector M1 Strength in $^6$Li at the Photon Point

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Udo Gayer, Christoph Romig, Volker Werner et al.

Newest data: Bergstrom (1975)

$^6$Li

$^{\gamma}$

$T_{1/2} = 60$ as

Model-dependent extrapolation to photon point

Claimed precision 2.3%

$^{4}$He + d

$0^+,0 \quad 1^+,0$

$1^+,0$

$3^+,0$

$2186$

$3562.9$

parity-forbidden

$0^+,1$

$J^\pi;T$

$1^+,0$

$0^+,1$

(keV)

$6^Li$
Towards ab-initio Nuclear Theory

- NN-potential from χEFT
- → Systematic expansion
- → Theoretical “error bars”
- Increasing complexity
- Ab-initio calculations possible for light nuclei

<table>
<thead>
<tr>
<th>LO ((Q/Λχ)^0)</th>
<th>2N Force</th>
<th>3N Force</th>
<th>4N Force</th>
<th>5N Force</th>
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<tr>
<td>NLO ((Q/Λχ)^2)</td>
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<td>NNLO ((Q/Λχ)^3)</td>
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<td>N^3LO ((Q/Λχ)^4)</td>
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<td>N^4LO ((Q/Λχ)^5)</td>
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<td>N^5LO ((Q/Λχ)^6)</td>
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D.R. Entem, R. Machleidt, Y. Nosyk, PRC 96 (2017)

Requires Consistent Transition Operator

- NN-potential from $\chi$EFT
- $\rightarrow$ Systematic expansion
- $\rightarrow$ Theoretical “error bars”

- Increasing complexity
  - Ab-initio calculations possible for light nuclei
  - Higher-order “effects” comparable to experimental uncertainties

Testing Theory for Consistent EM Transitions

Predominant decay modes of excited states of known $A \leq 6$ nuclei

- $^6$Li($3.562$ MeV) is the lightest system that decays predominantly via EM interaction
- $B(M1; 0^+ \rightarrow 1^+)$ one of the strongest known M1 transitions
- Ideal testing ground for ab-initio nuclear theory

**History of Experimental Data**

$T_{1/2} = 60$ as: direct lifetime measurement impossible

- Current ENSDF literature value based on three selected experiments; in conflict with running world-average

ENSDF Value based on these Data

\( B(M1,q) = B(M1)(1 - c_1 q^2 + c_2 q^4 + \ldots) \)

- Most precise value of \( B(M1) = 15.6(4) \, \mu_N^2 \) from extrapolation of \((e,e')\) form factor, **claimed 2.3%**

J.C. Bergstrom, I.P. Auer, R.S. Hicks, Nucl. Phys. **A251** (1975)
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Use Photons!
Nuclear Resonance Fluorescence

- Nuclear resonance fluorescence (NRF)
- Measurement at the photon point
- $\rightarrow$ no extrapolation
- Proportionality of cross section to level width / $B(M1)$ (in this case)

\[
I \propto \Gamma \propto \frac{h}{2\pi \tau} / \tau \\
\propto B(M1)
\]

F.R. Metzger, Prog. Nucl. Phys. 7 (1959)
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→ Measurement relative to calibration standard
Relative Self-Absorption

- Relative self-absorption (RSA) based on NRF

- Reduction of count rate depends on level width
- and atomic absorption

\[
R \left( \Gamma_{0+ \rightarrow 1^+} \right) = \frac{N_{NRF} - N_{RSA}}{N_{NRF}}
\]
Relative Self-Absorption

- Relative self-absorption (RSA) based on NRF

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\[ R \left( \frac{\Gamma_0 + \rightarrow 1^+}{N_{NRF} - N_{RSA}} \right) = \frac{N_{NRF}}{N_{RSA}} \]

- ‘Monitor target’ to correct for atomic absorption
Superconducting-DArmstadt LINear ACcelerator (S-DALINAC)

- Injector energy $\leq 10$ MeV
- Injector current $\sim 20$ $\mu$A
Darmstadt High-Intensity Photon Setup (DHIPS)
K. Sonnabend et al., NIM A640 (2011)

- Bremsstrahlungs-photon flux
  \( \sim 10^2 \text{ s}^{-1}\text{eV}^{-1} \)

- \( \gamma \)-ray detection by three 120%
  High-Purity Germanium (HPGe) detectors

**Spectrum**

- Normalization of atomic scattering to $^{11}$B monitor target
- Measuring times:
  - 122h (NRF)
  - 189h (RSA)

$$R \left( \Gamma_{0^+ \to 1^+} \right) = \frac{N_{NRF} - N_{RSA}}{N_{NRF}} = 0.5192(20)$$

→ Relative statistical uncertainty of 0.4%!
Determination of the level width

- Doppler-broadening due to effective temperature $T_{\text{eff}}$ of sample

\[
\sigma_D(E) = \int_{-\infty}^{\infty} dv \, \sigma_{BW}(E, \Gamma) \sqrt{\frac{M}{2\pi k_B T_{\text{eff}}}} e^{\frac{-Mv^2}{2k_B T_{\text{eff}}}}
\]

\[
N = \int_{z_0}^{z_1} dz \int_{-\infty}^{\infty} dE \, \sigma_D(E, \Gamma, T_{\text{eff}}) e^{-\sigma_D(E, \Gamma, T_{\text{eff}}) z}
\]

\[
R(\Gamma_0, T_{\text{eff}}) = \frac{N_{\text{NRF}} - N_{\text{RSA}}}{N_{\text{NRF}}}
\]
Determination of the effective temperature

- $T_{\text{eff}}$ for Li$_2$CO$_3$ from ab-initio atomic DFT via its relation to the Phonon density of states (phDOS) $g(\nu)$

- Use of different exchange-correlation functionals for uncertainty quantification

$$k_B T_{\text{eff}} = \int_0^\infty h \nu g(\nu) \left( \frac{1}{\exp(h \nu / k_B T)} + \frac{1}{2} \right)$$

W.E. Lamb, Phys. Rev. 55 (1938)

$T_{\text{eff}}(T = 293K) = 411(11)K$

(2.7% rel. unc.)
Uncertainty Budget

\[ B(M1) = 15.61 \pm 0.30 \]

(100\% \pm 1.9\%)

\[ \Delta \text{ statistics} = +0.23 - 0.21 \]
\[ \Delta \text{ atomic theory} = +0.19 - 0.21 \]
\[ \Delta \text{ target dimensions} = +0.04 \]
\[ \Delta \text{ numerical evaluation} = \pm 0.01 \]
Comparison with theory

- $\chi$EFT calculations of $B(M1; 1^+ \rightarrow 0^+)$ and $\mu(1^+)$ in the no-core shell model
- SRG-evolved next generation chiral NN+3N interactions up to N4LO+N3LO
  D.R. Entem, R. Machleidt, Y. Nosyk, PRC 96 (2017)
- Unevolved M1 operator, evolved M1 operator at LO, and evolved M1 operator at NLO
  → First complete chiral calculation of these observables

High experimental precision crucial to test state-of-the-art theory!
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