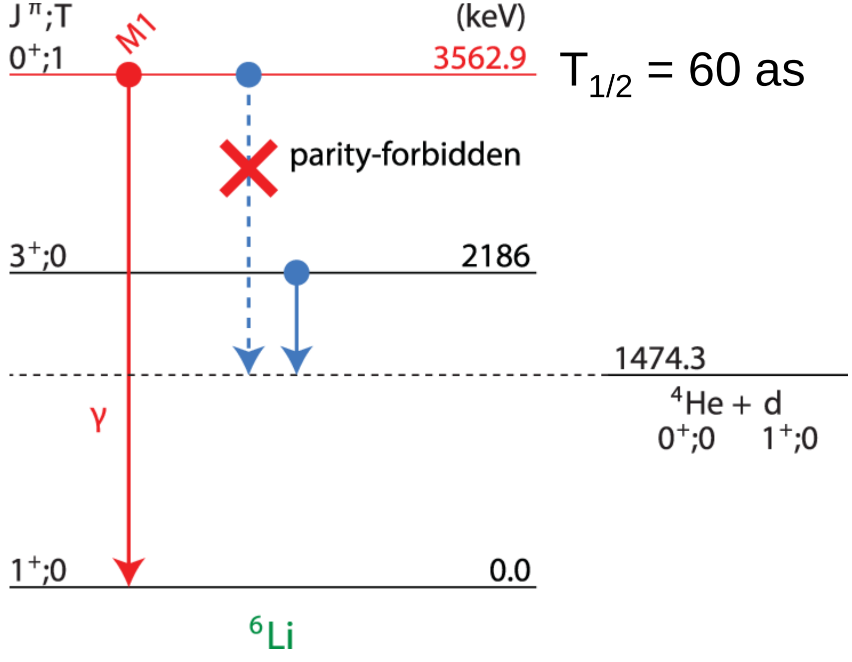
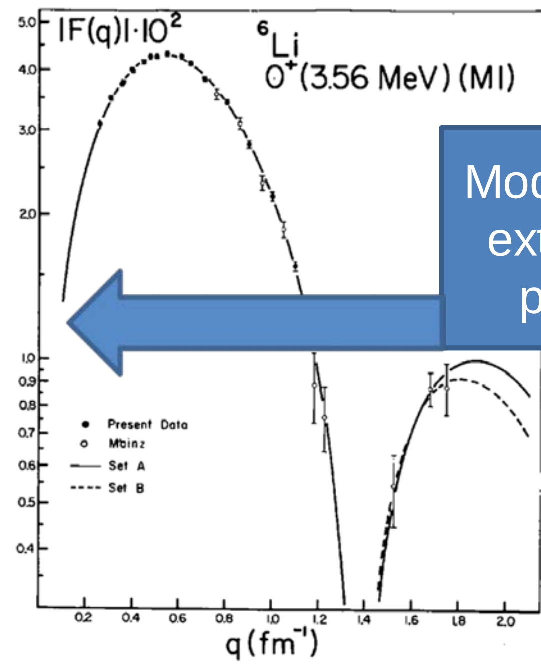
First High-Precision Measurement of the Isovector M1 Strength in ^{6}Li at the Photon Point

Norbert Pietralla + group, TU Darmstadt
Udo Gayer, Christoph Romig, Volker Werner et al.



$T_{1/2}$ = 60 as

Newest data: Bergstrom (1975)



Model-dependent extrapolation to photon point

Claimed precision 2.3%

Towards ab-initio Nuclear Theory

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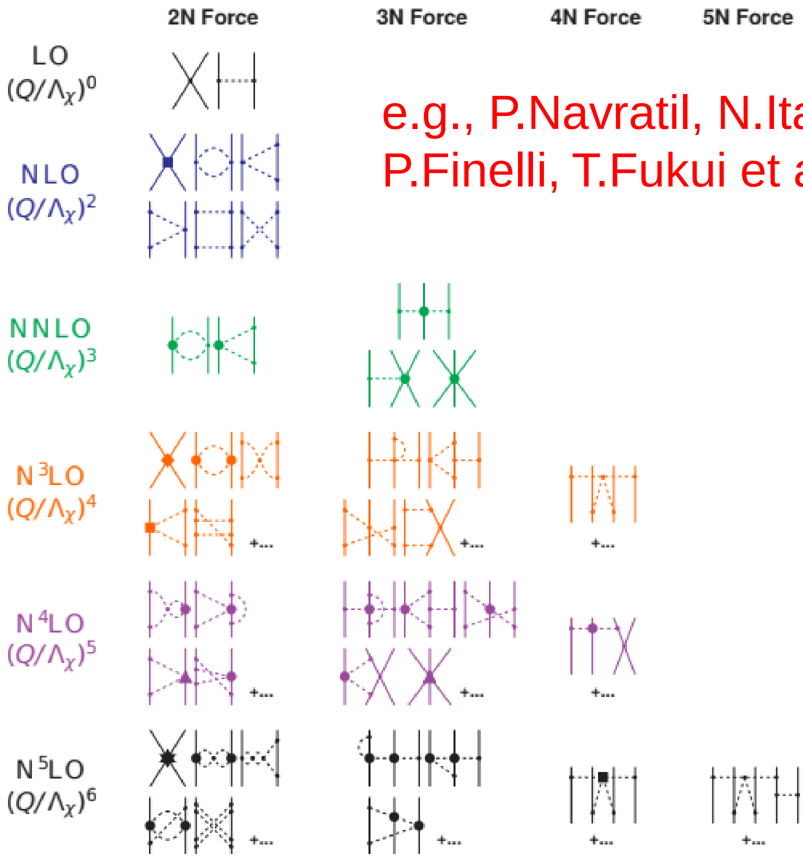


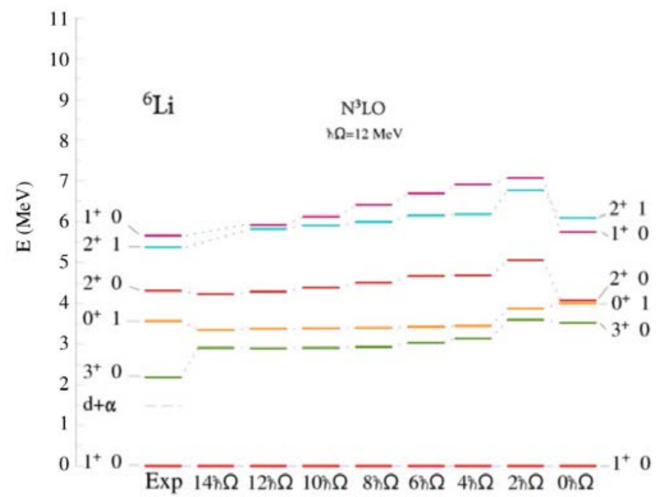
e.g., P.Navratil, N.Itaco, P.Finelli, T.Fukui et al.

D.R. Entem, R. Machleidt, Y. Nosyk, PRC **96** (2017)

- NN-potential from χEFT
- → Systematic expansion
- → Theoretical "error bars"

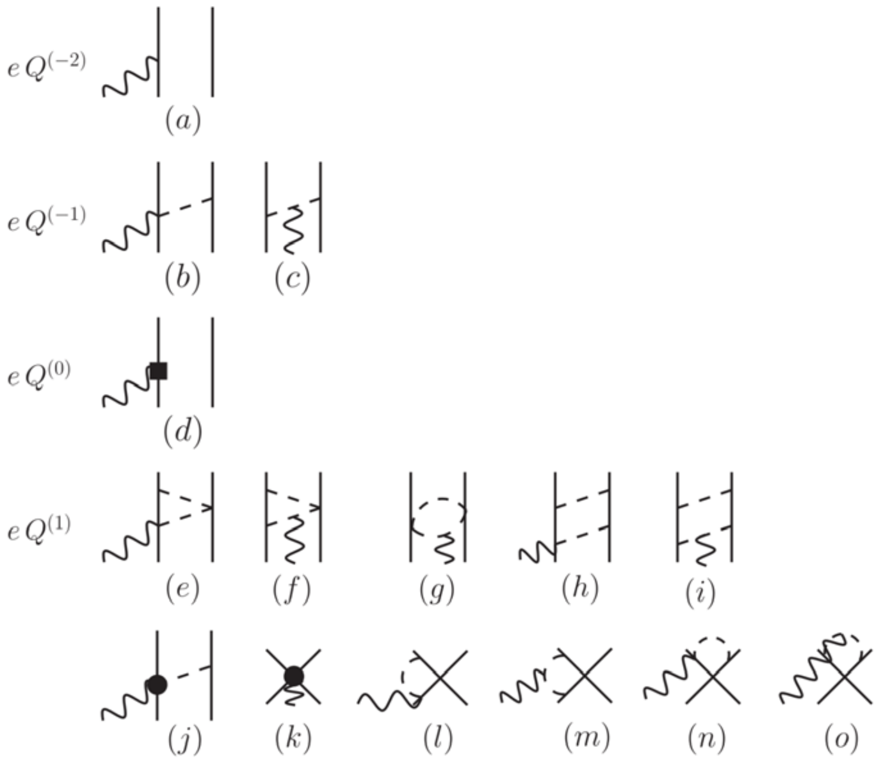
- Increasing complexity

- Ab-initio calculations possible for light nuclei



B.R. Barrett, P. Navrátil, J.P. Vary, Prog. Part. Nucl. Phys. **69** (2013)

Requires Consistent Transition Operator

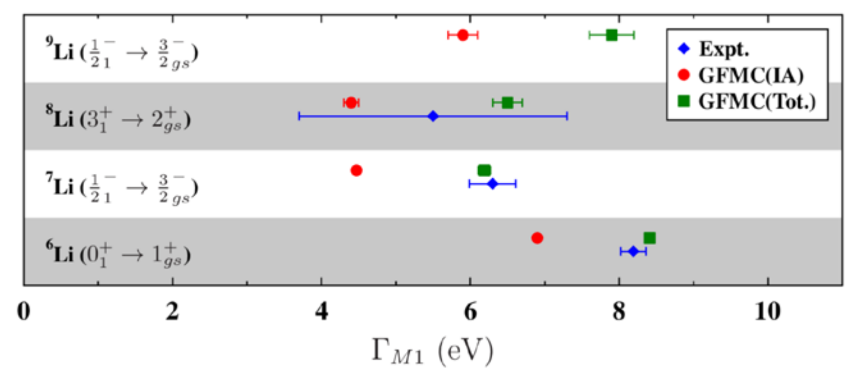


S. Bacca, S. Pastore, J. Phys. G **41**, 123002 (2014)

- NN-potential from χEFT
- → Systematic expansion
- → Theoretical "error bars"

- Increasing complexity

- Ab-initio calculations possible for light nuclei
- Higher-order "effects" comparable to experimental uncertainties

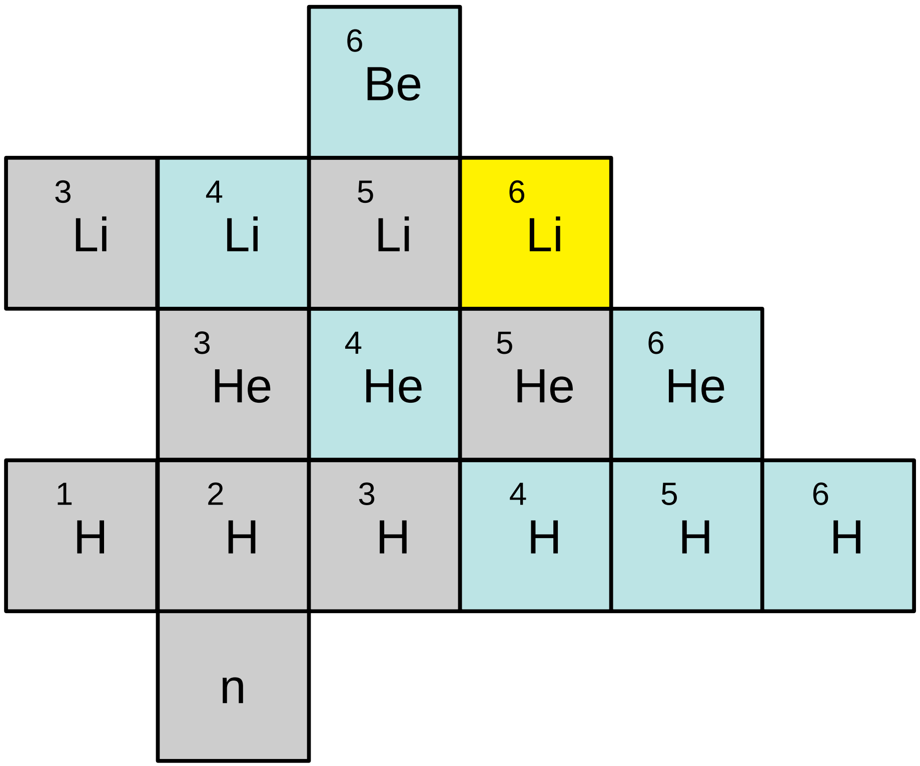


S. Pastore et al., PRC 87 (2013)

Figure: C. Romig, Doctoral Thesis, TU Darmstadt (2015)

Testing Theory for Consistent EM Transitions

Predominant decay modes of excited states of known A ≤ 6 nuclei



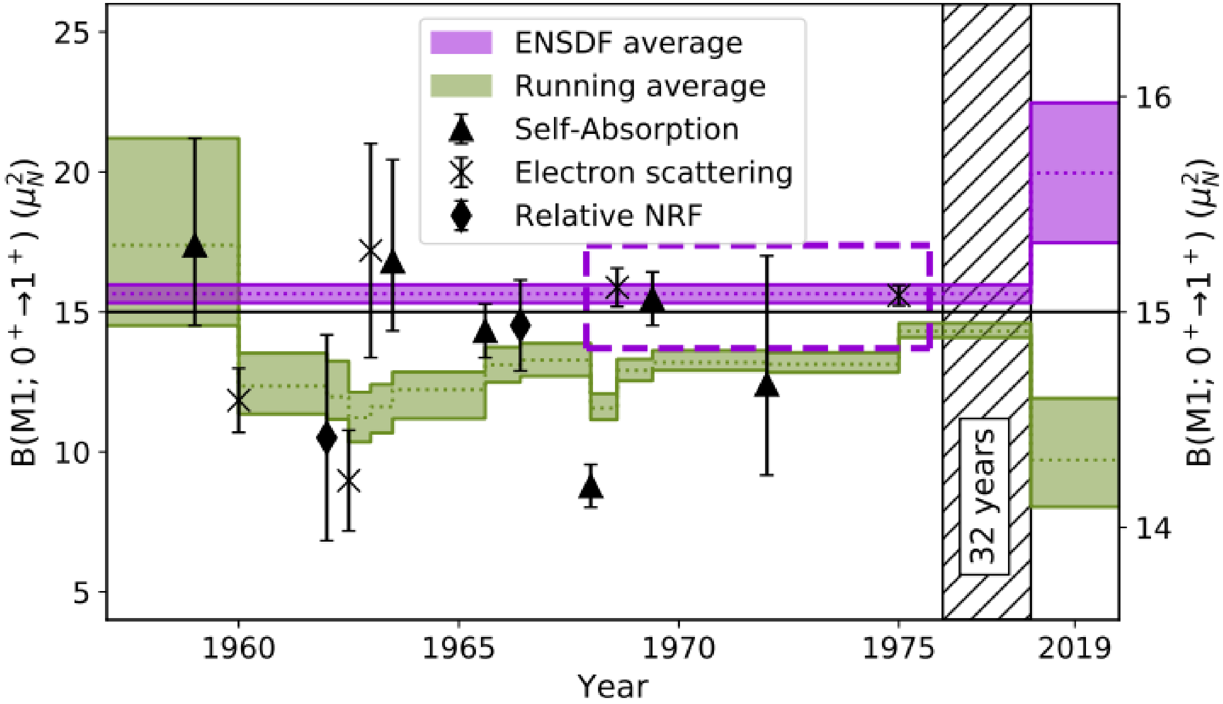
no bound excited state
particle emission
particle + γ emission

- ^{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

Decay data from: https://www.nndc.bnl.gov/ (03/25/2019)

History of Experimental Data

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



Claimed precision 2.3%

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

D.R. Tilley *et al.*, Nucl. Phys. **A708** (2002)

ENSDF Value based on these Data

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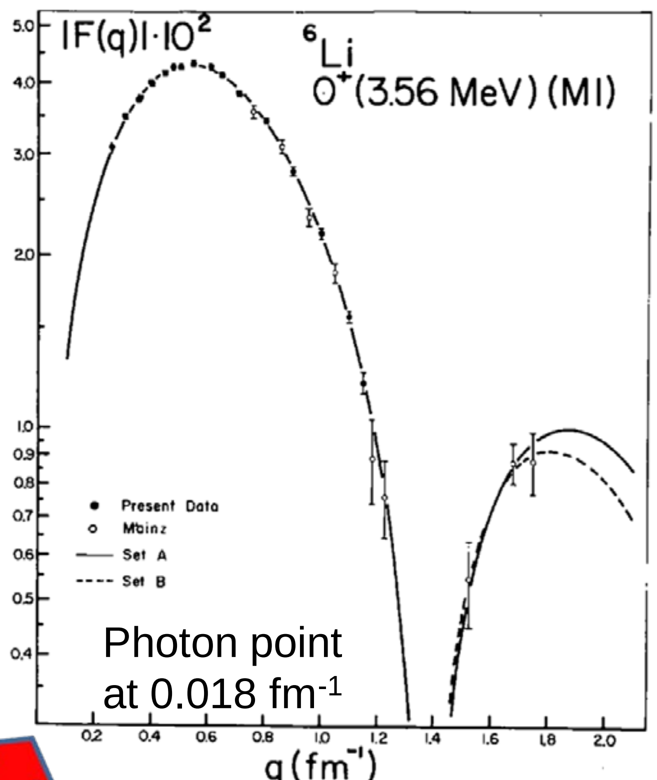
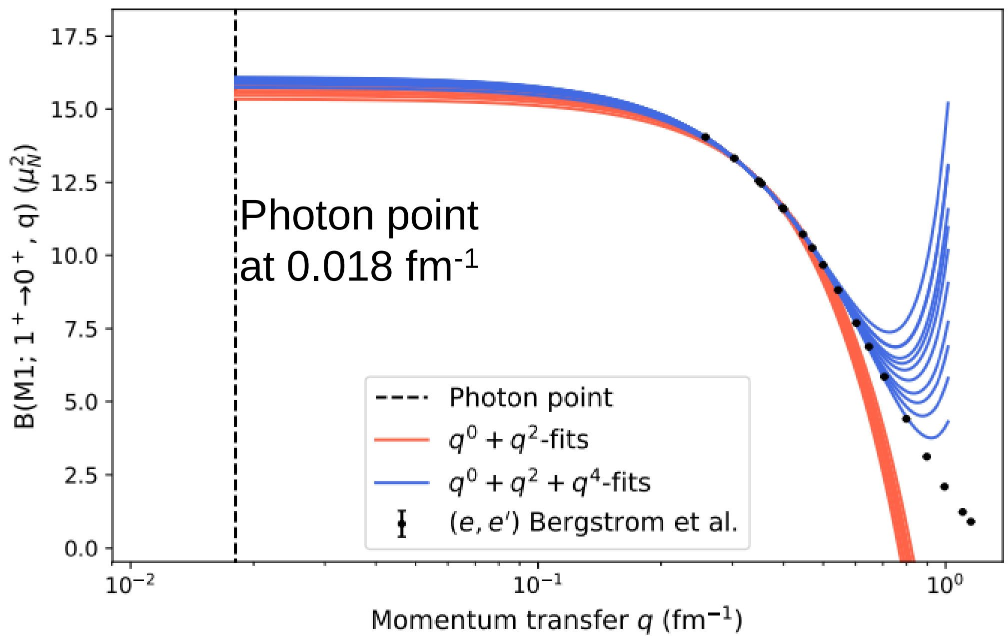
Plane-Wave Born Approximation

$$B(\mathrm{M1}, q) = B(\mathrm{M1})(1 - c_1 q^2 + c_2 q^4 + \dots)$$



Extrapolate to 0.018 fm^{-1}!



- Most precise value of B(M1) = 15.6(4) μ_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)

ENSDF Value based on these Data

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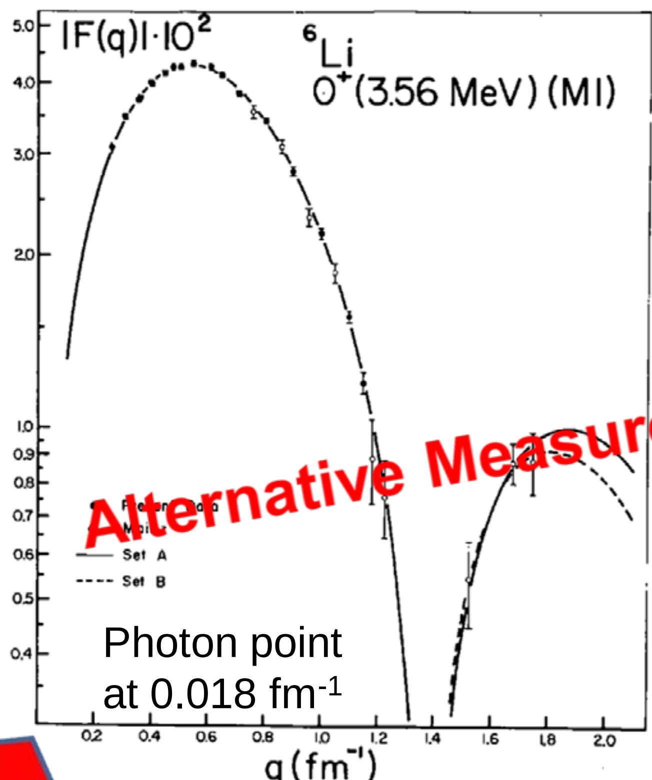
Plane-Wave Born Approximation

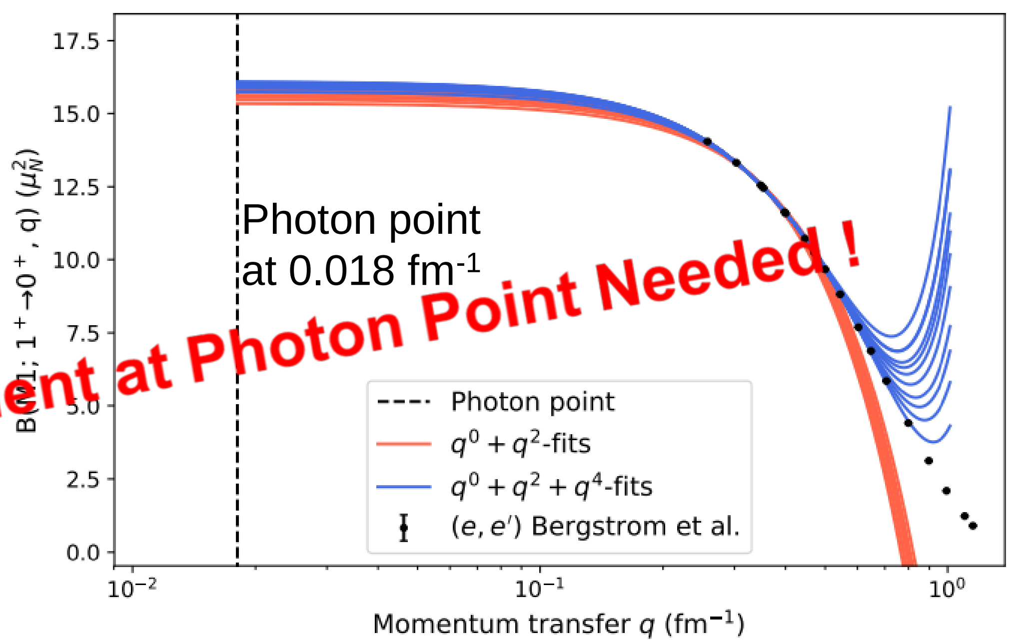
$$B(\mathrm{M1}, q) = B(\mathrm{M1})(1 - c_1 q^2 + c_2 q^4 + \ldots)$$

Alternative Measurement at Photon Point Needed !



Photon point at 0.018 fm^{-1}

Extrapolate to 0.018 fm^{-1}!



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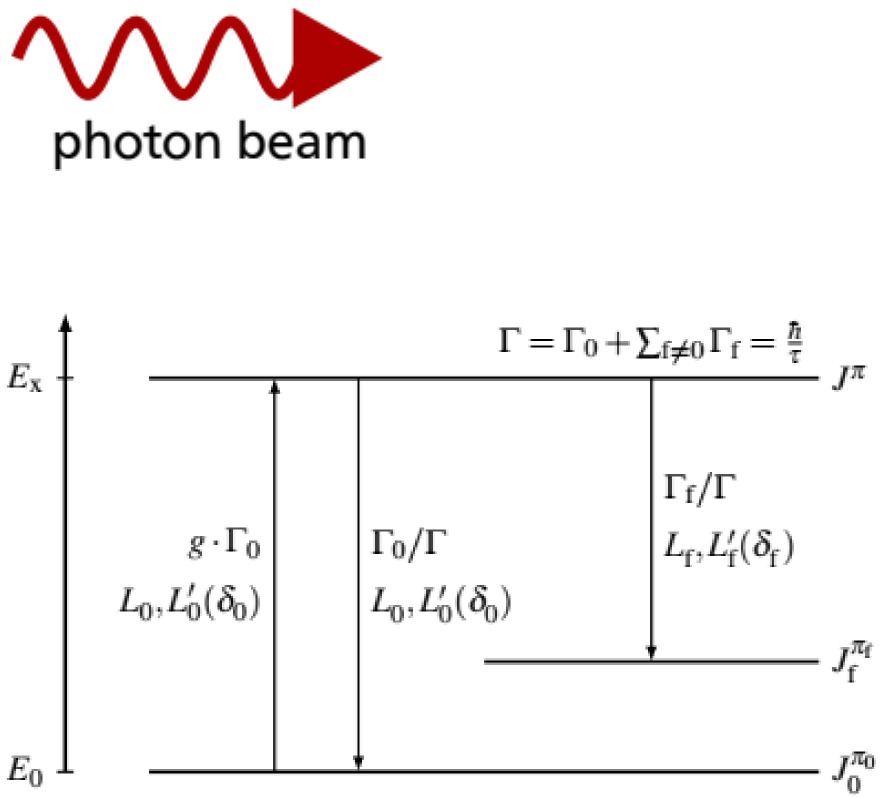
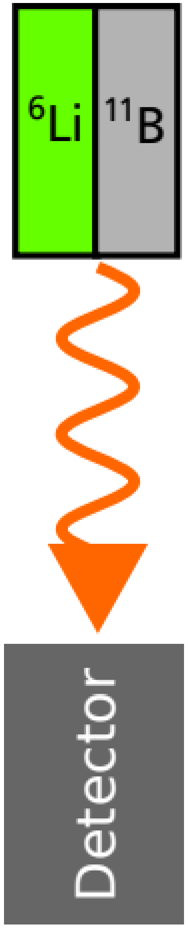
J.C. Bergstrom, I.P. Auer, R.S. Hicks, Nucl. Phys. **A251** (1975)

Use Photons!
Nuclear Resonance Fluorescence



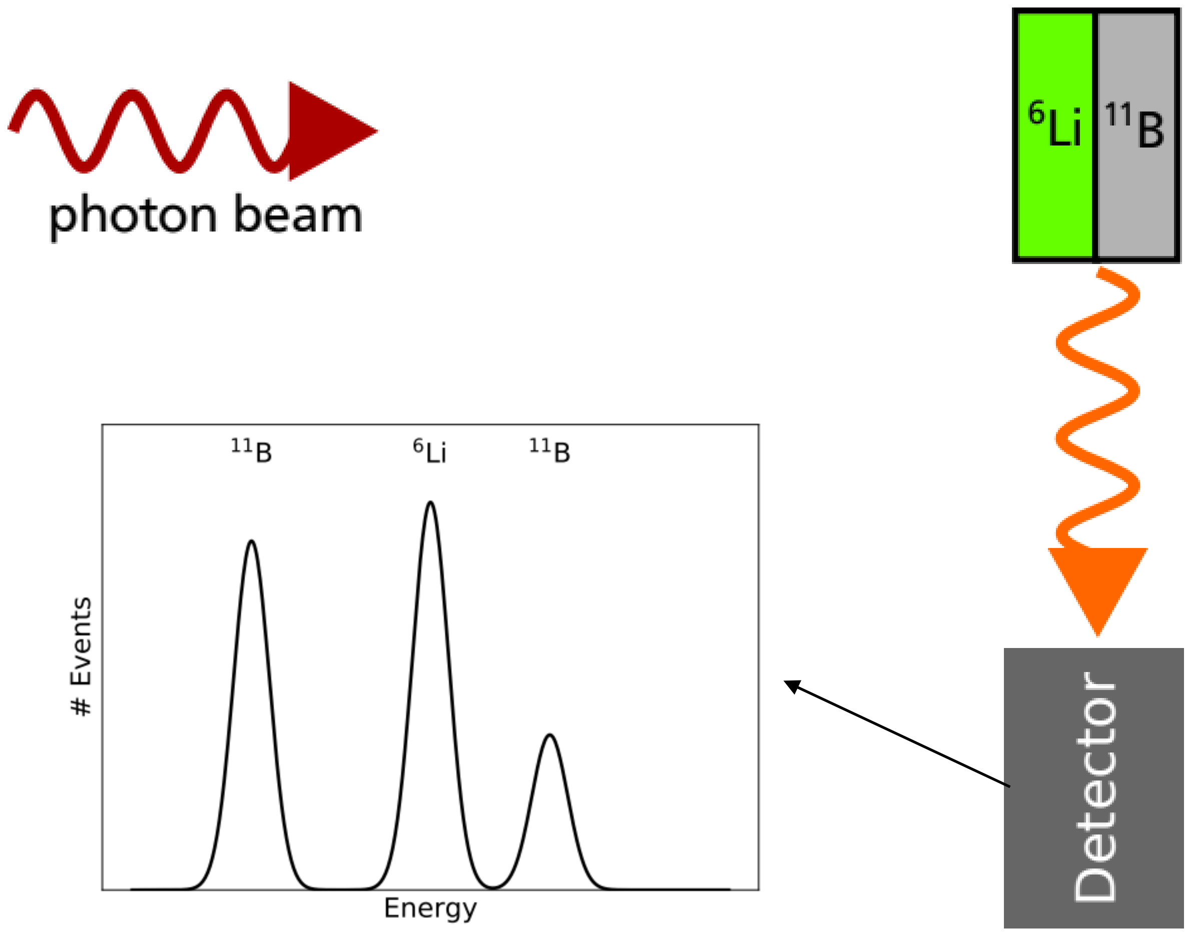
F.R. Metzger, Prog. Nucl. Phys. **7** (1959)



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

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

Nuclear Resonance Fluorescence



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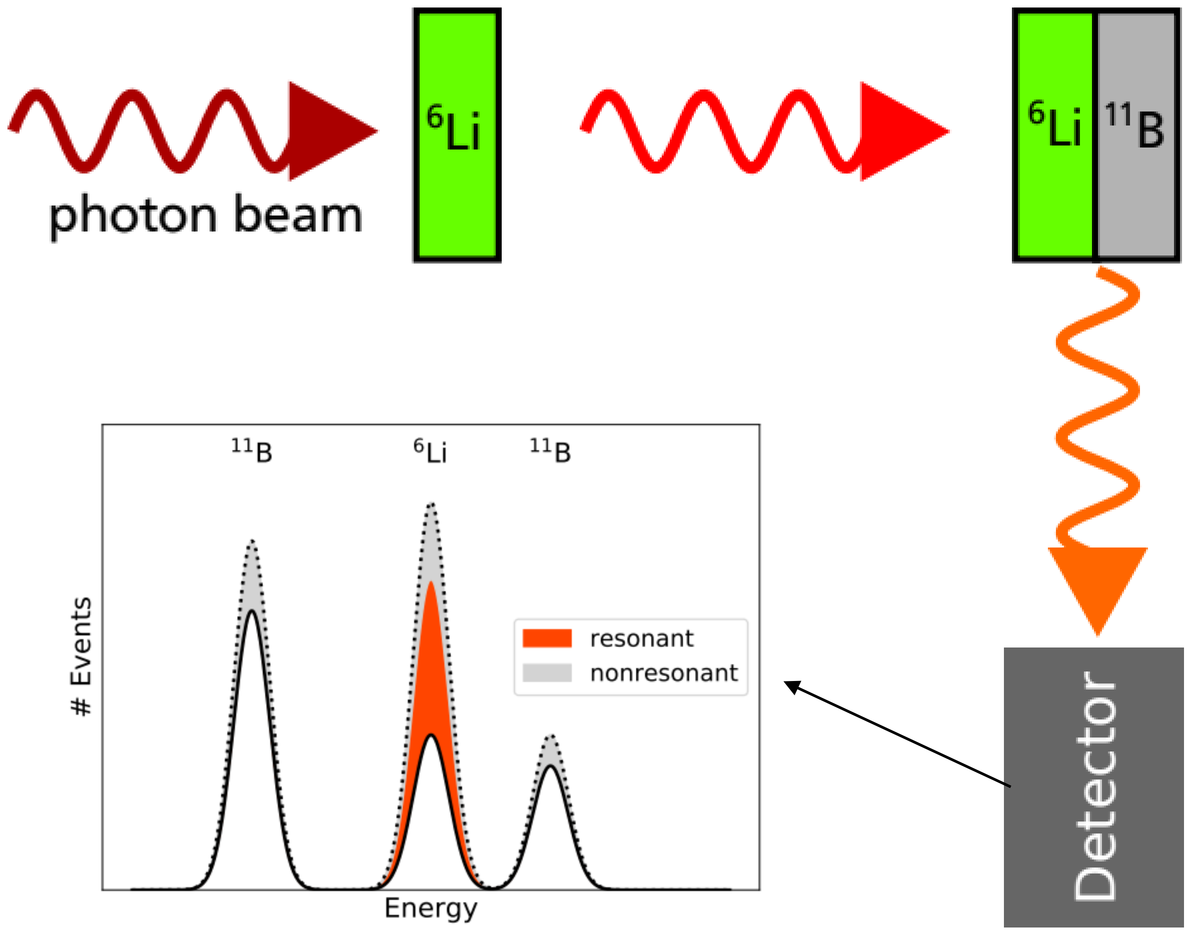
→ Measurement relative to calibration standard

Relative Self-Absorption



- Relative self-absorption (RSA) based on NRF

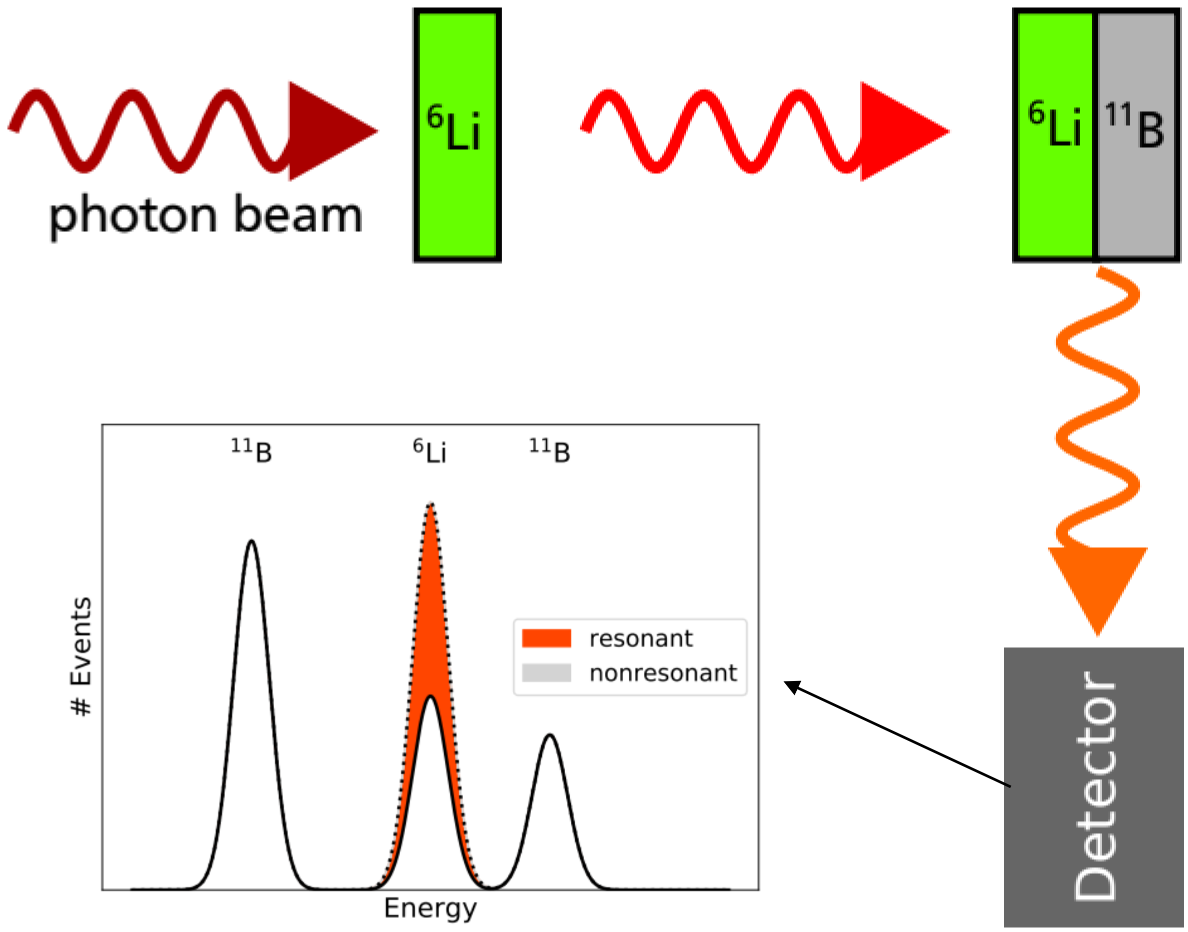
C. Romig *et al.*, Phys. Lett. B **744** (2015)

C. Romig, Doctoral Thesis, TU Darmstadt (2015)

- 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



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- 'Monitor target' to correct for atomic absorption

NRF @ S-DALINAC

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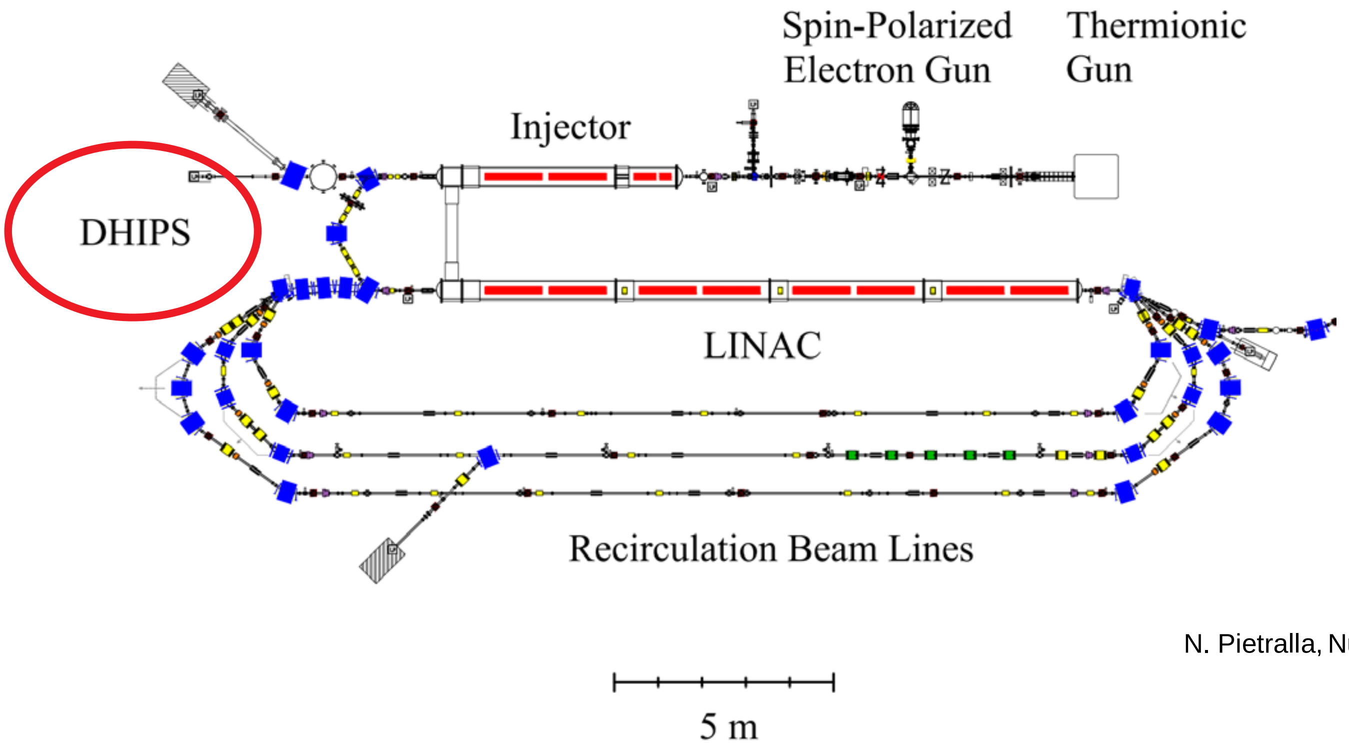


to spectrometers ...

N. Pietralla, Nucl. Phys. News **28** (2018)

Superconducting-DArmstadt LINear ACcelerator (S-DALINAC)

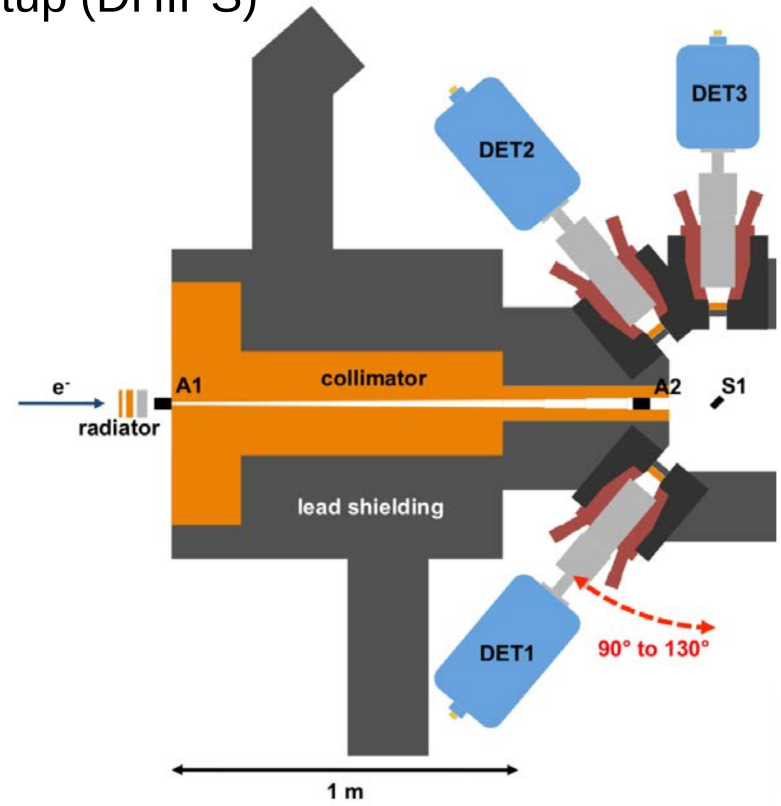
- Injector energy ≤ 10 MeV
- Injector current ~ 20 μA

NRF @ S-DALINAC

Darmstadt High-Intensity Photon Setup (DHIPS)

K. Sonnabend et al., NIM **A640** (2011)

- Bremsstrahlungs-photon flux $\sim 10^2\ s^{-1}eV^{-1}$
- γ-ray detection by three 120% High-Purity Germanium (HPGe) detectors



C. Romig, Doctoral Thesis, TU Darmstadt (2015)

Spectrum

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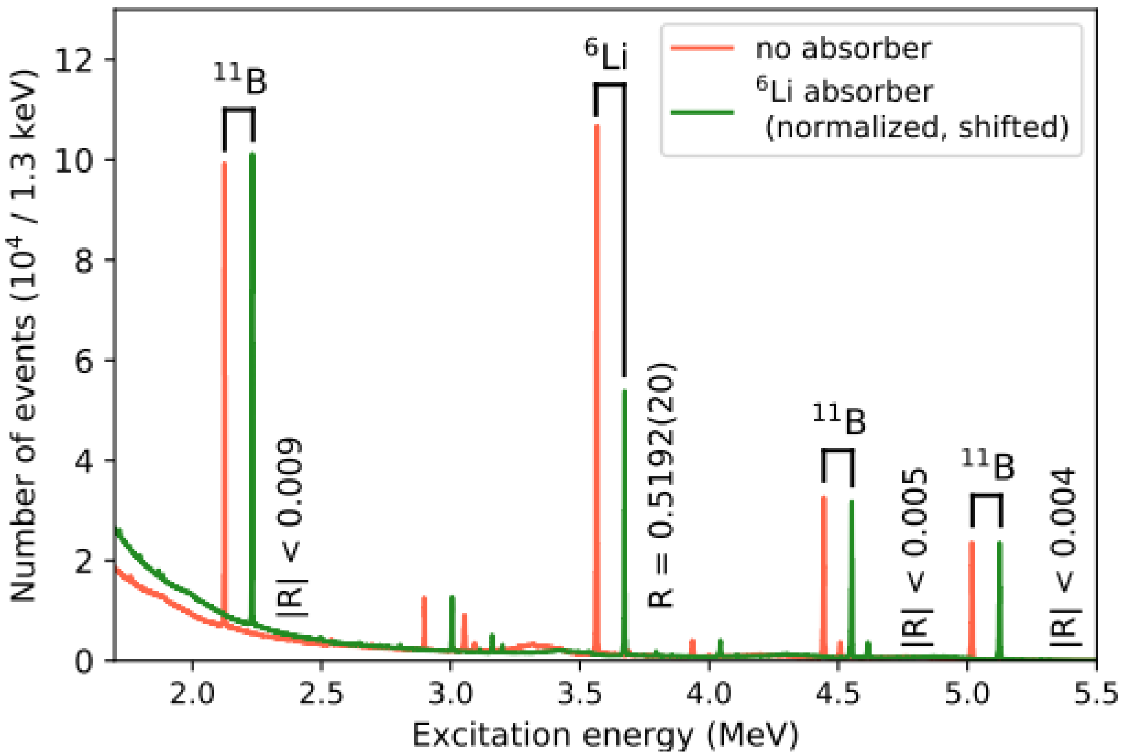


- Normalization of atomic scattering to ^{11}B monitor target

- 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_{eff} of sample

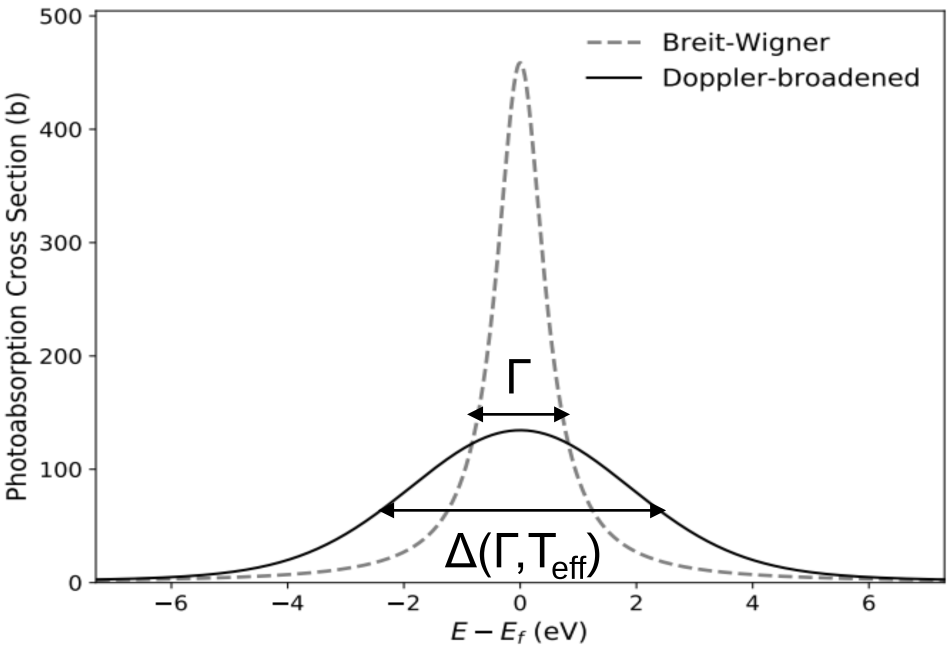
$$\sigma_D(E) = \int_{-\infty}^{\infty} dv\, \sigma_{BW}(E,\Gamma)\, \sqrt{\frac{M}{2\pi k_B T_{eff}}}\, e^{\frac{-Mv^2}{2k_B T_{eff}}}$$

↓

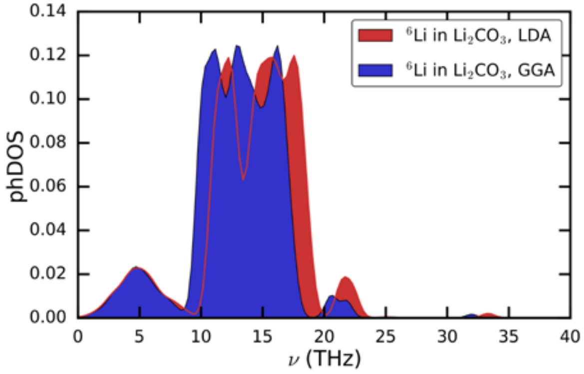
$$N = \int_{z_0}^{z_1} dz \int_{-\infty}^{\infty} dE\, \sigma_D\left(E,\Gamma,T_{eff}\right) e^{-\sigma_D\left(E,\Gamma,T_{Eff}\right) z}$$

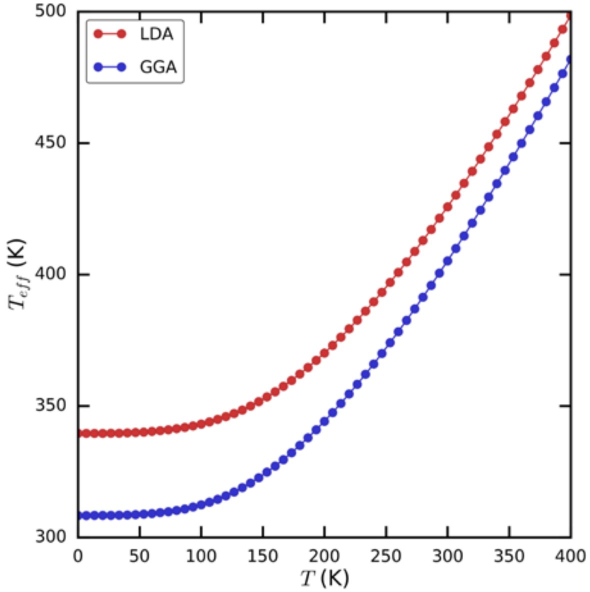
↓

$$R\left(\Gamma_0, T_{eff}\right) = \frac{N_{NRF} - N_{RSA}}{N_{NRF}}$$



Determination of the effective temperature





- T_{eff} for Li_2CO_3 from ab-initio atomic DFT via its relation to the Phonon density of states (phDOS) g(v)

- Use of different exchange-correlation functionals for uncertainty quantification

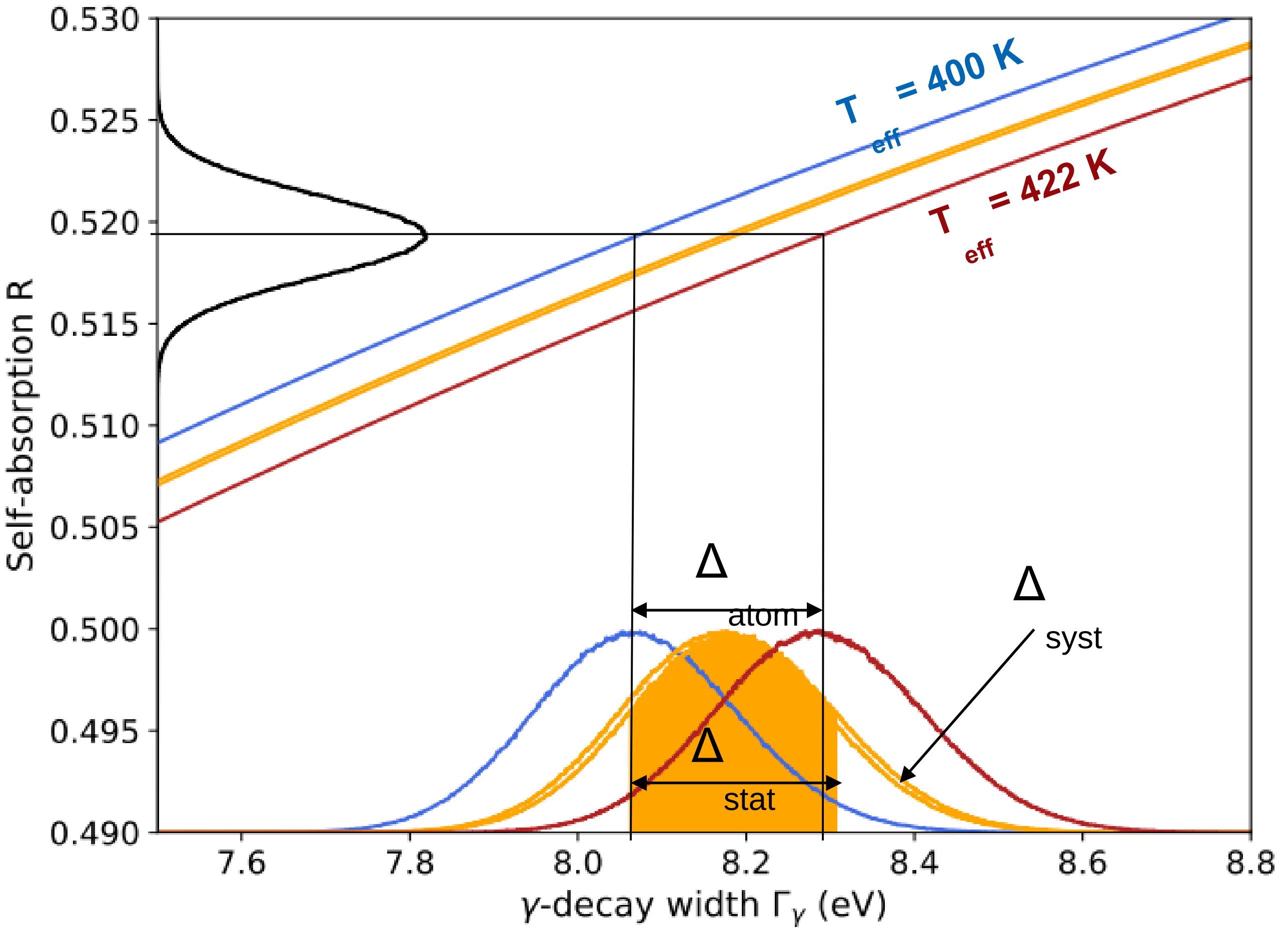
$$k_B T_{eff} = \int_0^\infty h\nu g(\nu) \left(\frac{1}{exp(h\nu/k_B T)} + \frac{1}{2} \right)$$

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

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

(2.7% rel. unc.)

Uncertainty Budget



B(M1) = 15.61

Δ_{stat} statistics

+0.23 – 0.21

Δ_{atom} atomic theory

+0.19 – 0.21

Δ_{syst} target dimensions

+-0.04

Δ_{num} numerical evaluation

+- << 0.01

= 15.61 +- 0.30
(100% +- 1.9%)

Comparison with theory

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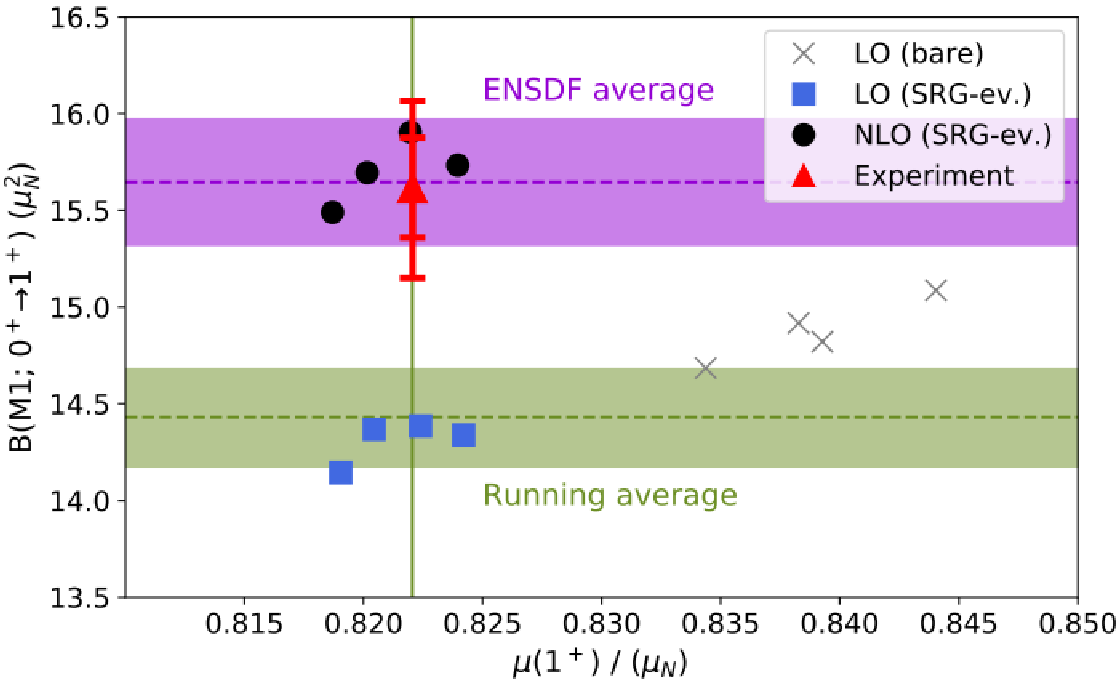


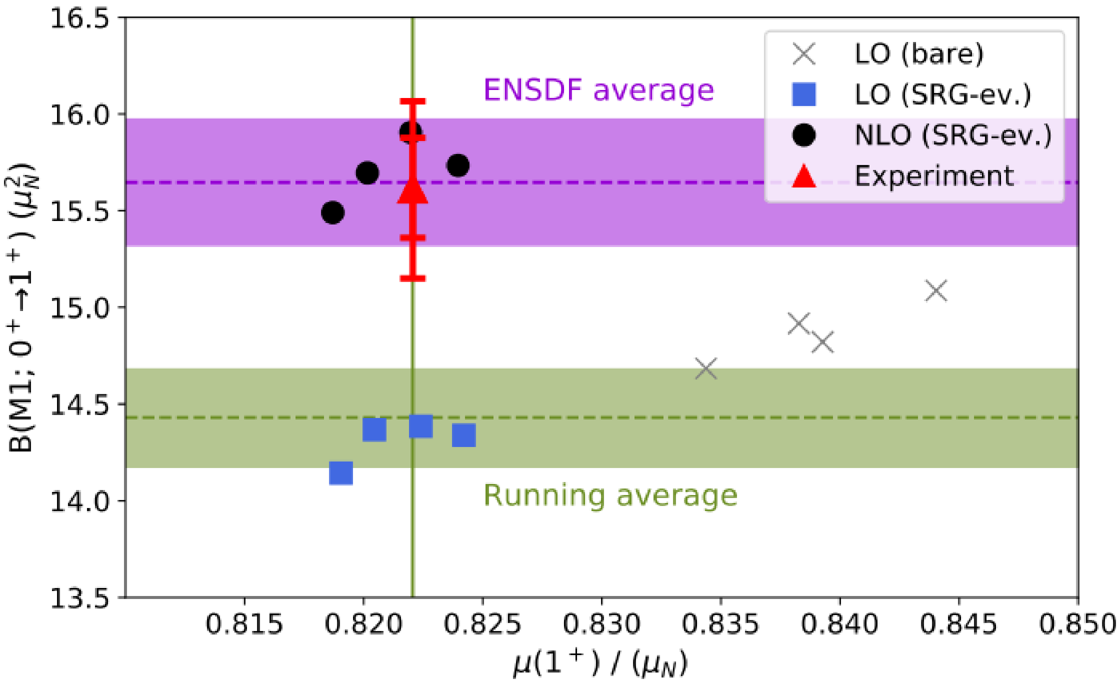
- χEFT calculations of $B(M1;1^+\rightarrow0^+)$ and $\mu(1^+)$ in the no-core shell model
- SRG-evolved next generation chiral NN+3N interactions up to N4LO+N3LO

  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!

Comparison with theory



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Thank you!

Thanks to U.Gayer for preparation of slides

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