# Extracting B(E1) distribution from reaction cross sections

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# Summary

# 1. A very broad and general introduction

- Why do we (Nuclear reactions people) do what we do?
- Why should society pay us to do what we do?
- What part of what we do now, will be relevant in 30 years time?

# Why do we do what we do?

- Nuclear reaction experimentalists use special accelerators to smash more and more exotic nuclei on different targets, to measure the fragments with sophisticated detectors, and determine certain cross sections.
- Nuclear reaction theorists use sophisticated reaction mechanisms, implemented in powerful reaction codes, to relate the nuclear properties associated to structure models, with the cross sections measured by experimentalists.
- The combination of nuclear reaction experiments and reaction theory allows to explore the nuclear structure.

# Structure and reactions

Jan Vaagen (1990s): "To obtain the beauty of nuclear structure, requires people ready to tame the beast of nuclear reactions"

# Why should society pay us to do what we do?

- We train expert people who can eventually dedicate to energy production, cancer treatment, radioprotection, as well as modelling, computing, etc.
- We contribute to the development of new technology in detectors, electroncs, etc.
- We provide essential data which is neccesary for astrophysics, radiation therapy planning, applications, etc.
- The goal of extending ab-initio and QCD related fundamental interactions requires accurate data on a variety of nuclear systems.

# What part of what we do now, will be relevant in 30 years time?

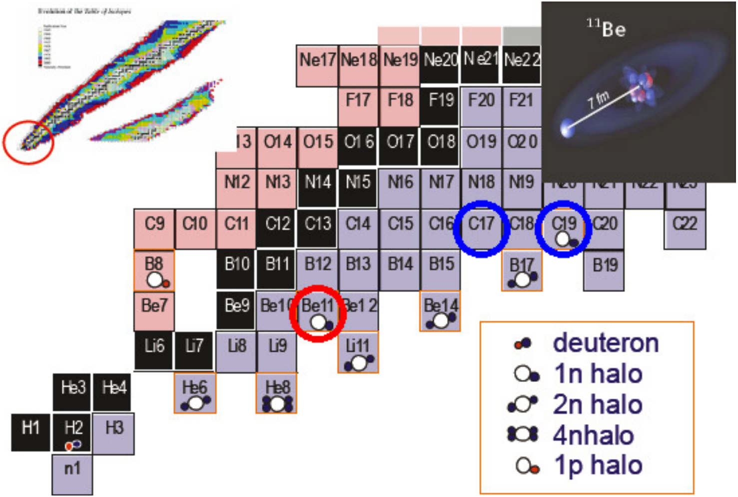
What part of what it was in the 1980's in nuclear reactions is relevant now?

- Experiments: Accelerator technology, Detector technology Data acquisition, ...
- Theory: Key reaction formalism (G.R. Satchler), Coulomb excitation, Continuum Discretization methods, Key reaction codes (FRESCO, I.J. Thompson).
- Accurate Data
  - Radii and density distributions, Excitation energies, Nuclear moments, masses, decay times, spectroscopic factors, ...
  - $B(E\lambda)$ (From Coulomb excitations)

A guess for the future:

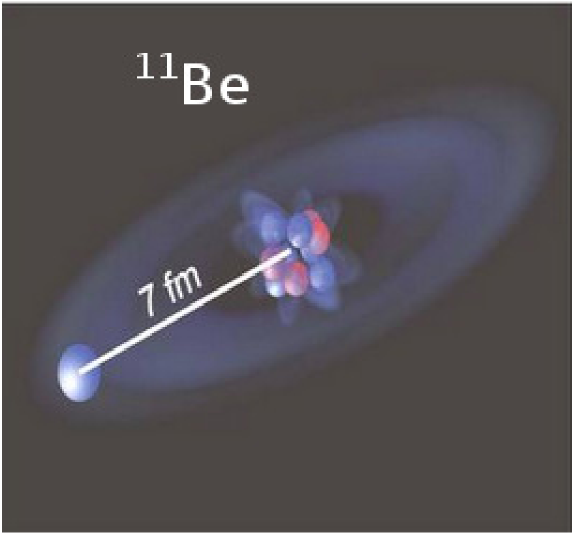
- Experiments (?)
- Theory (?)
- Data
  - Radii, Resonance energies and widths, Spectroscopic factors (from (p,2p)), lifetimes, masses, ...
  - $B(E\lambda)$ distributions (from Coulomb excitation)

# Halo nuclei



$^{11}$Be
7 fm
Ne17 Ne18 Ne19 Ne20 Ne21 Ne22
F17 F18 F19 F20 F21
O14 O15 O16 O17 O18 O19 O20
N12 N13 N14 N15 N16 N17 N18 N19
C9 C10 C11 C12 C13 C14 C15 C16 C17 C18 C19 C20 C22
B8 B10 B11 B12 B13 B14 B15 B17 B19
Be7 Be9 Be11 Be14
Li6 Li7 Li8 Li9 Li11
He3 He4 He6 He8
H1 H2 H3
n1
deuteron
1n halo
2n halo
4nhalo
1p halo

# 11Be



# The Equivalent Photon Method

- K. Alder, A. Winther, Electromagnetic excitation: theory of Coulomb excitation with heavy ions, North-Holland Pub. Co., 1975
- Semiclassical, First order, Pure Coulomb Excitation. $\xi = \frac{e_n a_0}{\hbar v}$

$$\left(\frac{d\sigma}{d\Omega}\right)_{gs\rightarrow n} = \left(\frac{Ze^2}{\hbar v}\right)^2 \frac{B(E\lambda, gs \rightarrow n)}{e^2 a_0^{2\lambda-2}} f_\lambda(\theta,\xi)$$

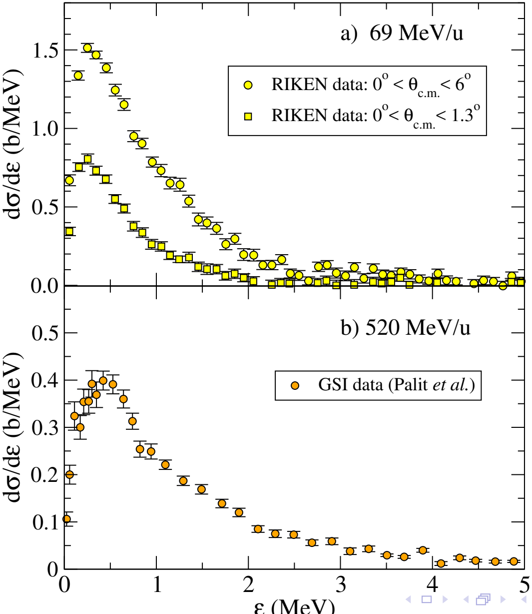
- Including the ever-present nuclear interaction:

$$\left(\frac{d\sigma}{d\Omega}\right)^{Exp}_{gs\rightarrow n} = \left(\frac{d\sigma}{d\Omega}\right)^{Nuc}_{gs\rightarrow n} + \left(\frac{Ze^2}{\hbar v}\right)^2 \frac{B(E\lambda, gs \rightarrow n)}{e^2 a_0^{2\lambda-2}} f_\lambda(\theta,\xi)$$

- The inelastic (or break-up) cross section depends linearly on the corresponding $B(ElLambda)$. The slope is a known analytic function.
- The practical application of the EPM for angle-integrated experiments requires an estimate of nuclear break-up, and a cutoff parameter to simulate absorption.

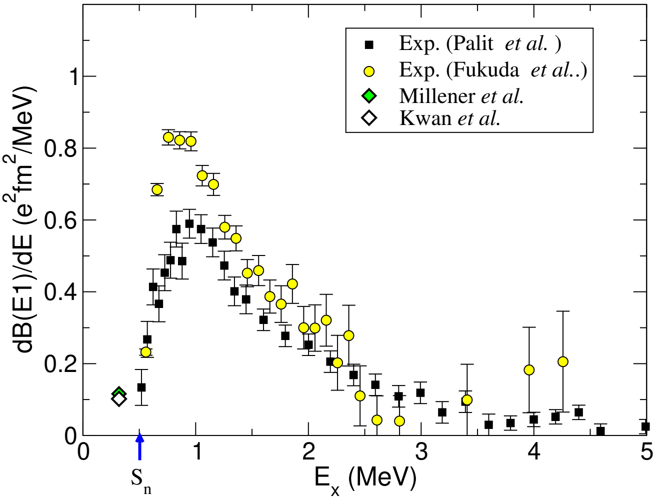
# Break-up cross section mesurements

- Palit el al Phys. Rev. C, 68 (2003), 034318. GSI, E= 520 MeV/u.
- Fukuda et al Phys. Rev. C, 70 (2004), 054606. RIKEN, E=69 MeV/u.

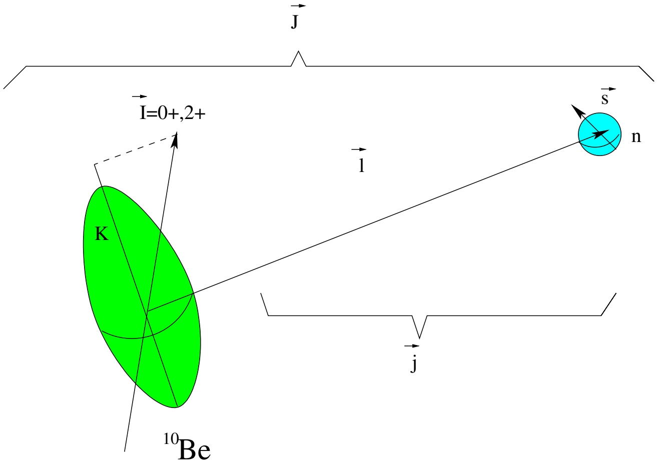


# Experimental B(E1) distributions

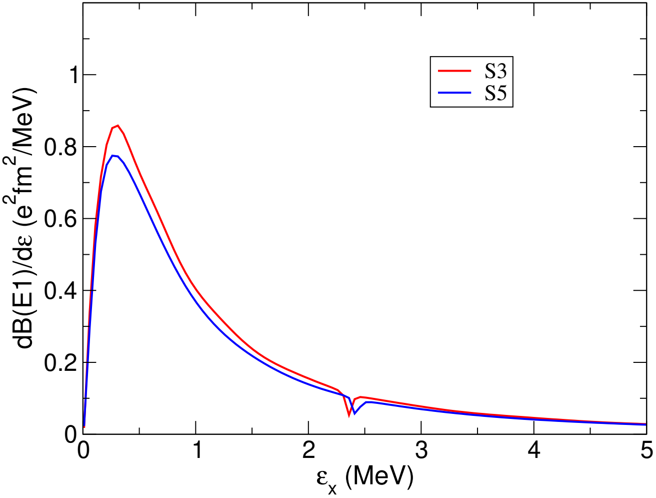
- Palit el al Phys. Rev. C, 68 (2003), 034318
- Fukuda et al Phys. Rev. C, 70 (2004), 054606



# Nuclear structure in a few body model(simple beauty)

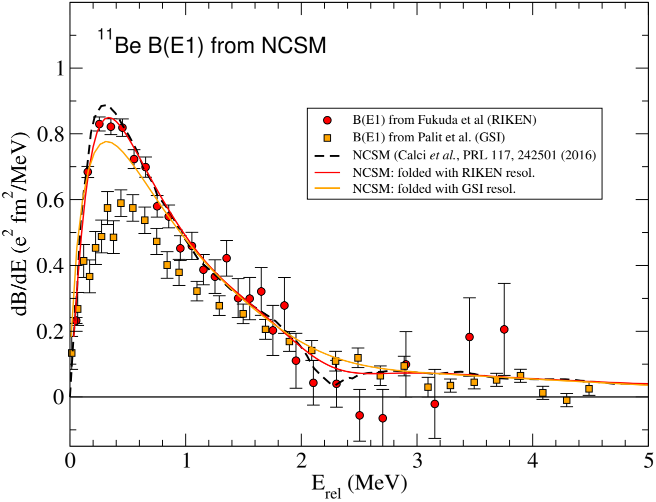


## B(E1) distribution in a few body model (simple beauty)



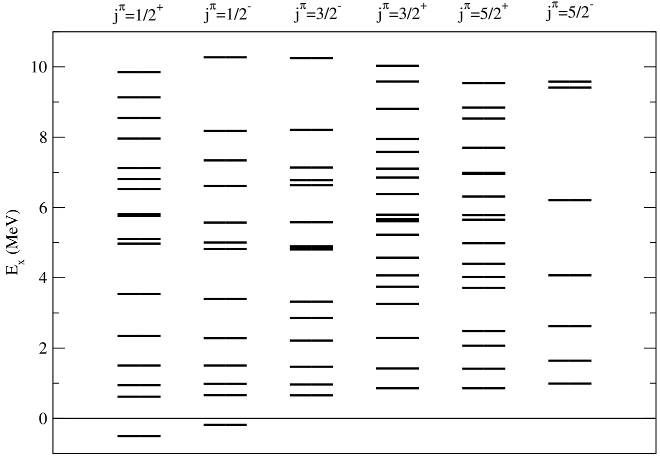

N. Summers et al, Phys. Lett. B 650(2007) 124.
S3: rms(n-$^{10}$Be)=6.72 fm; 88% 0+; $B(E1gs \to 1/2^-) = 0.116$ e$^2$ fm$^2$.
S5: rms(n-$^{10}$Be)=6.47 fm; 84% 0+; $B(E1gs \to 1/2^-) = 0.096$ e$^2$ fm$^2$.

# B(E1) distribution in an ab-initio calculation (sophisticated beauty)

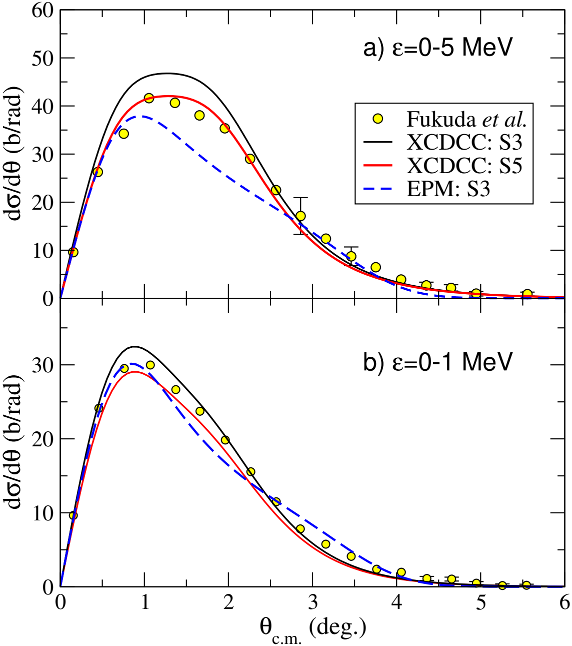


# Reaction theory. X-CDCC (the beast)

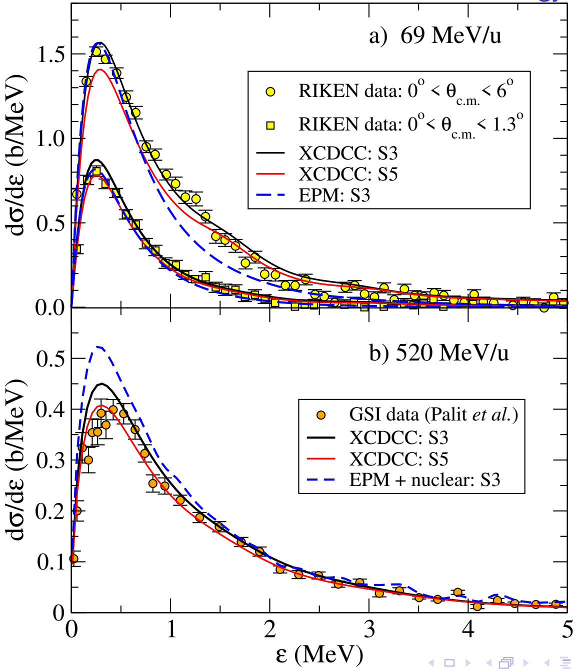
X-CDCC: N. Summers et al, Phys. Rev. C74 (2006) 014606; R. De Diego et al, Phys. Rev. C89 (2014) 064609
Basis required for the few body model of 11Be (This work)
https://arxiv.org/abs/2004.14612:



# Break up differential cross section w.r.t. angle RIKEN data, 69 MeV/u



# Break up cross section as a function of the excitation energy



## EPM is not so good. XCDCC is much better. So what?

- We understood the reaction cross sections measured at both energies, on the basis of a few body description of $^{11}$Be and a sophisticated XCDCC calculation.
- Time to publish and move on to something else? Or reanalyze the data?

Our procedure:

- Assume that our few body models (S3, S5) are not perfect, and the real $\langle i|M(E1)|f\rangle$ matrix elements could be somewhat different from the model (CF. effective charges in shell model).
- The modified $B(E1)$ values are equal to the model $B(E1)$ times a correction factor

$$B^m(E1, e_i) \simeq B^0(E1, e_i)(1 + 2\delta(e_i))$$

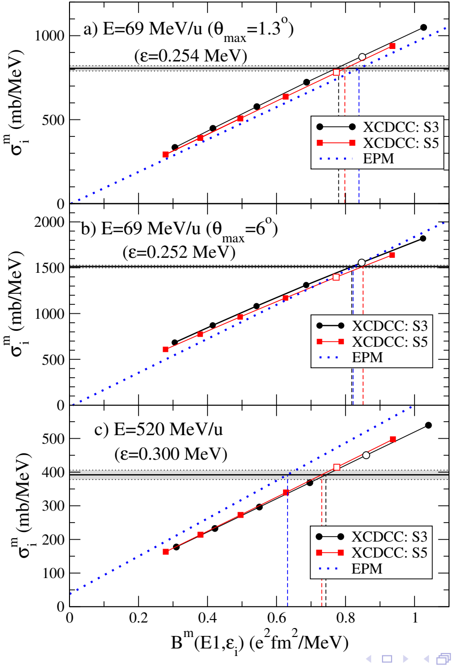
- The break-up cross sections will be modified by the same correction factor

$$\sigma_i^m \simeq \sigma_i^0 + \delta(e_i)\,\sigma'_i$$

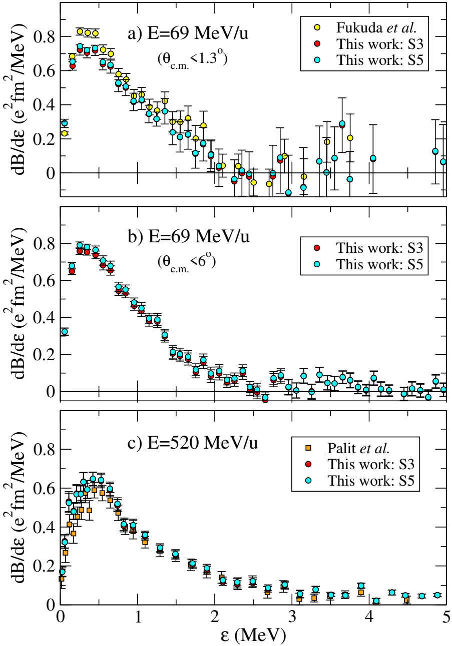
- The (small) difference between the exoperimental and the model cross section allows to determine the correction parameter $\delta(e_i)$, for each excitation energy, and this allows to obtain the experimental B(E1):

$$B^e(E1, e_i) = B^0(E1, e_i)\left(1 + 2\frac{\sigma_i^e - \sigma_i^0}{\sigma'_i}\right).$$

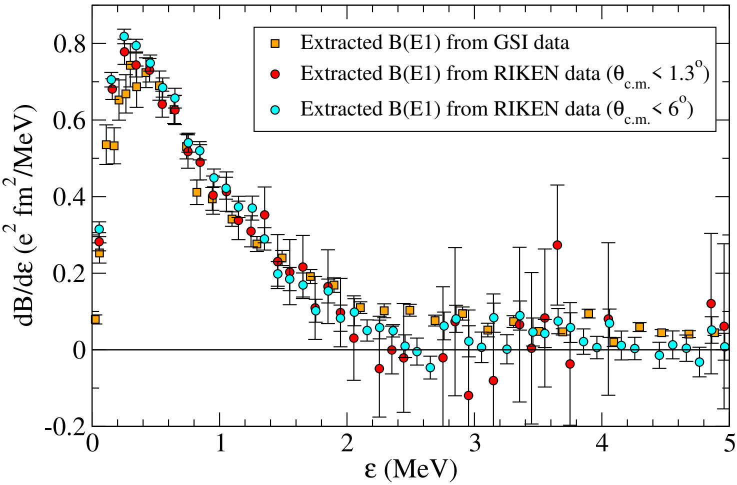
# Extracting B(E1) from the cross sections using XCDCC plus S3-S5 models



# Comparing new B(E1) with previous values (folding with energy resolution)



# Unfolded B(E1) distributions obtained (XCDCC+S3)



# Concluding remarks

- We should generate accurate nuclear structure data for the next generations.
- The relation of what we measure (cross sections) and the structure data that we want to obtain is not given accurately by simple relations, like the EPM. **No safe Coulomb!**.
- Given the cost (equipment, manpower) required to perform radioactive beam experiments, it may be advisable to dedicate some extra effort to improve reaction calculations strongly focused on extracting structure quantities.
- The beam time allocation at international facilities should pay more attention to experiments focused on obtaining more accurate data, instead of just discovering new phenomena.
- The theory community should dedicate more effort to establish the uncertainties of their methods, and the effect that those uncertainties have on the structure data obtained.