First Measurements of the Quadrupole Moment of the 2_1^+ State and B(E2) Value of the 4^+ State in ^{110}Sn from Coulomb Excitation

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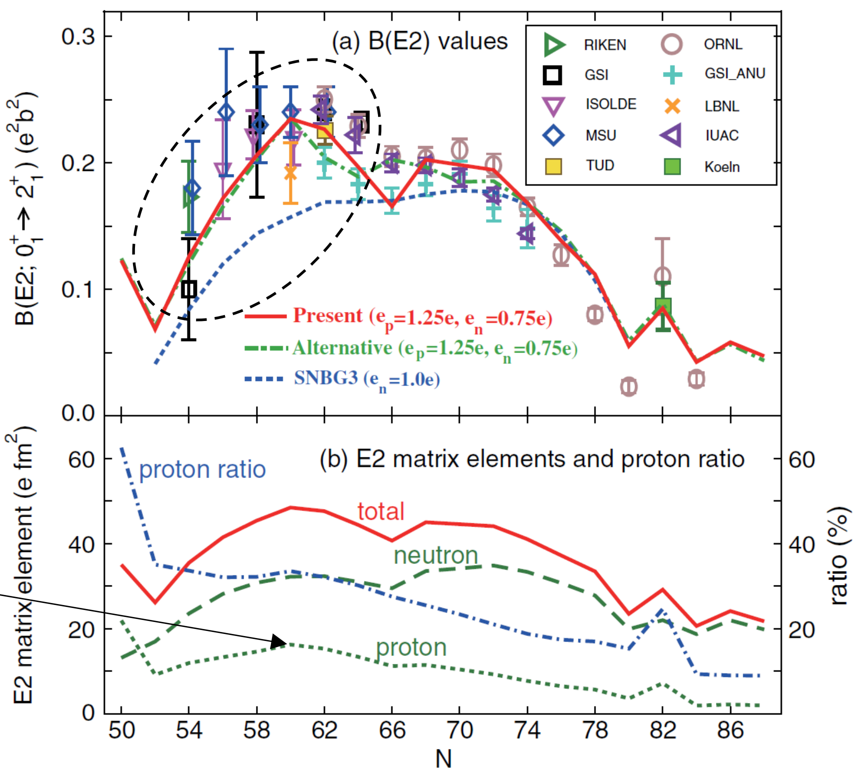
Physics motivation

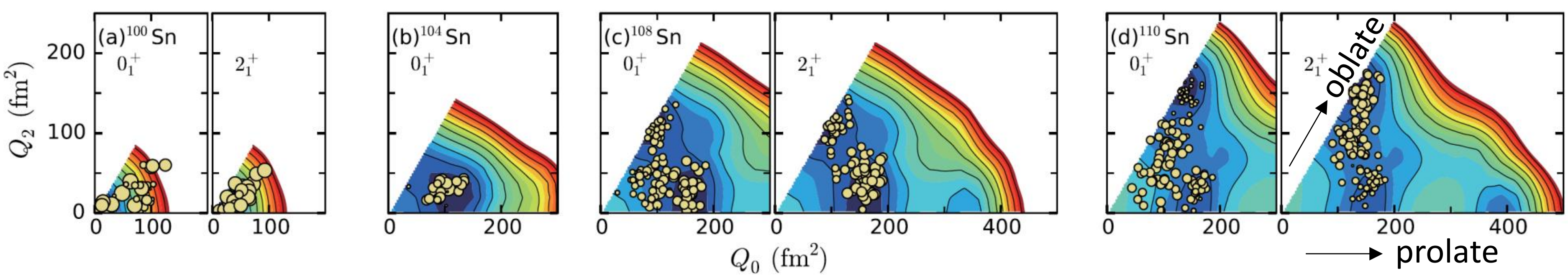
Enhanced B(E2) values in light Sn isotopes towards ^{100}Sn, compared to expectations based on simple seniority scheme

- Isospin-dependent effective charges?
- Quasiparticle phonon model?
- Proton core excitation?

MCSM: huge model space for proton and neutron $g_{9/2}$, $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, $h_{11/2}$, $f_{7/2}$, $p_{3/2}$ orbitals above ^{80}Zr (e_π, e_ν) = (1.25, 0.75), TBME's from JUN45/SNBG3

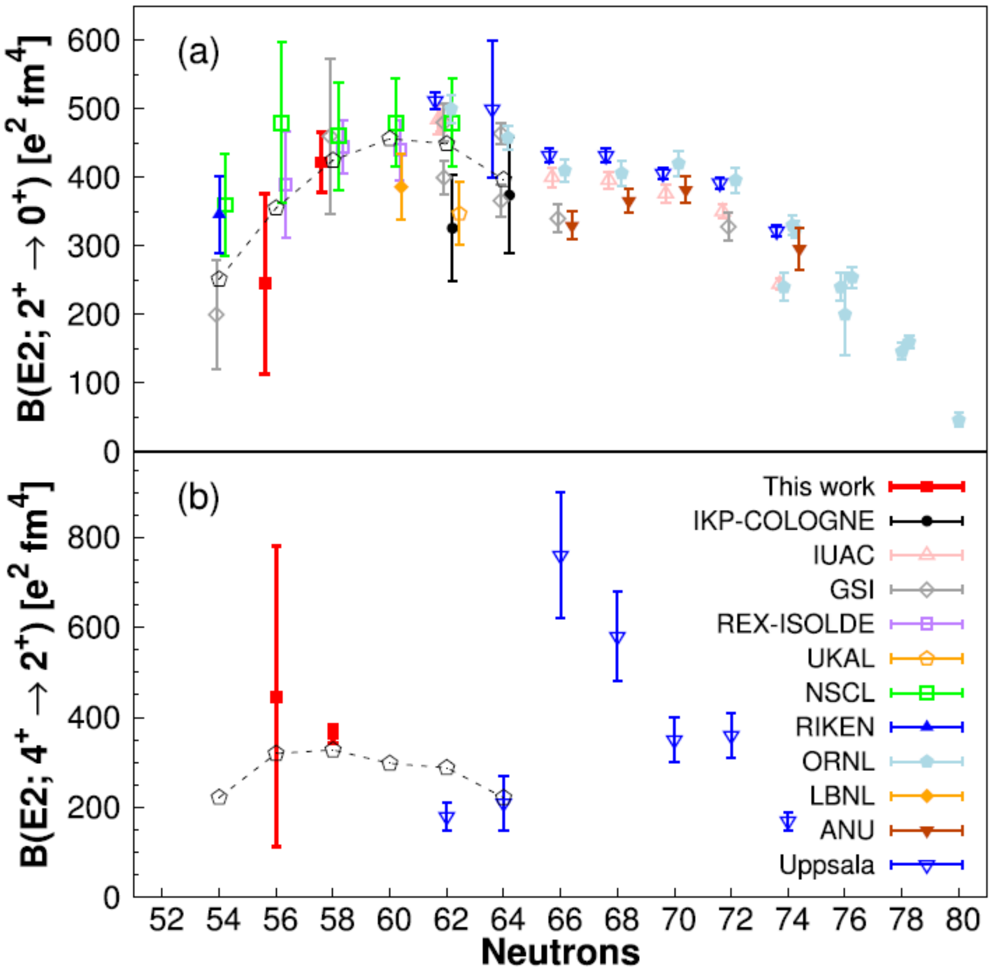
MCSM reproduces B(E2) trend via strong proton core excitation which peaks at ^{110}Sn, with oblate deformation predicted for 2_1^+





T. Togashi *et al.*, PRL 121, 062501 (2018)

Pairing-quadrupole interplay in Sn?



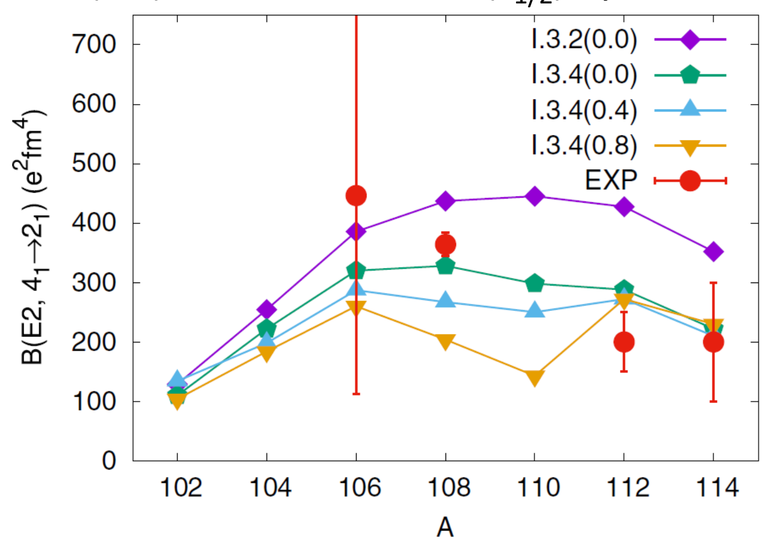
M. Siciliano *et al.*, PLB 806, 135474 (2020)

First B(E2) measurements of $\mathbf{4_1^+}$ states in ^{106,108}Sn via RDDS at GANIL, $^{\mathbf{110}}$**Sn missing** in systematics

Realistic SM interaction with limited model space to describe B(E2) trends in light Cd/Sn isotopes, including 4_1^+

(e_π, e_ν) = (~~1.4~~, 0.72), neutron *gds* orbitals

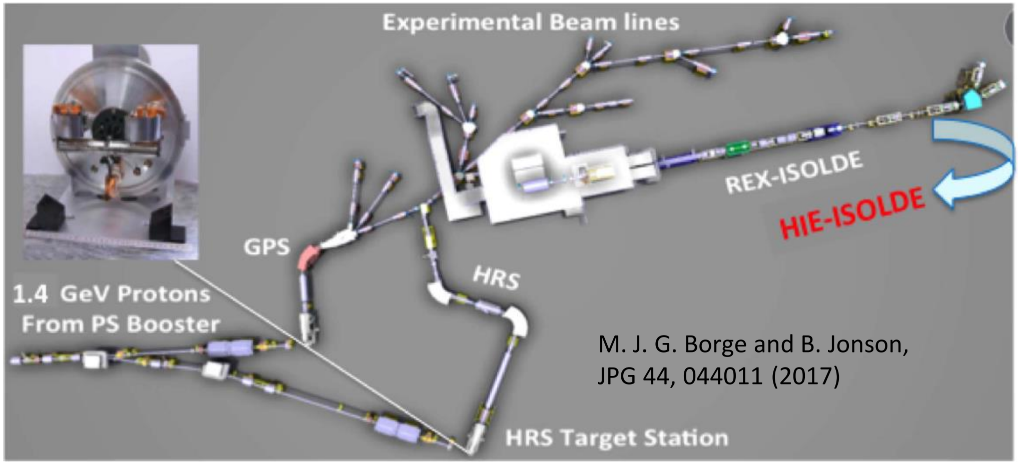
"I.*q*.*p*": pairing-quadrupole enhancements
E2 component *q* × 10%
J = 0, *T* = 1 pairing *p* × 10%
(0.*k*): shift in neutron $E(s_{1/2})$ by 0.*k* MeV



A. P. Zuker, PRC 103, 024322 (2021)

Experiments at CERN-ISOLDE

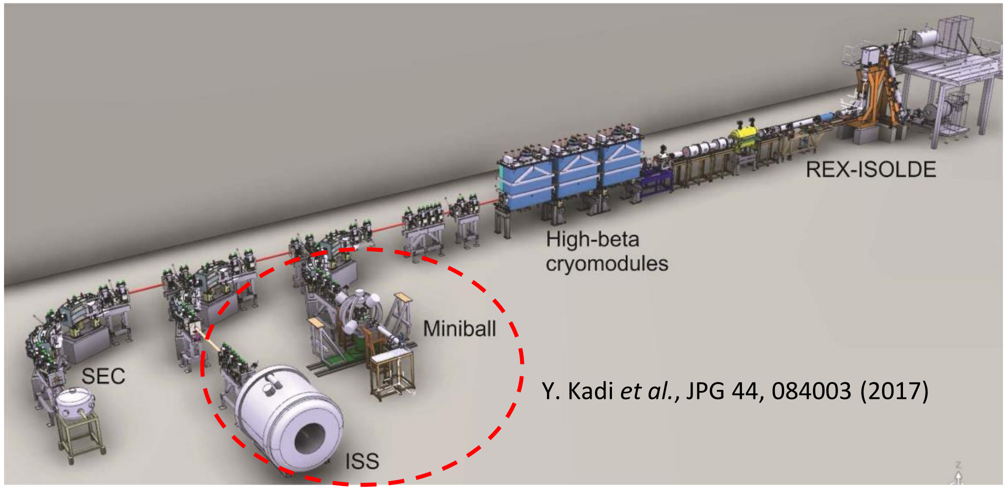
Spallation of 1.4-GeV protons from PS booster on LaC_x target, transport through GPS
Isobaric contamination ($^{106,108,110}In$) suppressed with Resonance Ionization Laser Ion Source (RILIS)



M. J. G. Borge and B. Jonson, JPG 44, 044011 (2017)

Final isobaric contamination level:
$R(^{110}In/^{110}Sn) \sim 1\text{-}2\%$
$R(^{108}In/^{108}Sn) \sim 10\%$
$R(^{106}In/^{106}Sn) \sim 50\%$

Post-acceleration at HIE-ISOLDE: 4.4-4.5 MeV/u for Coulex and 8.0 MeV/u for (d,p) transfer experiments



Y. Kadi *et al.*, JPG 44, 084003 (2017)

<u>2 dedicated campaigns</u>

<u>IS562</u>: Coulex of $^{106,108,110}Sn$ with Miniball (completed)

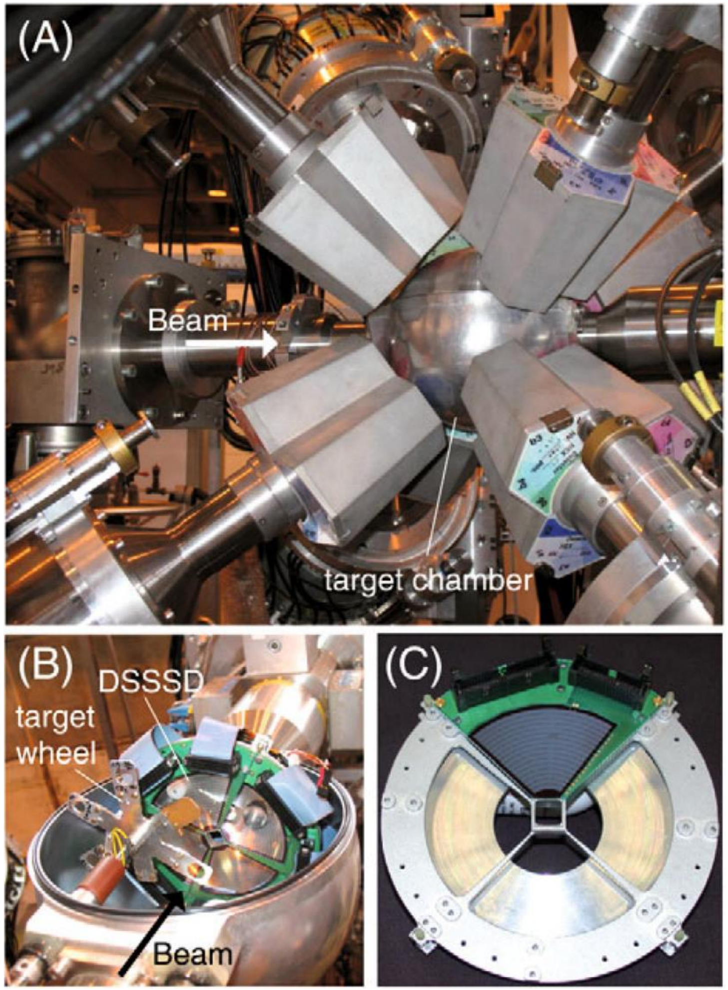
<u>IS686</u>: (d,p) transfers on $^{106,108,110}Sn$ with ISOLDE Solenoidal Spectrometer (ongoing)

The Miniball spectrometer setup

Segmented HPGe detectors for Doppler correction following Coulex reactions

24 HPGe crystals × 6 segments = 144 unique γ-ray detection angles

^{206}Pb target, 4.2-4.7 mg/cm^2



N. Warr *et al.*, EPJA 49, 40 (2013)

E_{beam} = 4.4-4.5 MeV/u

Just below safe-energy threshold for ^{106,108,110}Sn + ^{206}Pb combination

4-quadrant DSSSD with 16 × 16 rings and sectors for beam/particle scattering angles

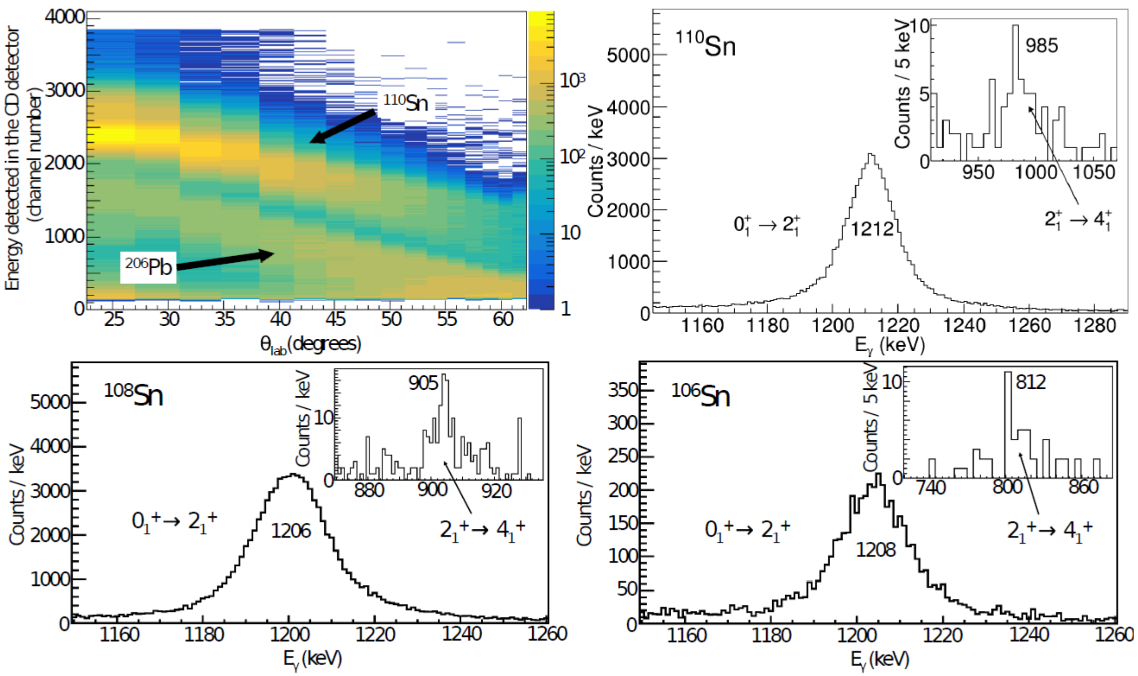
New Coulex statistics for $^{106,108,110}Sn$

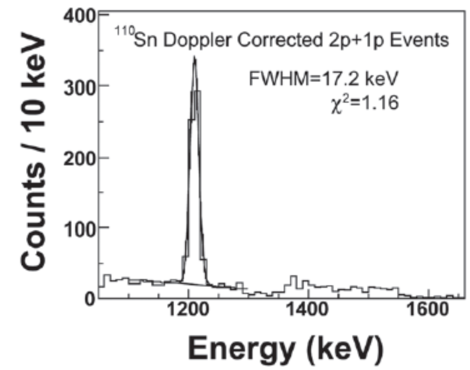
3 experiments for ^{110}Sn (2016), ^{108}Sn (2017), and ^{106}Sn (2018)

20-50 increase in statistics with heavier target and E_{beam}: ^{58}Ni (2.8 MeV/u) → ^{206}Pb (4.4 MeV/u)

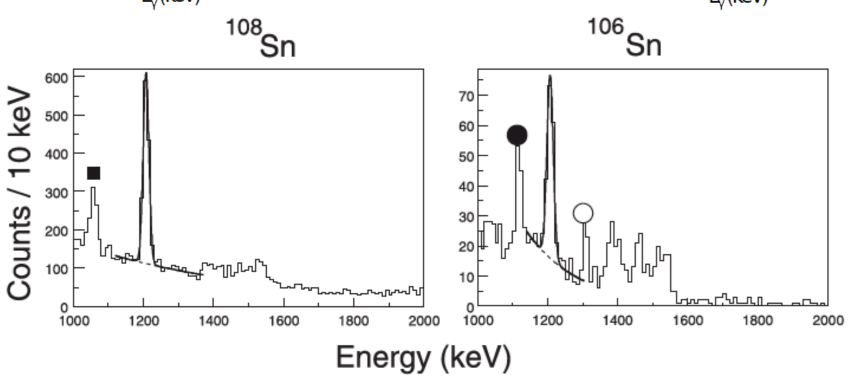
Excitations to 4_1^+ states observed for the first time in safe-energy Coulex

JP *et al.*, JPS Conf. Proc. 32, 010036 (2020)





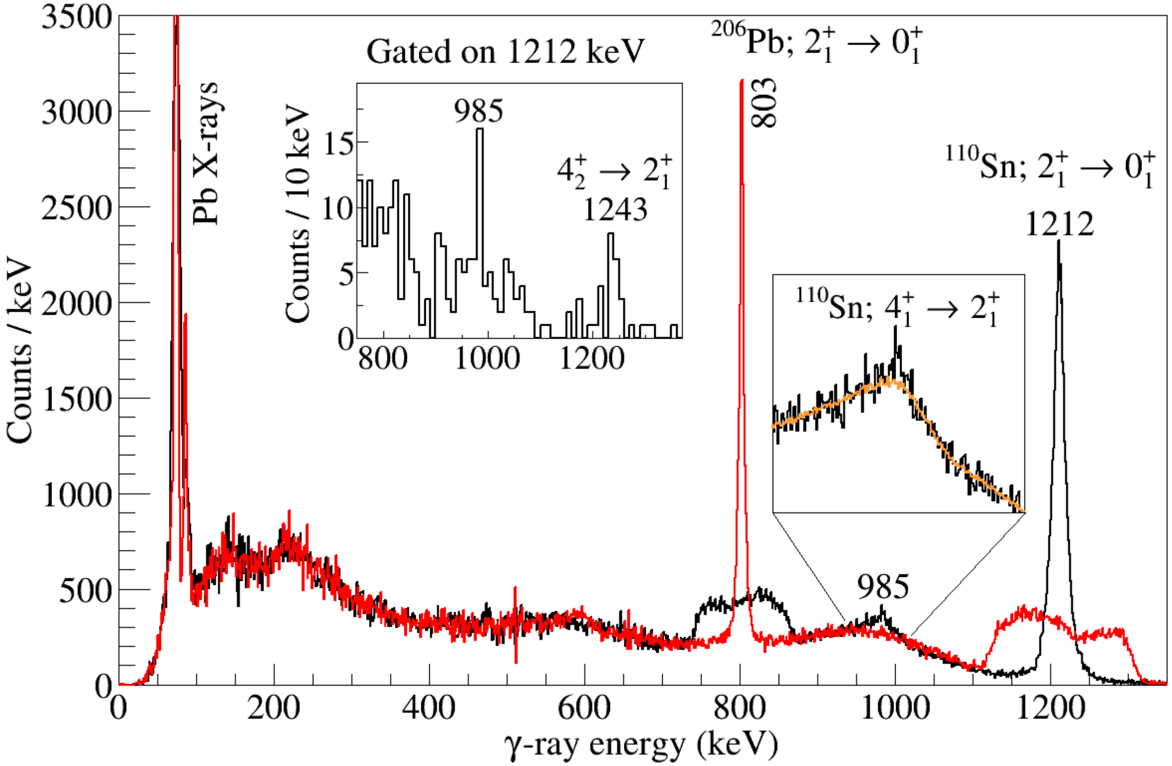
J. Cederkäll *et al.*, PRL 98, 172501 (2007)



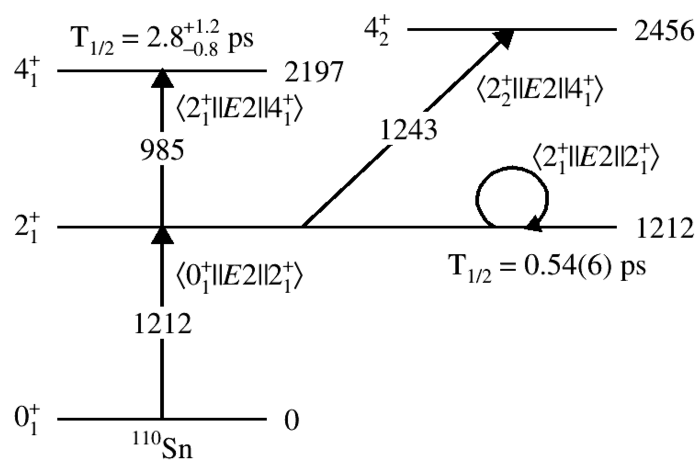
A. Ekström *et al.*, PRL 101, 012502 (2008)

Total gamma-ray spectrum for ^{110}Sn

Record γ-ray statistics for ^{110}Sn, additional γ-γ coincidence at 1243 keV to 4_2^+ state observed



E2 matrix elements determined from this experiment

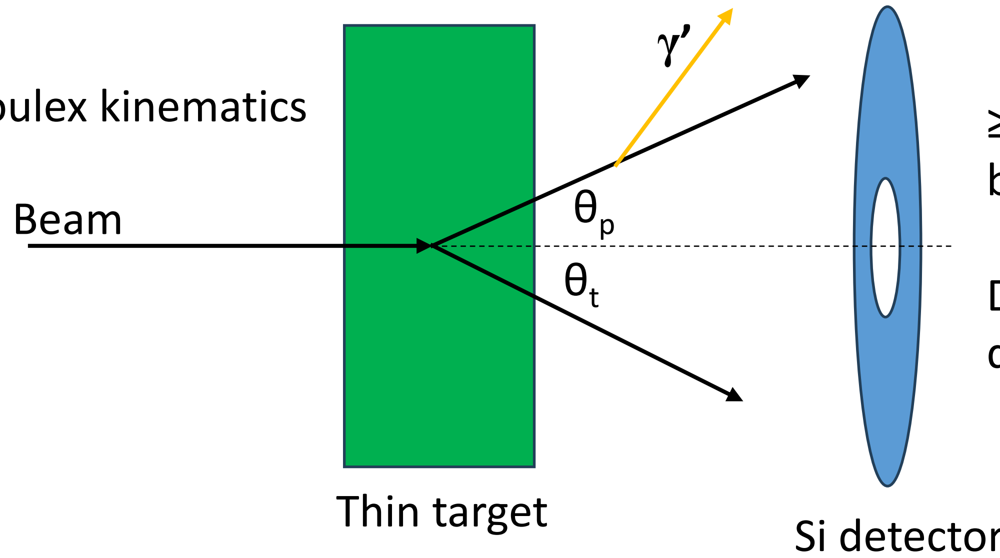


Little evidence of excitations to other states in ^{110}Sn, ^{206}Pb

1246-keV γ from 3_1^- state in ^{110}Sn ruled out; 262-keV side branch unobserved

Combined Coulex-DSAM analysis for B(E2)

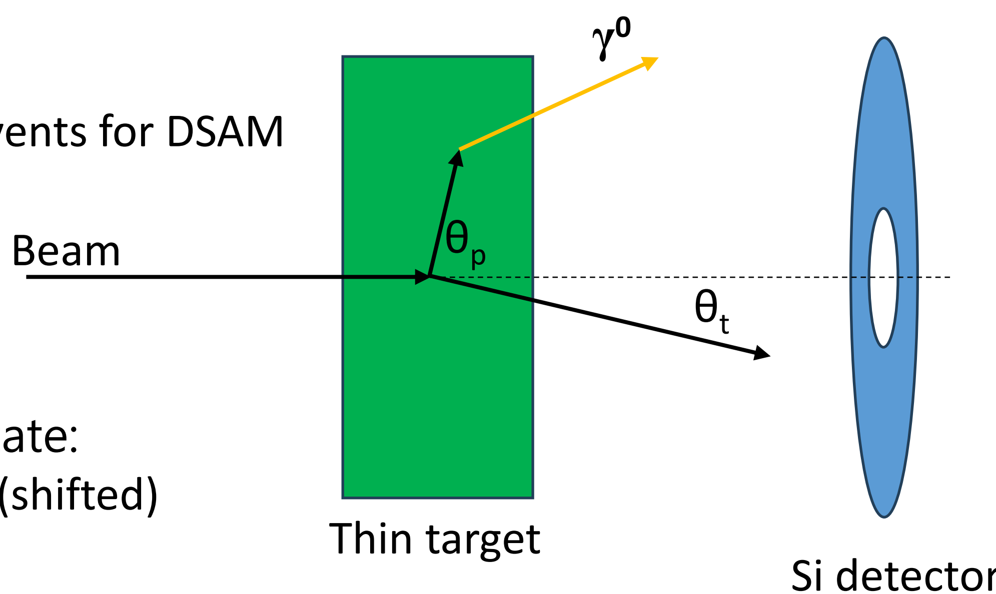
Usual safe-energy Coulex kinematics



≥ 1 particle detected, both escape the target

Doppler-shifted γ detected

Subset of Coulex events for DSAM



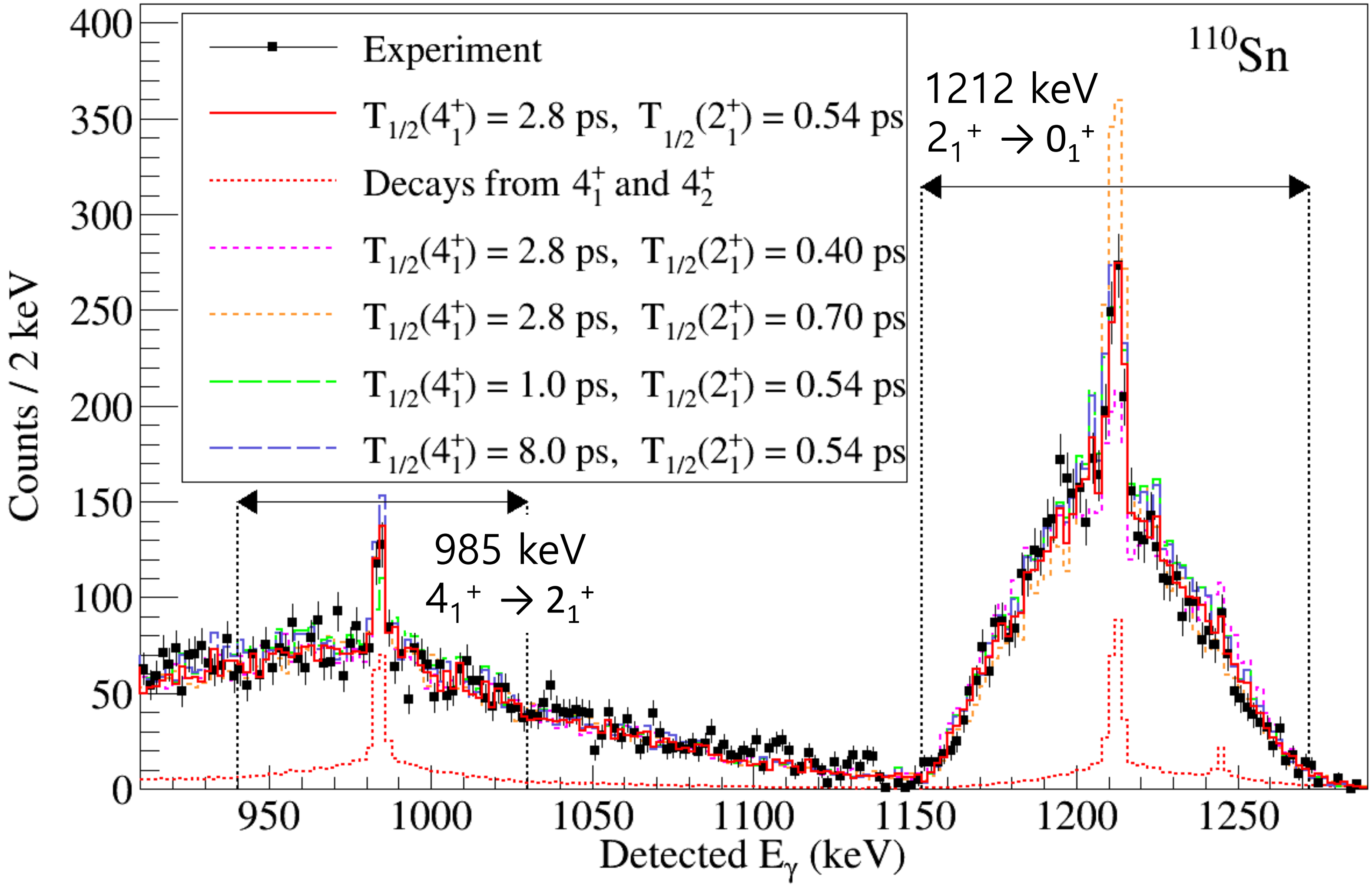
1 particle detected, the other stopped in target

Unshifted γ from stopped particle

Longer $T_{1/2}$ of state:
N_γ(unshifted) > N_γ(shifted)

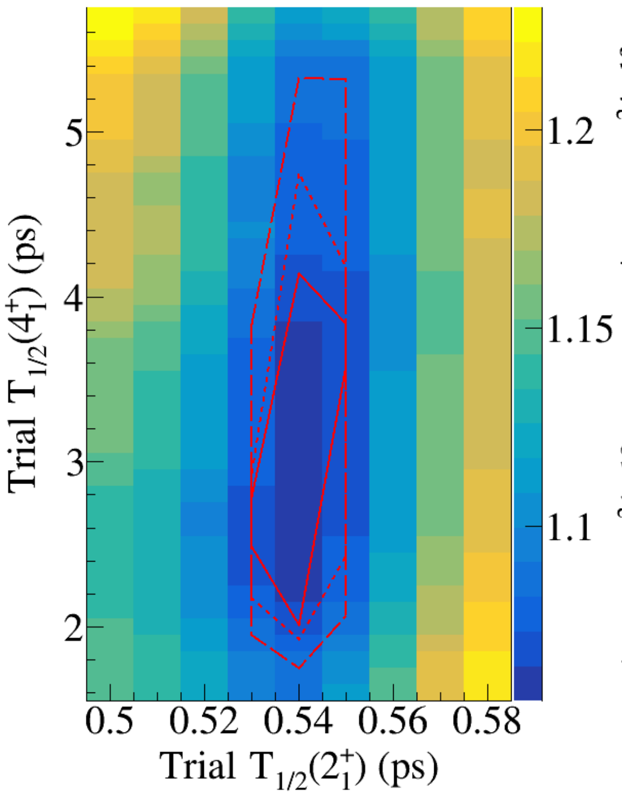
$T_{1/2}$ analysis with DSAM simulation including cascade decays

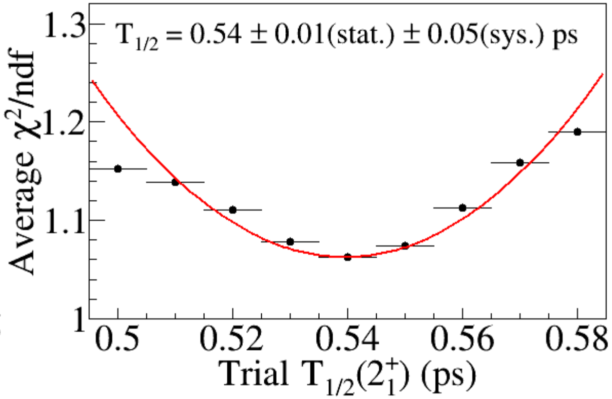
Feeding from long-lived 4_1^+ state taken into account, minor contribution from 4_2^+ also

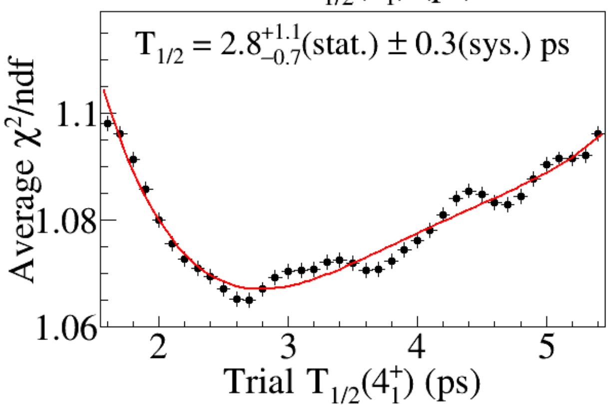


Simulated spectra normalized to experiment within χ^2 evaluation ranges

Correlated $T_{1/2}$ analysis of 4_1^+ and 2_1^+ states



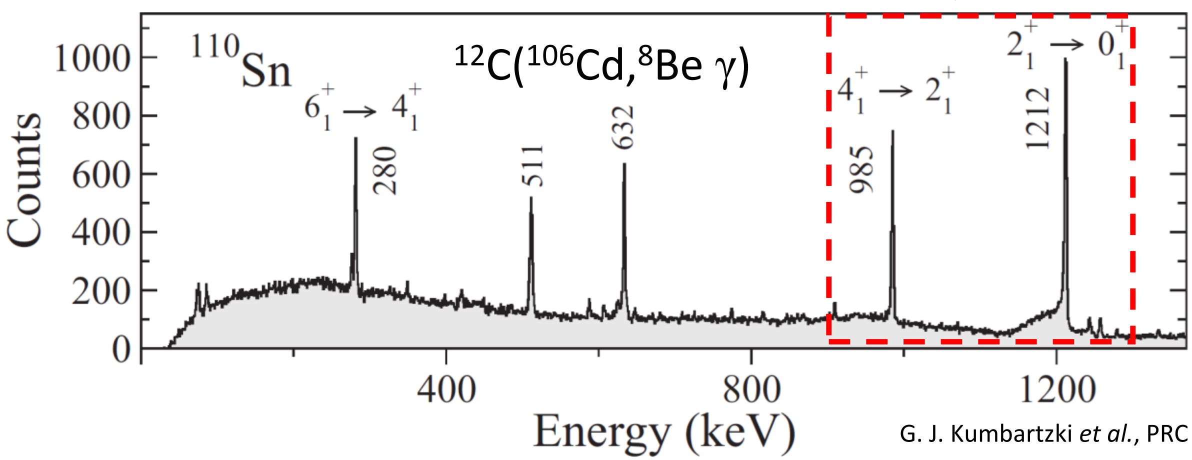




Small correlation in χ^2 between $T_{1/2}(2_1^+)$ and $T_{1/2}(4_1^+)$

$T_{1/2}(2_1^+)$ = **0.54(6) ps**

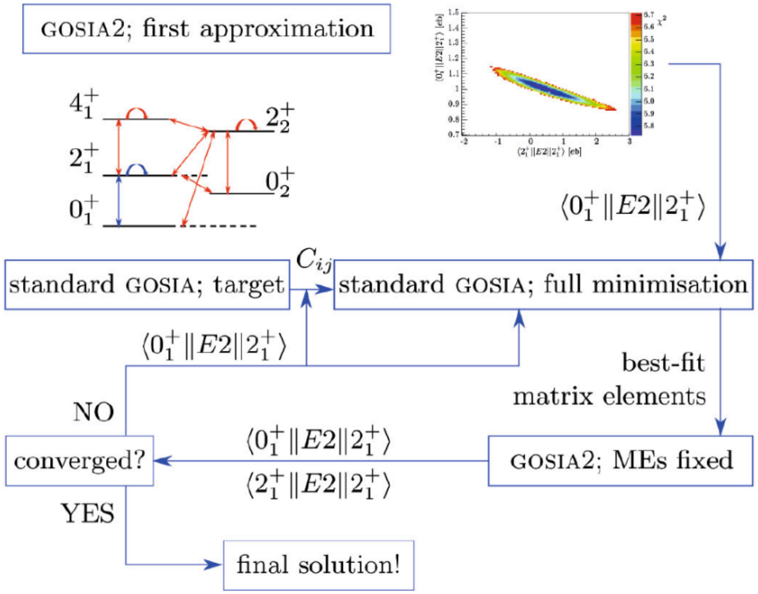
$T_{1/2}(4_1^+)$ = $\mathbf{2.8^{+1.2}_{-0.8}}$ **ps**



DSAM literature:
$T_{1/2}(2_1^+)$ = **0.56(7) ps**
$T_{1/2}(4_1^+)$ > **2.77 ps**

G. J. Kumbartzki *et al.*, PRC 93, 044316 (2016)

Combined GOSIA-GOSIA2 analysis



M. Zielińska *et al.*, EPJA 52, 99 (2016)

Standalone GOSIA2 analysis not applicable due to multi-step Coulex to higher states in ^{110}Sn

Iterative GOSIA-GOSIA2 approach applied

5 subdivisions of γ-ray yield data for B(E2) vs Q(2_1^+)

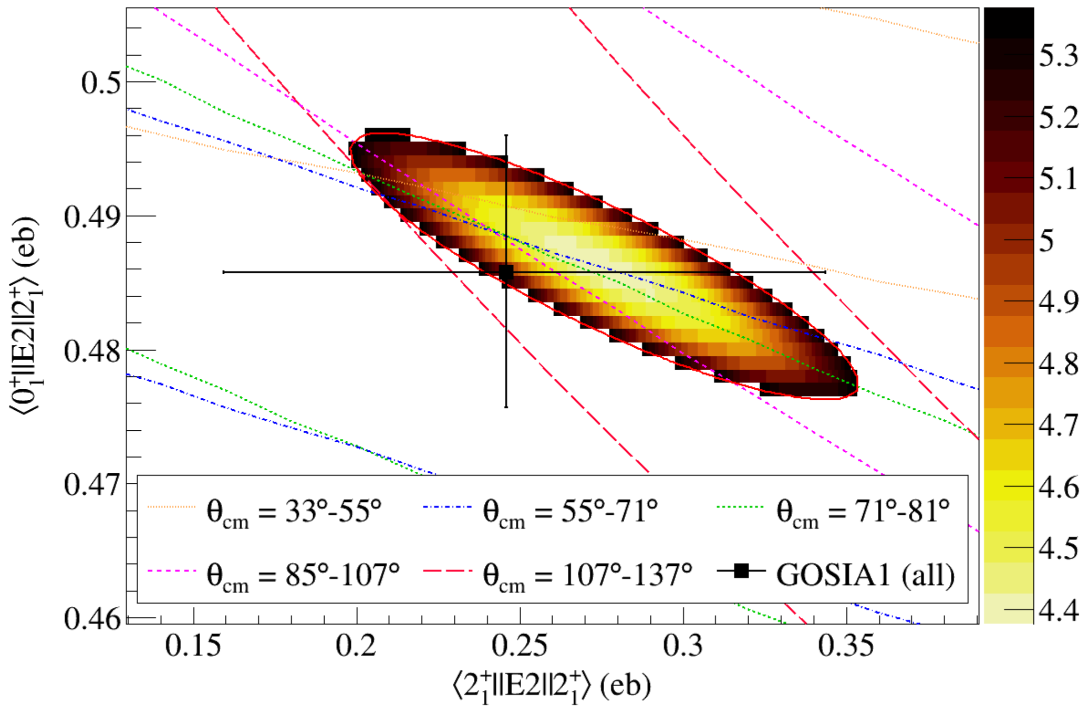
$$\langle 0_1^+ \| E2 \| 2_1^+ \rangle = 0.486(10) \text{ eb}$$

$$B(E2; 2_1^+ \rightarrow 0_1^+) = \begin{cases} \mathbf{472(20)}\ e^2fm^4 \text{ (Coulex)} \\ \mathbf{400^{+50}_{-40}}\ e^2fm^4 \ (T_{1/2}) \end{cases}$$

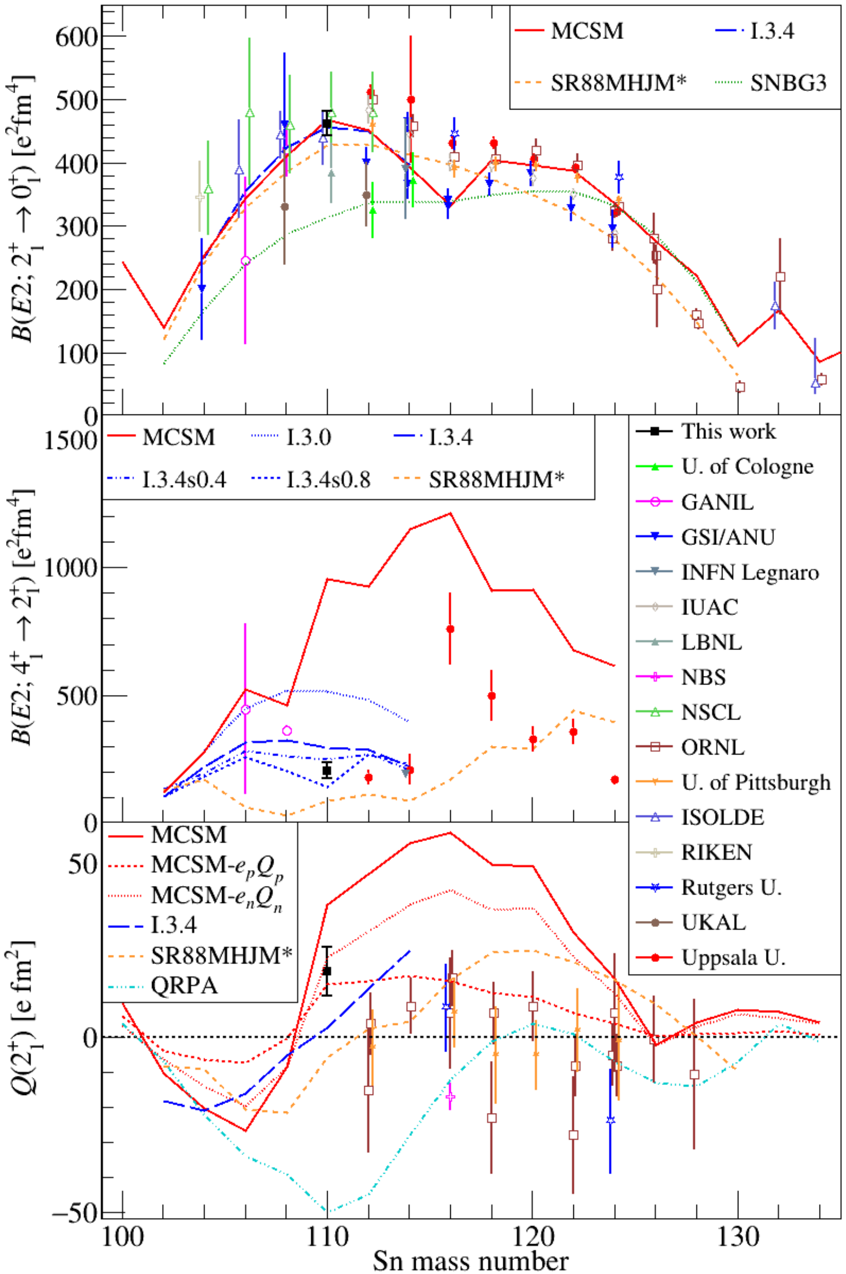
$$\langle 2_1^+ \| E2 \| 2_1^+ \rangle = 0.25^{+0.10}_{-0.09} \text{ eb}$$

Q(2_1^+) = **+0.19(7)** eb

<u>Q > 0, oblate deformation by > 2σ</u>



Comparisons with shell model calculations



$\Delta B(E2)/B(E2) \approx 4\%$ for 2_1^+, down from 10%

Little discrepancy with different SM's

$B(E2; 4_1^+ \to 2_1^+) = \begin{cases} \mathbf{203(33)}\ e^2fm^4\ \text{(Coulex)} \\ \mathbf{218^{+87}_{-65}}\ e^2fm^4\ (T_{1/2}) \end{cases}$

$B(E2; 4_2^+ \to 2_1^+) =$ **237(59)** e^2fm^4

Small $B(E2; 4_1^+ \to 2_1^+)$ for ^{110}Sn, closer to ^{112,114}Sn than ^{106,108}Sn

Pairing effects quenching B(E2) of $B(E2; 4_1^+ \to 2_1^+)$?

$Q(2_1^+)$ of ^{110}Sn the largest among known isotopes, oblate shape consistent with MCSM and I.3.4

Q magnitudes overestimated by MCSM, large contributions from e_pQ_p and e_nQ_n

Important to measure $Q(2_1^+)$ of lighter Sn, shape change to prolate predicted for A ≤ 108

Data analysis for ^{106,108}Sn underway

Summary and outlook

Coulomb excitation of ^{110}Sn on ^{206}Pb at HIE-ISOLDE

- Most precise B(E2) for 2_1^+
- New B(E2) measurements for 4_1^+ and 4_2^+, pairing effects eroding quadrupole collectivity
- First determination of Q(2_1^+) in the light unstable Sn, oblate shape in agreement with MCSM and SM predictions
- To be submitted soon!

Follow-up studies of B(E2) and Q(2_1^+) systematics with ^{106,108}Sn

- Improved precision on B(E2), new Q(2_1^+) and B(E2; $4_1^+ \rightarrow 2_1^+$) expected
- DSAM simulations for independent B(E2) measurements and comparisons

IS562 experiment campaign and Miniball collaborators:

J. Park[a,b], J. Cederkäll[a,*], C. Fahlander[a], P. Golubev[a], A. Knyazev[a], A. Lopez[a], E. Rickert[a], J. Snäll[a], A. N. Andreyev[c,d], J. Konki[c], A. Welker[c], K. Wrzosek-Lipska[e], A. Gawinek[e], J. Iwanicki[e], M. Saxena[e], G. de Angelis[f], L. P. Gaffney[g], Th. Kröll[h], C. Henrich[h], T. Habermann[h], M. Schilling[h], M. Seidlitz[h], C. Stahl[h], K. Arnswald[i], A. Blazhev[i], P. Reiter[i], D. Rosiak[i], N. Warr[i], S. Saha[j], G. Rainovski[k], R. Zidarova[k], C. Raison[d], A. Boukhari[c,l], L. Barber[m], D. M. Cullen[m], B. S. Nara Singh[m], C. Berger[n], C. Berner[n], R. Gernhäuser[n], L. Werner[n], M. J. G. Borge[c,o], J. Díaz Ovejas[o], O. Tengblad[o], S. Viñals[o], T. Berry[p], D. M. Cox[q,r], A. Görgen[s], T. W. Johansen[s], G. Tveten[s], A. Illana[f,q,t], M. Stryjczyk[t], P. Van Duppen[t], H. De Witte[t], J. J. Valiente-Dobón[u]

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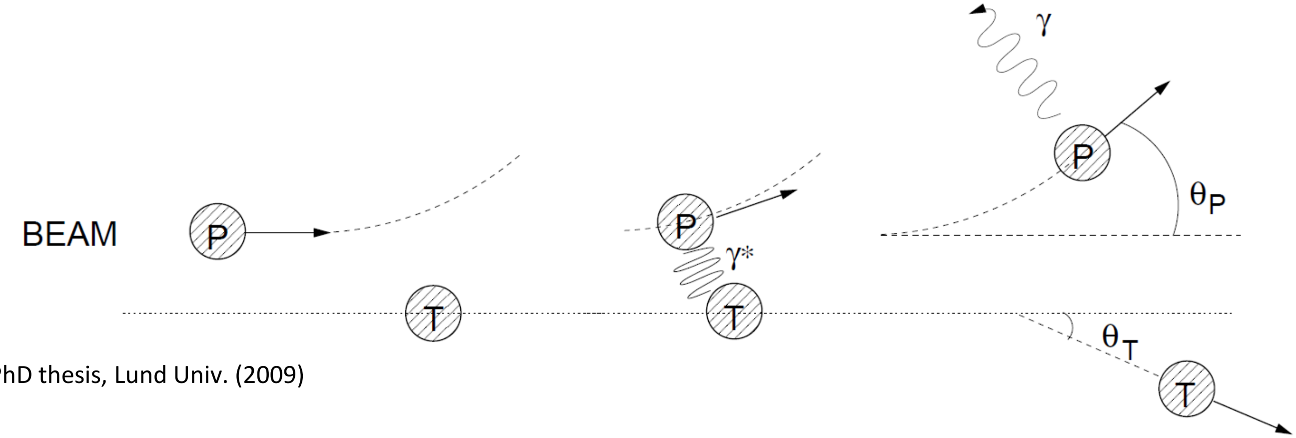
Safe-energy Coulex experiment design details



A. Ekström, PhD thesis, Lund Univ. (2009)

- Electromagnetic excitation between projectile (beam) and target nucleus through Coulomb field
- Detection of γ rays and Doppler correction using kinematics ($\beta = v/c$), θ_γ, θ_p and θ_t
- Nuclear excitation can be separated from pure electromagnetic interaction at "safe" Coulex energy:

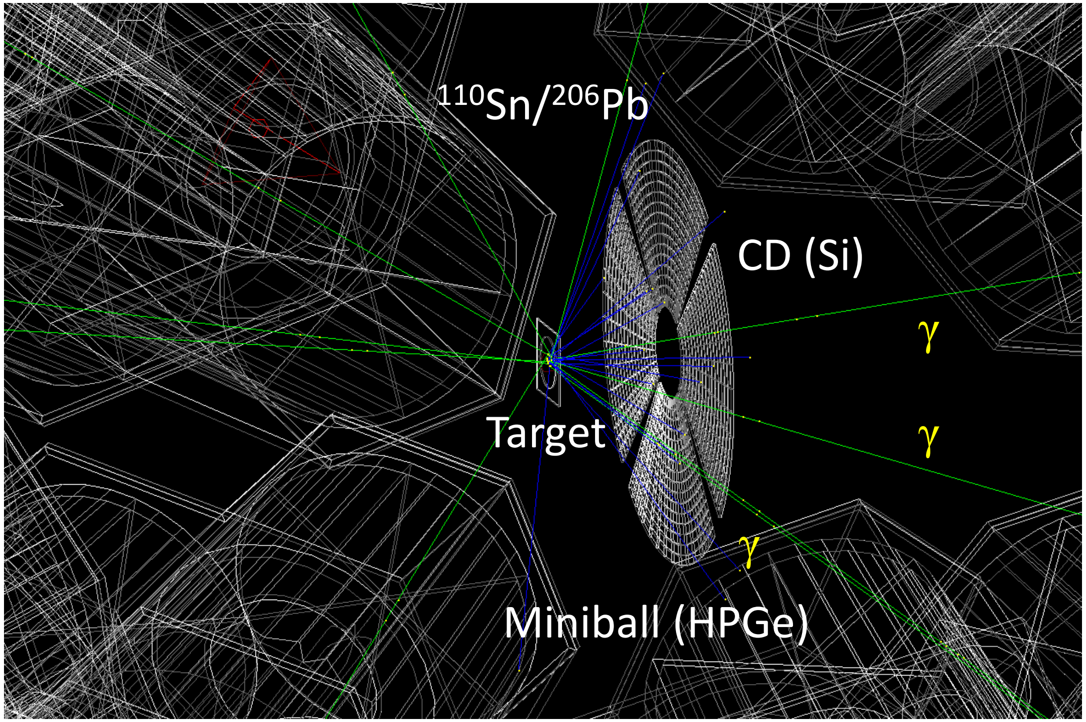
$$E_{\text{safe}} = 1.44 \frac{A_p + A_t}{A_t} \frac{Z_p \cdot Z_t}{1.25(A_p^{1/3} + A_t^{1/3}) + 5} \text{MeV}$$

K. Alder and A. Winther, *Electromagnetic Excitation* (1975)

Coulex experiments performed at HIE-ISOLDE using ^{206}Pb target (Z_t = 82, A_t = 206)

Z_p	A_p	E_{safe} (MeV)	E_{safe}/A_p (MeV)	E_{exp}/A_p (MeV), year
50	110	493	4.48	4.40 (2016)
50	108	491	4.54	4.50 (2017)
50	106	489	4.61	4.40 (2018)

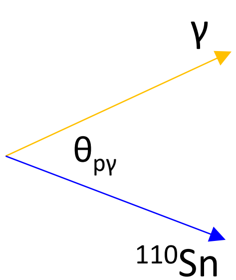
DSAM simulation with Geant4



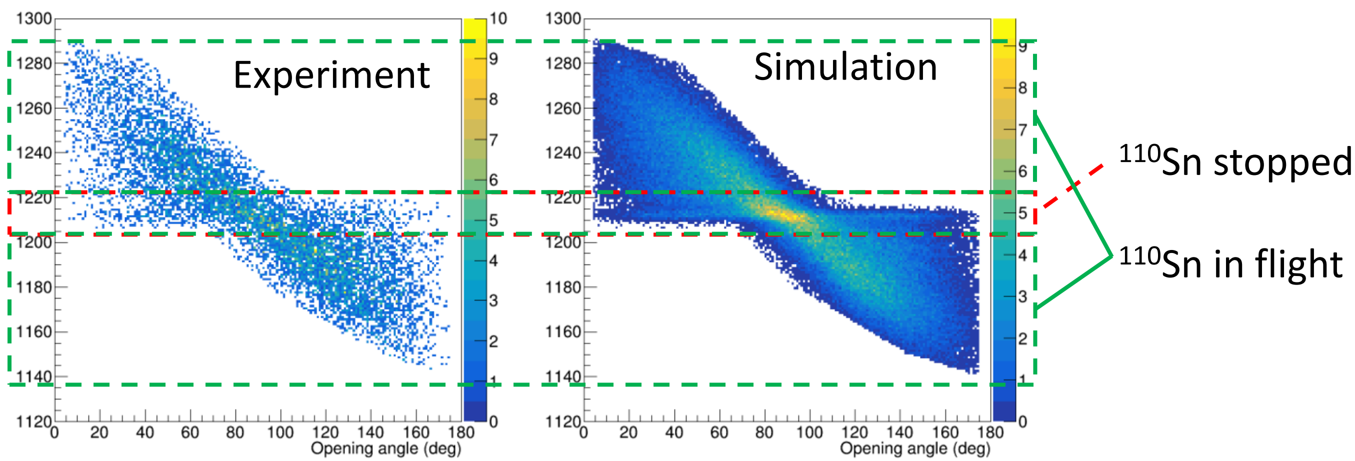
Event selection cut:
Low θ_{lab} for ^{206}Pb,
more ^{110}Sn stopped inside target
→ better sensitivity for DSAM

Stopping power of ^{206}Pb calculated with SRIM

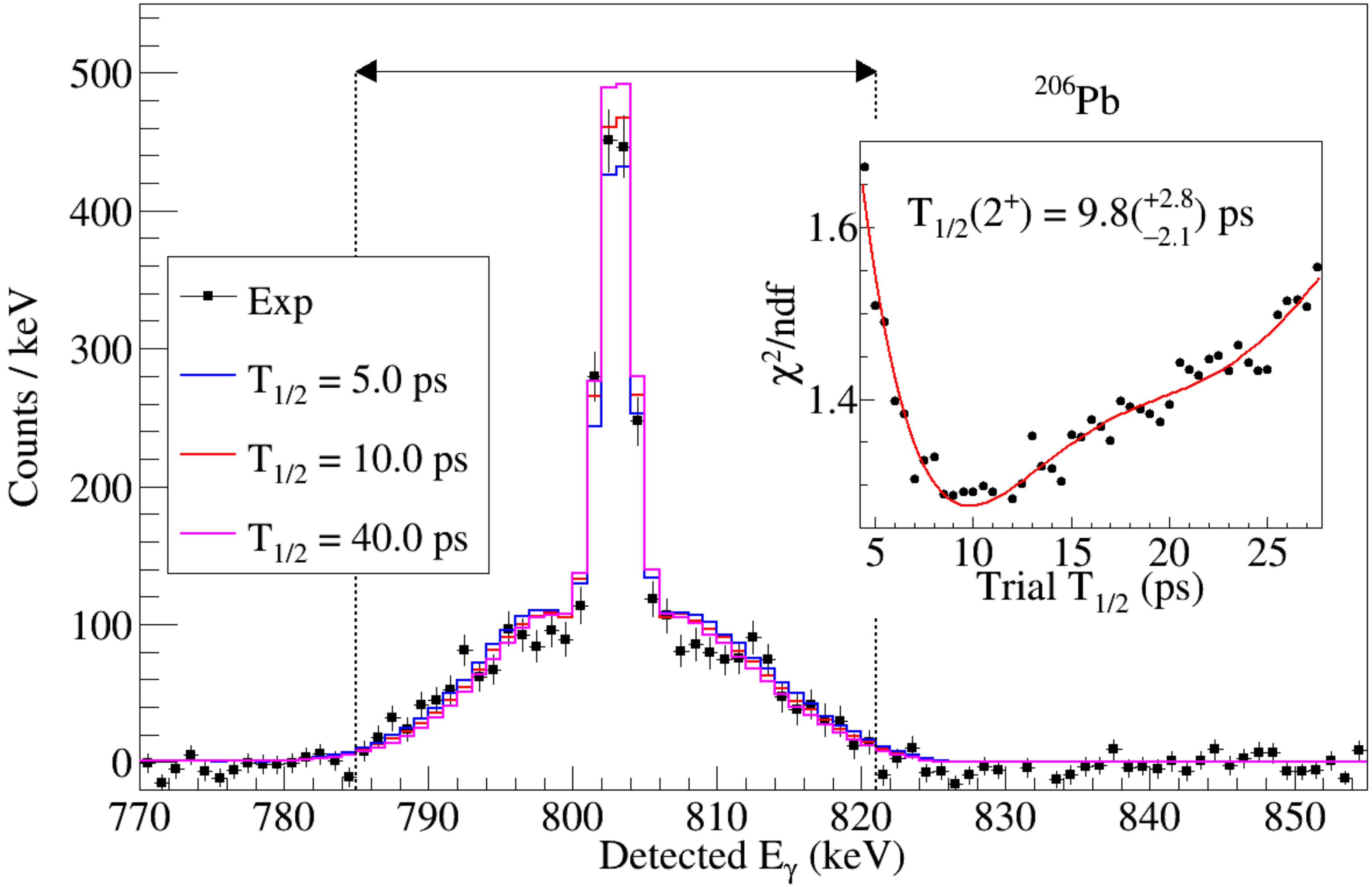
10% systematic uncertainty in $T_{1/2}$



$$E_\gamma = E_0 \frac{\sqrt{1-\beta^2}}{1-\beta\cos\theta}$$



DSAM simulation for $T_{1/2}$ of ^{206}Pb



Literature $T_{1/2}$:

9.1(6) ps: J. L. Quebert *et al.*, Nucl. Phys. A 150 (1970) 68

12(3) ps: D. Ralet *et al.*, Phys. Lett. B 797 (2019) 134797