Study of EM Properties along the Carbon Isotopic Chain & O-21

A Status Report From A03

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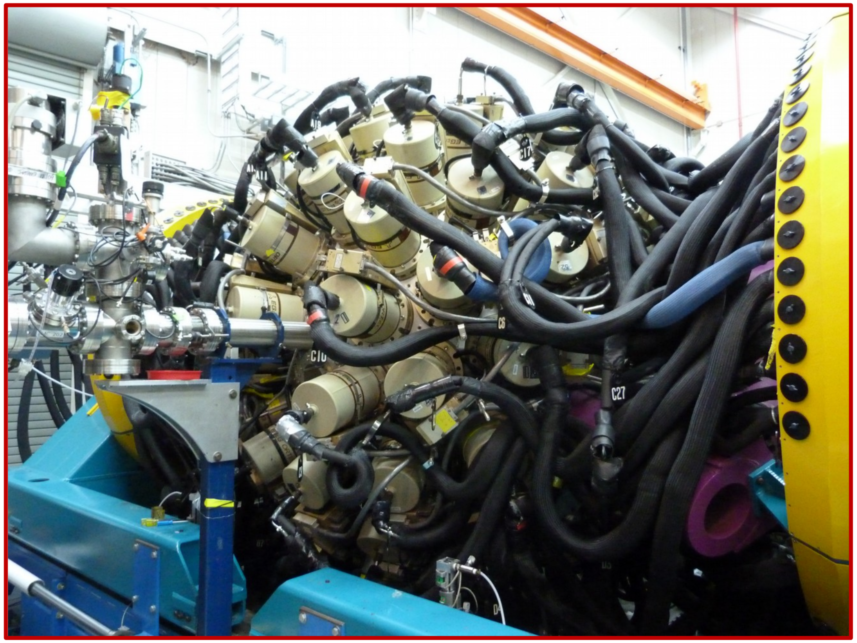
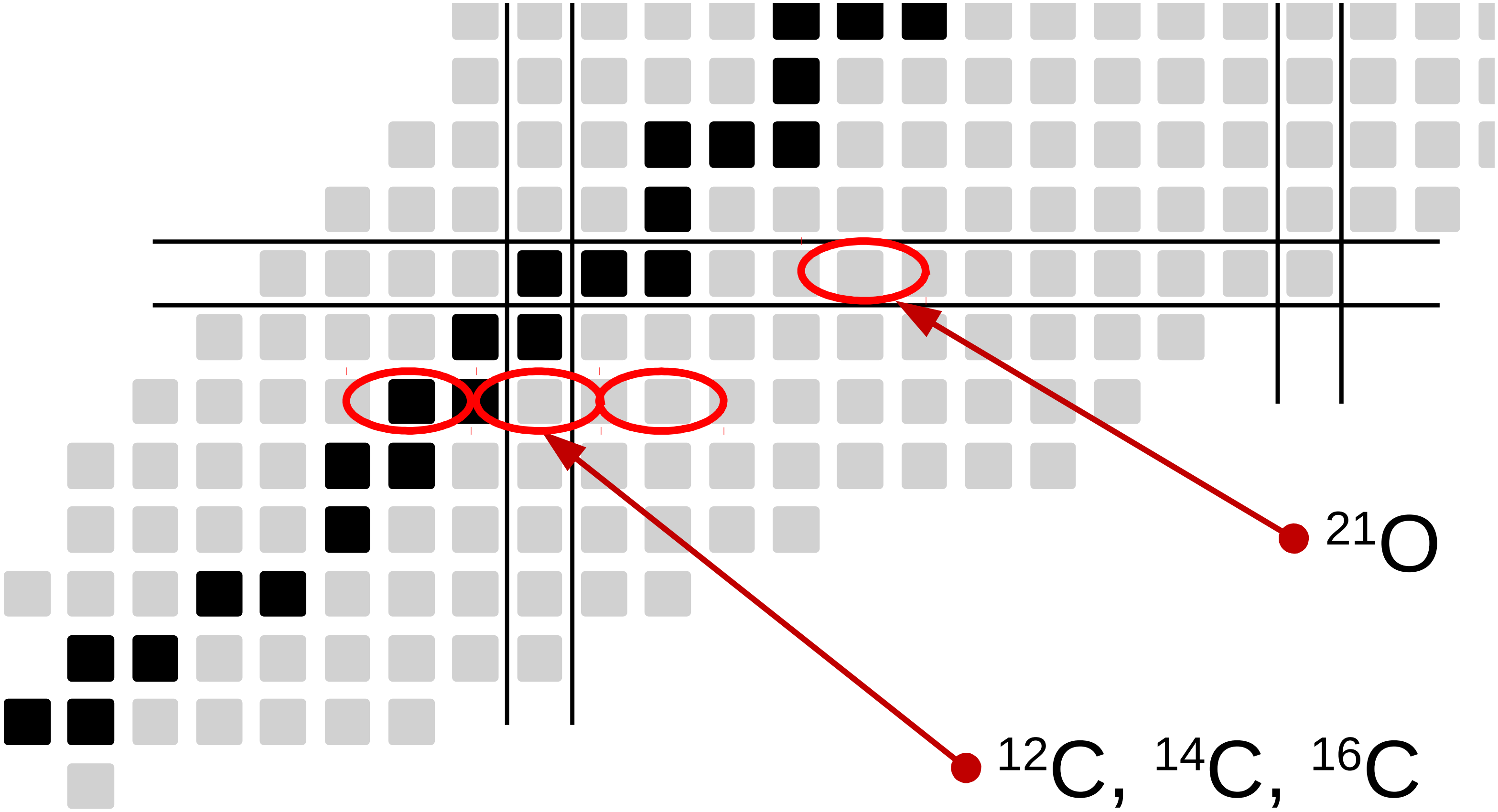


This work was supported by the DFG under contract No. SFB 1245.

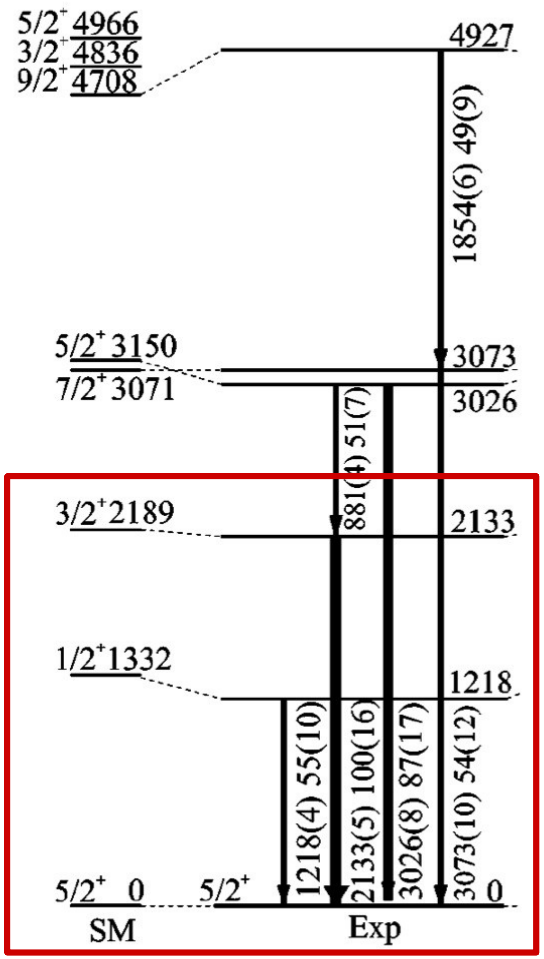
Outline

A03 Studies EM properties of:



Oxygen-21

Oxygen-21: Motivation



Theoretical shell model predictions for low lying excited states differ significantly:

Transition	BR [%] USDB*	BR [%] NN+3N**	Lifetime [ps] USDB*	Lifetime [ps] NN+3N**
$\frac{1}{2}^+ \rightarrow \frac{5}{2}^+$			178	709
$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$	80	87	2.7	1.9
$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	20	13		

*(** A. Schwenk et al., Private Communication)*
(B. Alex Brown et al., MSU, Private Communication)*

Oxygen-21: Experimental Setup

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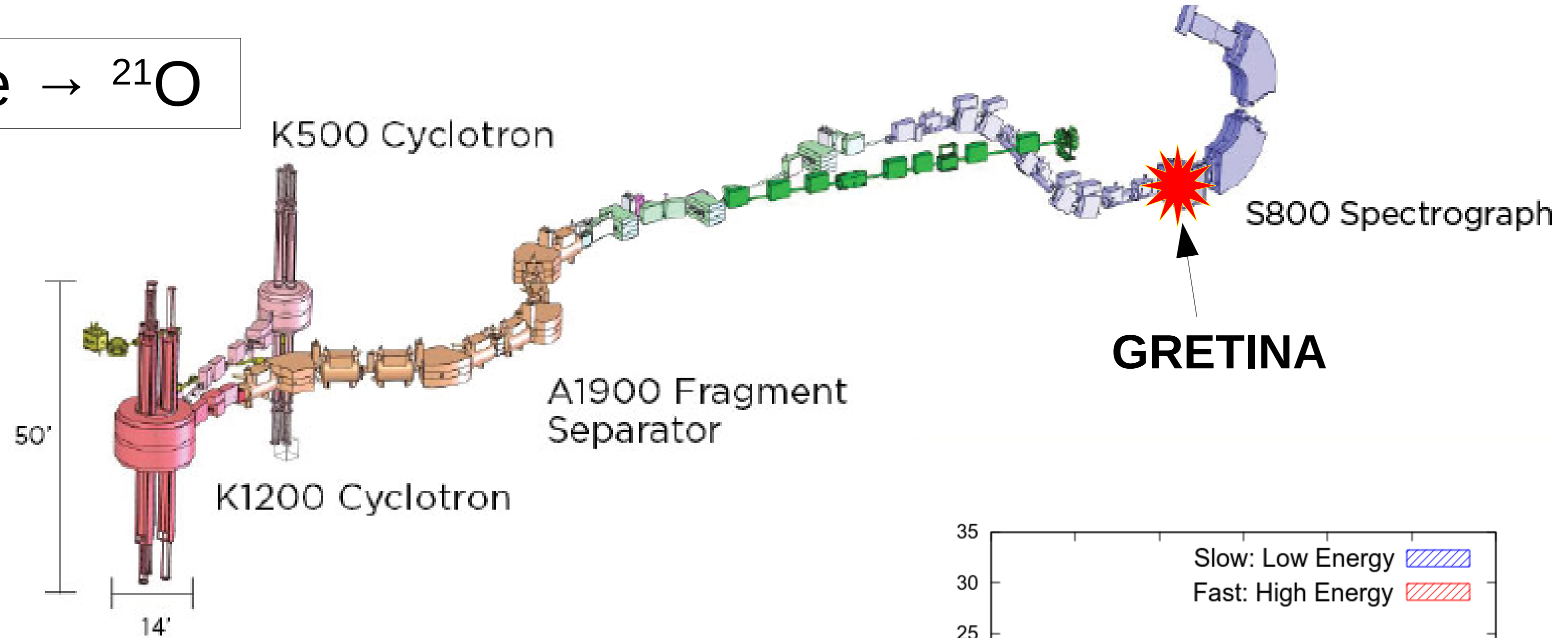
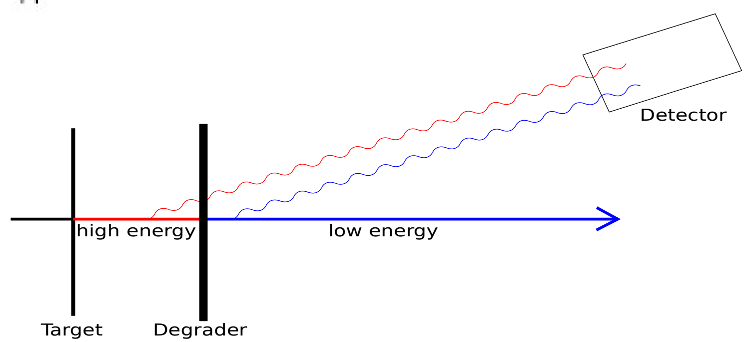
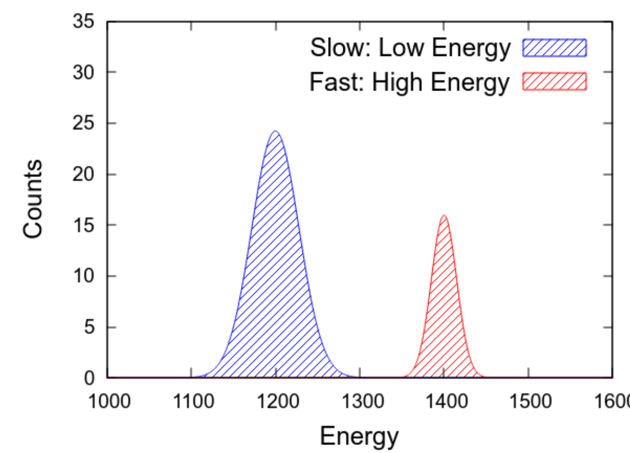
Measured lifetime of 1/2$^+$ in ^{21}O at NSCL:

$^{24}F + {}^{9}Be \rightarrow {}^{21}O$



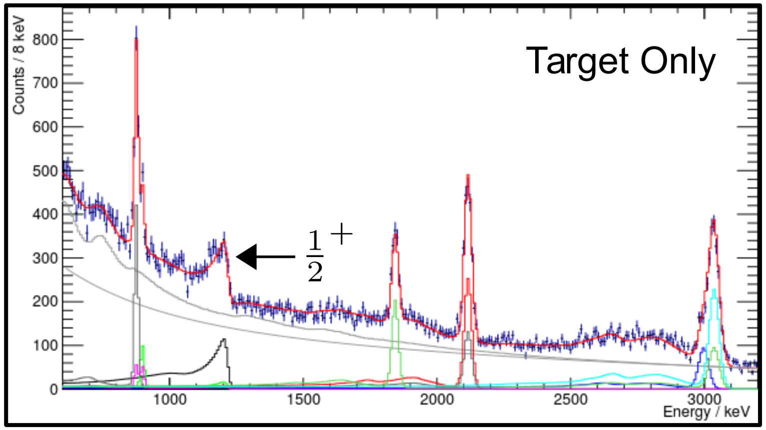
Doppler Shift Recoil Method:

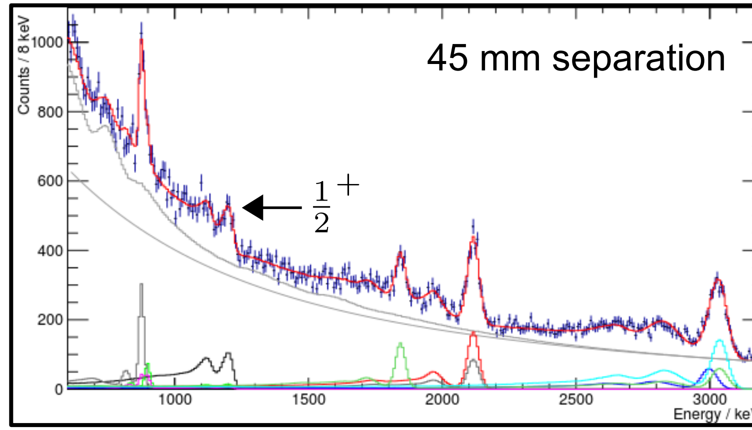




Oxygen-21: Updated Results for $1/2^+$

- Latest results with improved background description:





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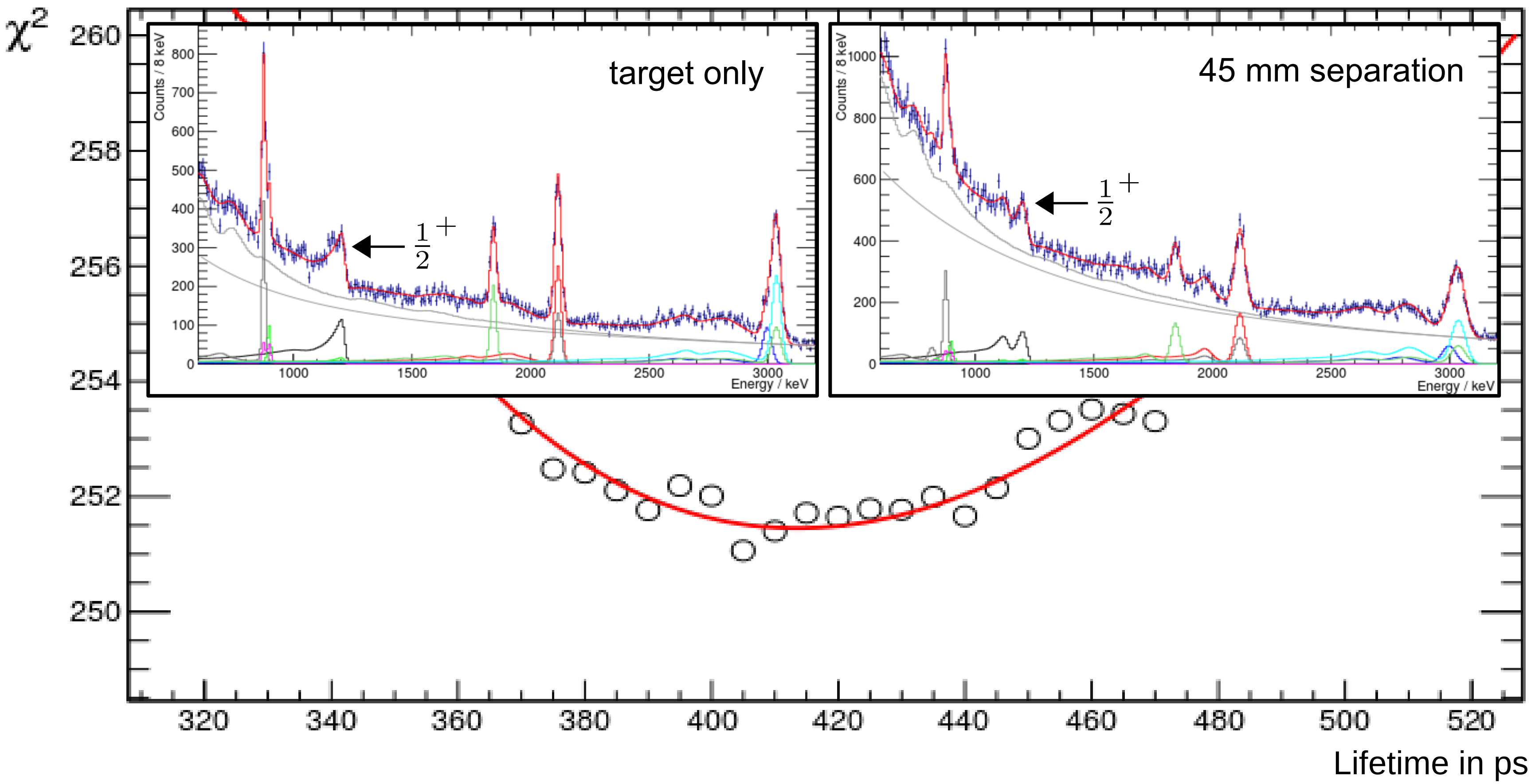

Oxygen-21: Updated Results for 1/2$^+$

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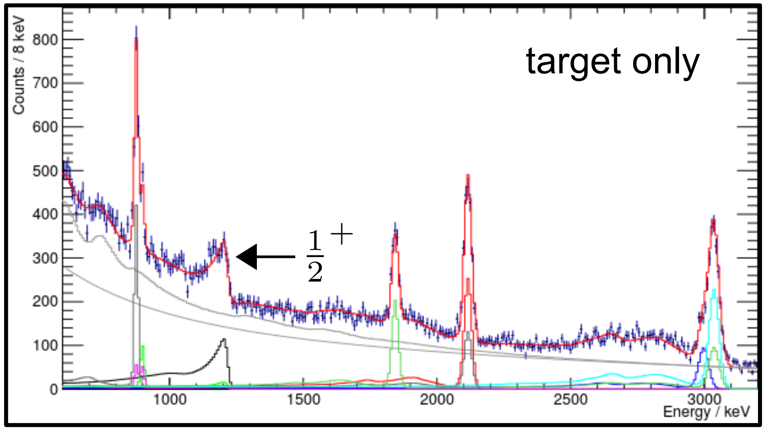
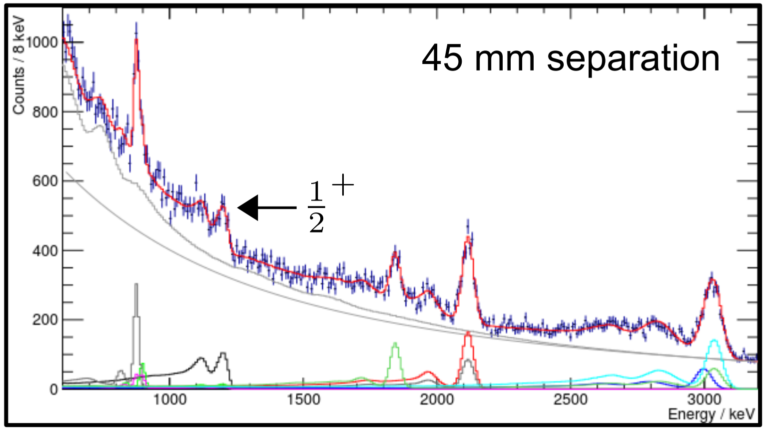


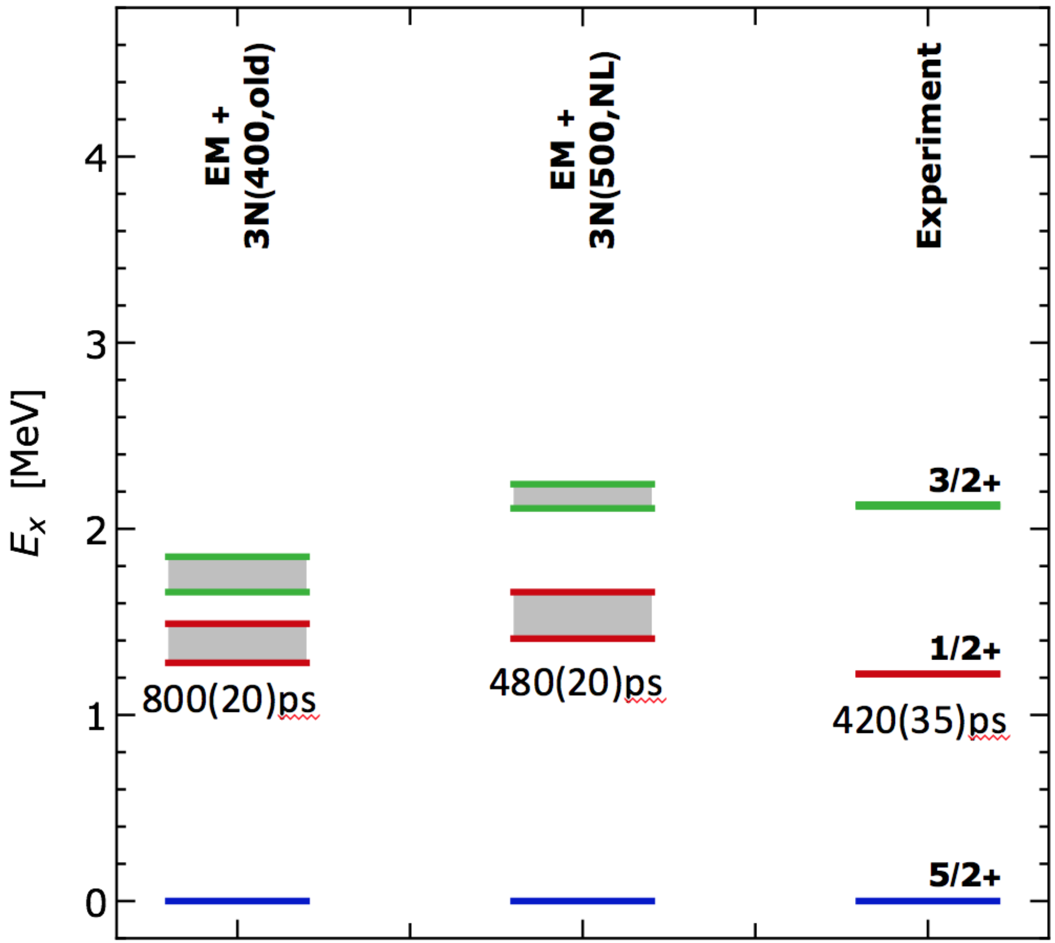


Transition	BR [%] Exp	BR [%] USDB	BR [%] NN+3N	Lifetime [ps] Exp	Lifetime [ps] USDB	Lifetime [ps] NN+3N
$\frac{1}{2}^+ \rightarrow \frac{5}{2}^+$				$420^{+32}_{-35}(\text{stat})^{+34}_{-12}(\text{sys})$	178	709
$\frac{3}{2}^+ \rightarrow \frac{5}{2}^+$	88.8 ± 1.0	80	87	$7.5^{+7.5}_{-5.5}$	2.7	1.9
$\frac{3}{2}^+ \rightarrow \frac{1}{2}^+$	11.2 ± 1.0	20	13			

- Ph.D. thesis and paper about this topic will be finished soon by S. Heil.

Oxygen-21: Updated Results for 1/2$^+$

- Latest theoretical calculations from A04:



(Calculations done by Vobig, Huether and Roth, 2018)

Carbon-16

Carbon-16: Motivation & Recap

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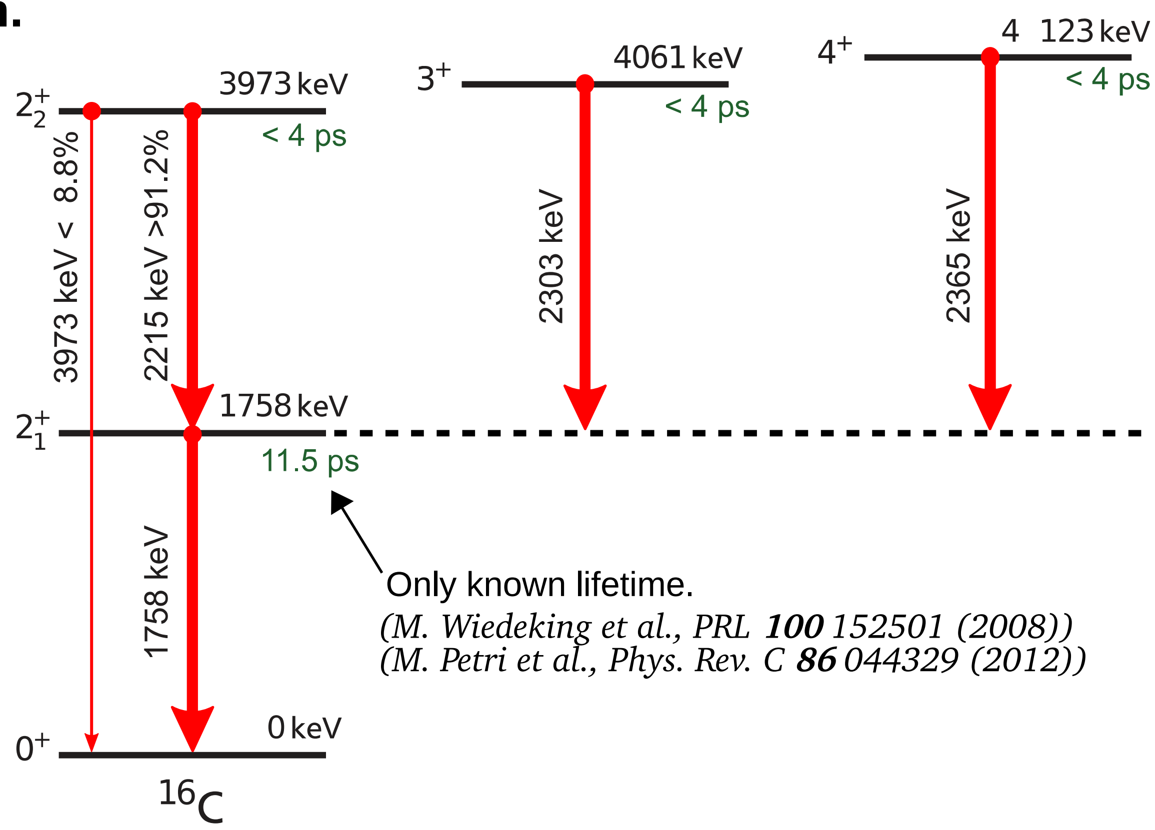
- **EM observables in ^{16}C are strongly sensitive to the details of the nuclear Hamiltonian.**

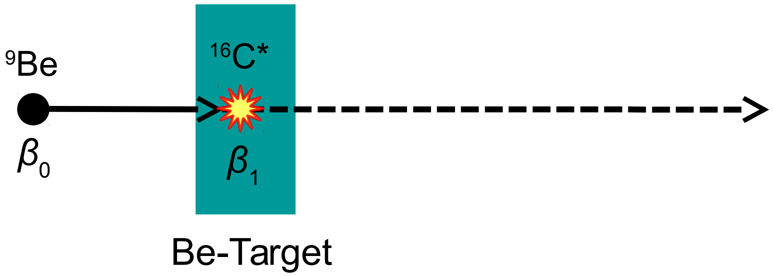


- **Used GAMMASPHERE and μ-Ball at Argonne National Lab to measure:**

  The lifetimes of the 2_2^+, 3^+ and 4^+ states.

Carbon-16: Motivation & Recap

- Use fusion-evaporation to produced ^{16}**C**: **^{9}Be(^{9}Be,2p)^{16}C***
- Gate on 2**p** with particle detector ***μ*-Ball** and detect the emitted γ-rays in coincidence with **GAMMASPHERE**.
- Expected lifetimes with $\tau_{cm} < 4$ ps are rather short.



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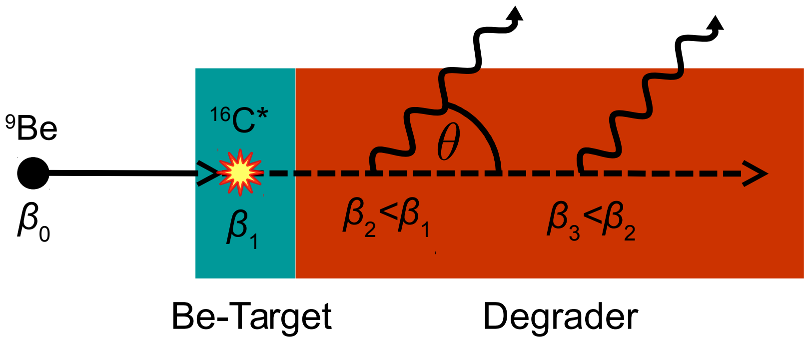
- Gate on 2**p** with particle detector ***μ*-Ball** and detect the emitted γ-rays in coincidence with **GAMMASPHERE**.
- Expected lifetimes with τ_{cm} < 4 ps are rather short.
- Measure τ in-fight with the Doppler-shift-attenuation method:

$$E_{\text{Lab}} = E_{\text{CM}} \frac{\sqrt{1-\beta^2}}{1-\beta\cos(\theta)}; \; \beta = v/c$$



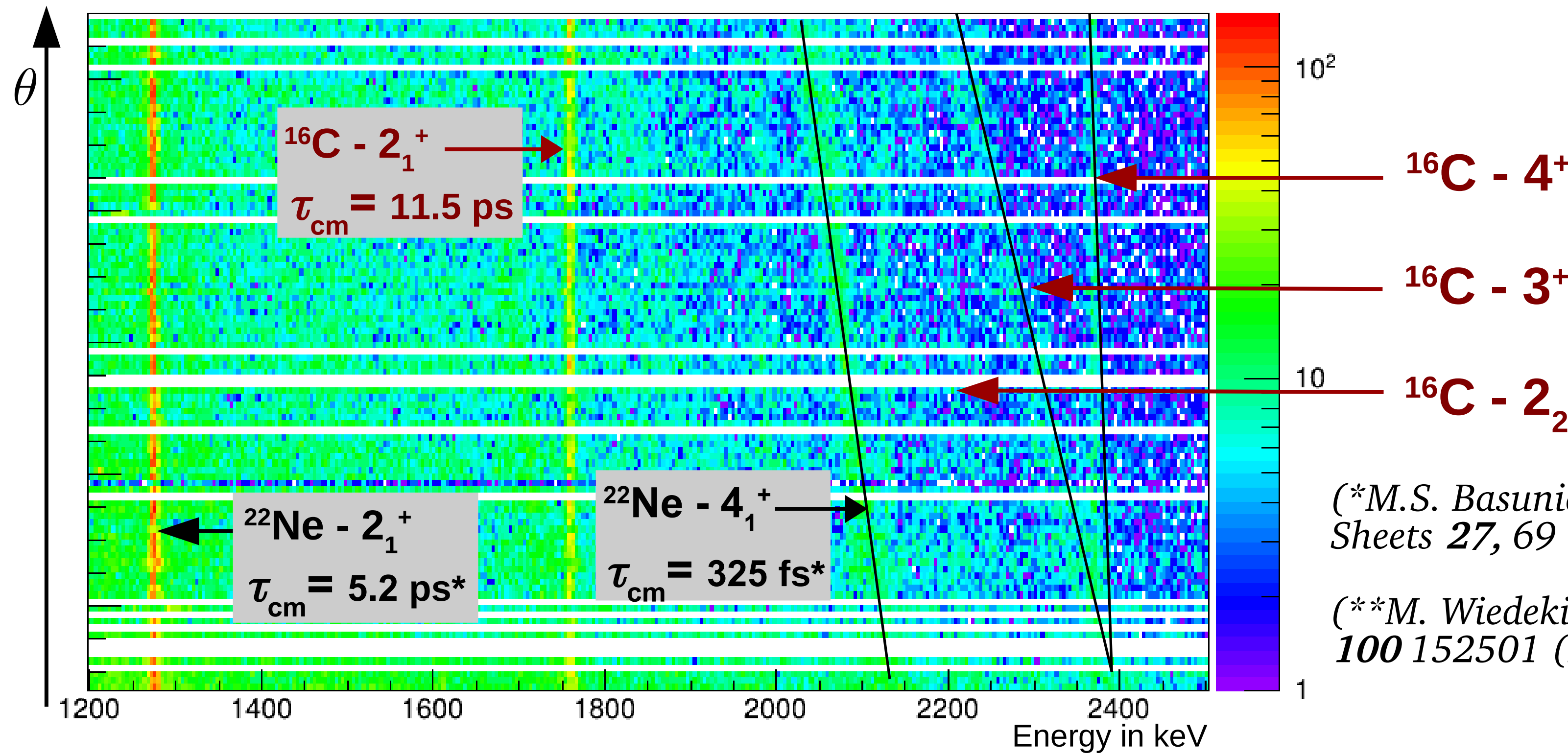
- Shorter τ → Larger mean decay β → Stronger energy shift due to Doppler effect.

Energy shift for different radiation angle $\theta \rightarrow \tau$

Carbon-16: Motivation & Recap

Detector Angle θ vs. Uncorrected Energy with 2p Cut:

Preliminary



(*M.S. Basunia, Nucl. Data Sheets **27**, 69 (2015))

(**M. Wiedeking et al., PRL **100** 152501 (2008))

- **Origin of ^{22}Ne:** Target was oxidized: **^{9}Be + ^{16}O → ^{22}Ne + 2p + n**
- Slope is sensitive to lifetime → Compare with Geant4 simulations.

Carbon-16: Latest Progress

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Simulation:

- Improved Geant4 simulations: Realistic resolutions and improved stopping powers.

Experiment: Can we find the 2_2^+?

- Improved event building in sorting algorithms

  → Increased statistics for $^{16}C\ 2_1^+$ events by 6%

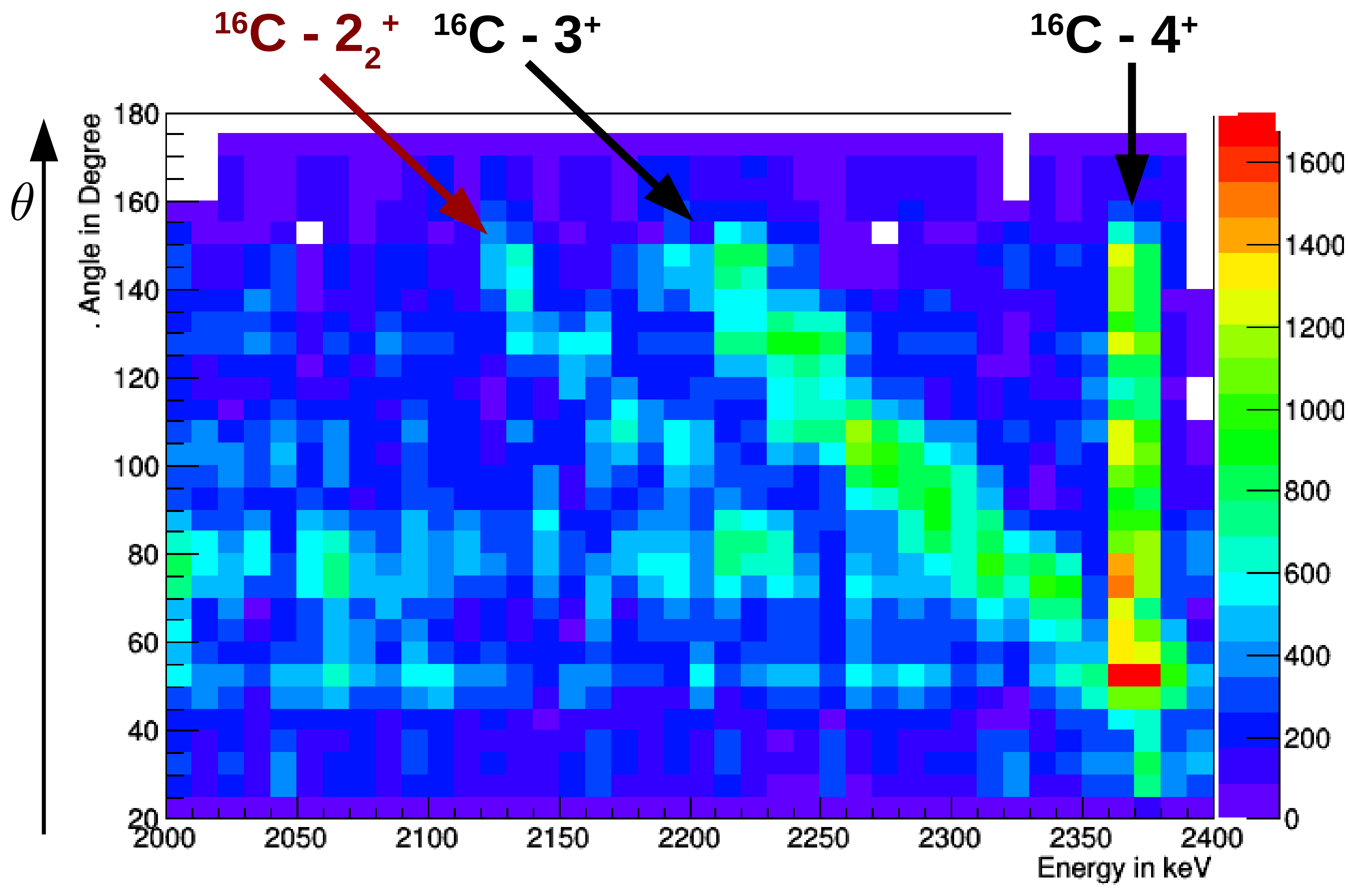
- Low *μ*-Ball eff. for protons is major issue for insufficient statistics
  AND
  the 2_2^+ mostly feeds into the 2_1^+

  → Don't gate on 2 protons

  → Gate on 1 proton and in addition gate on the gamma energy of the 2_1^+ state

Carbon-16: Latest Progress

Detector Angle vs. Uncorrected Energy for 1p Cut and Gate on 2_1^+ State:



1p cut analysis done for the LT of Ne-22 4_1^+: Deviation from literature value 1% to 14%

Carbon-16: Time-Line

SFB Milestones for the ^{16}C Experiment:

2016

- Run ^{16}C experiment at ANL → Done in Summer 2016 ✅

2017

-

2018

- Analysis of ^{16}C experiment at ANL is completed → On track ✅
- Results of ^{16}C experiment at ANL are published → On track ✅

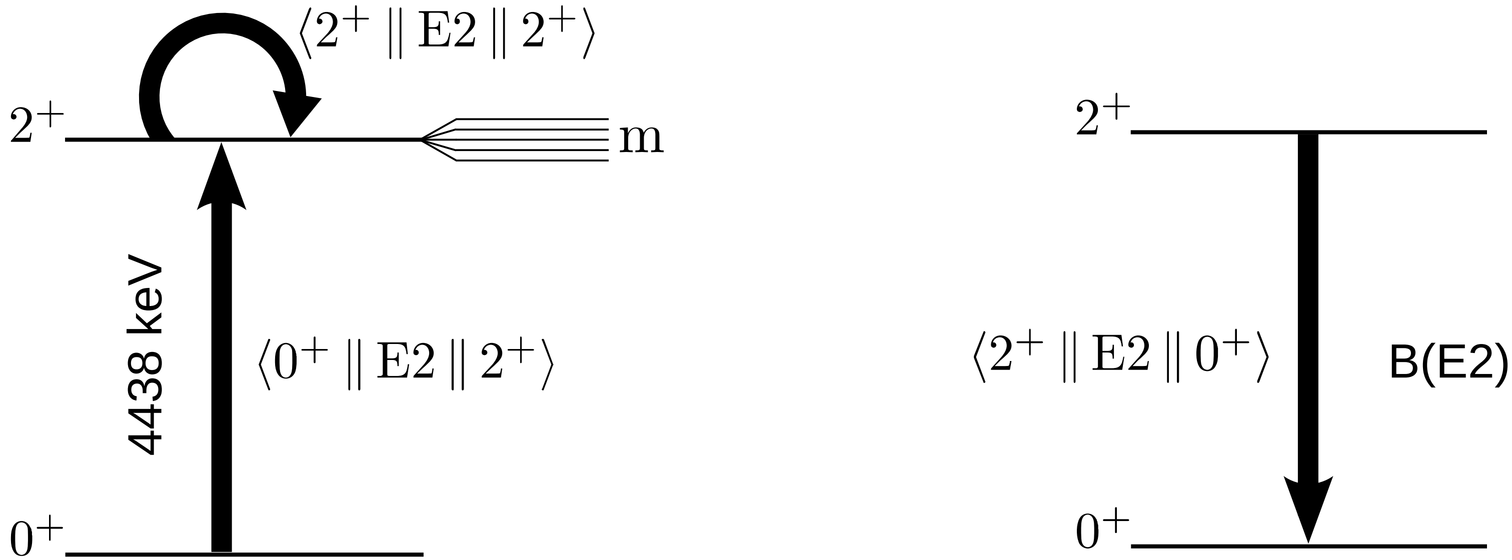
2019

-

Carbon-12

Carbon-12: Motivation

- Carbon-12 is a prime nucleus for many ab initio calculations.
- Exp. $Q(2^+)$ uncertainties are larger than theory's.

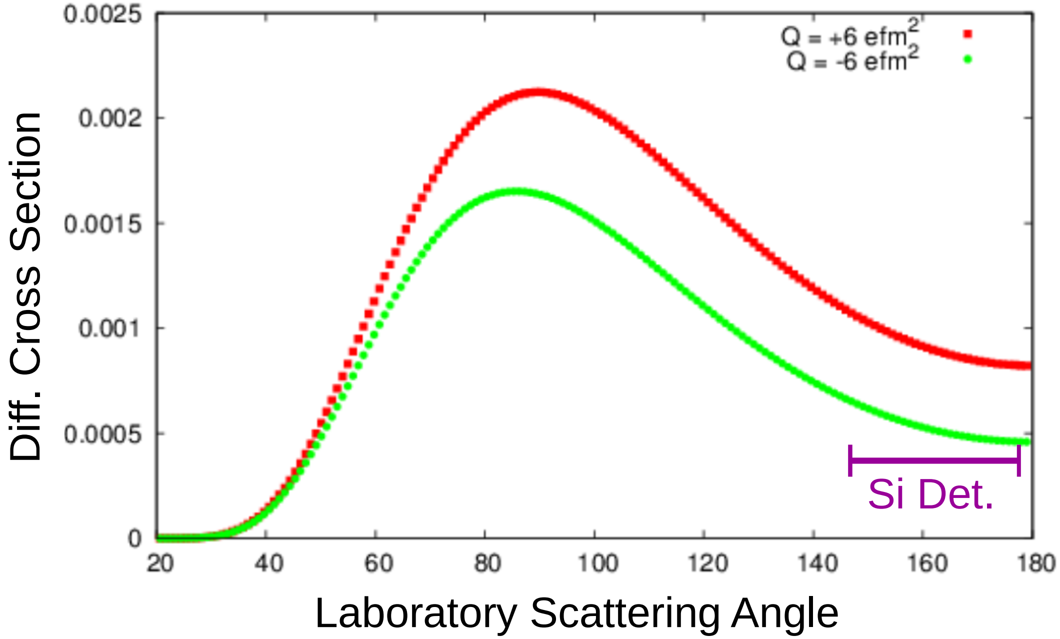


Coulomb Excitation @ JYFL

(e,e') @ SDALINAC

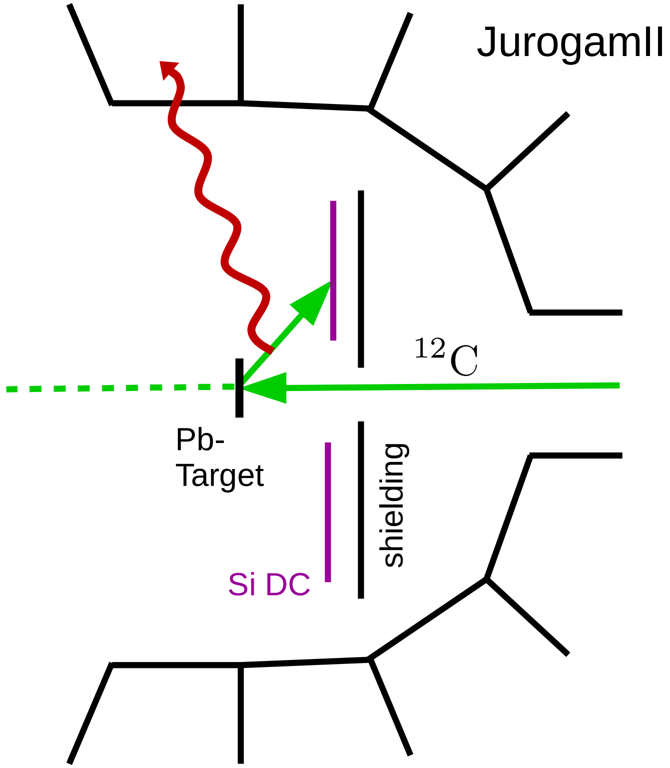
Carbon-12: The Experiment at JYFL

- Measure scattered C-12 at backward angles with position sensitive silicon detectors.



Carbon-12: The Experiment at JYFL

- Measure scattered C-12 at backward angles with position sensitive silicon detectors.
- Measure relative to Pb-208 3_1^- state @ 2614 keV: Precision of B(E3) ~1.5%!
- Use $^{\mathrm{nat}}\mathrm{Zn(p,xn)}^{66}\mathrm{Ga}$ for high gamma energy calibration.



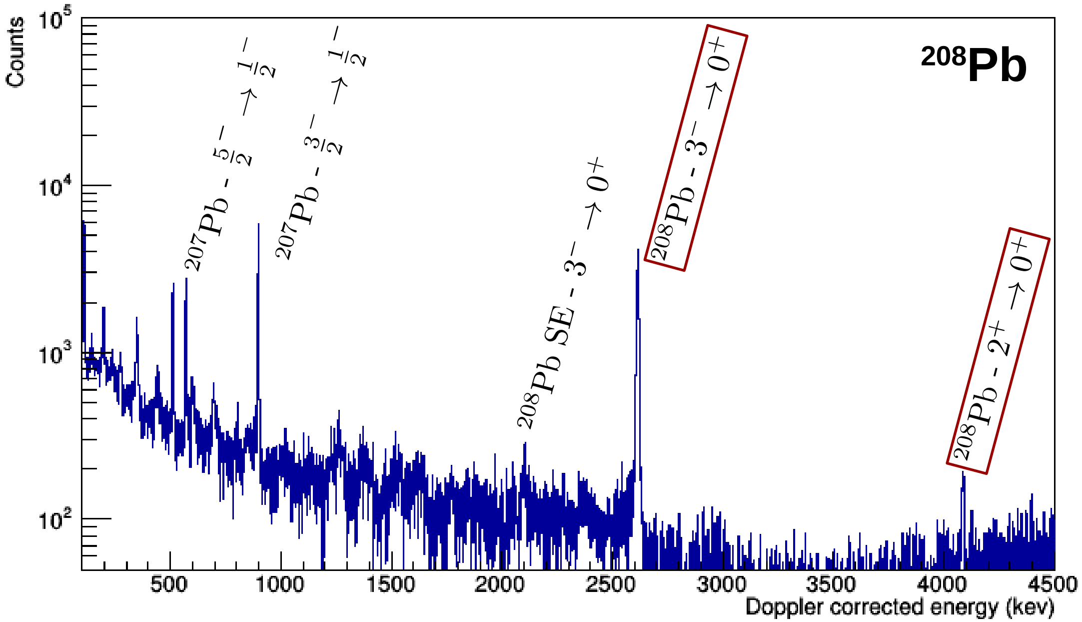
Realistic Goals:

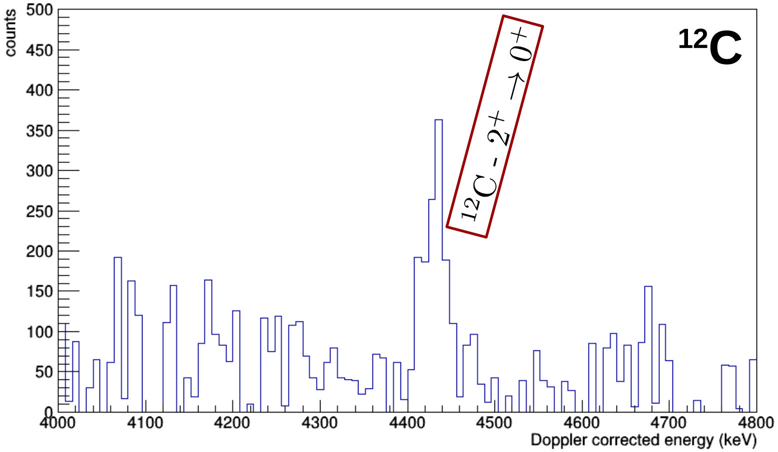
Without new B(E2) measurement: **<29%** uncertainty in the Q(2+)

With new B(E2) measurement: **<18%** uncertainty in the Q(2+)

Carbon-12: First Results

- Detectors are calibrated and a proper coincidence is established.
- Cleaned (Gate on SiCD rings energy) and Doppler corrected gamma-ray spectra:





- **Next Step:** Feed these experimental results and settings as input into GOSIA to extract a proper Q(2^+).

Carbon-12: Time-Line

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SFB Milestones for the ^{12}C Experiments:

2016

- Design and construction of the target chamber → Done at the end of 2016 ✓
- Setup chamber & detectors at JYFL → Done in Spring 2017 ✓
- Run Coulomb excitation experiment at JYFL → Done in Spring 2017 ✓

2017

-

2018

- Analysis of ^{12}C Coulomb excitation experiment is completed → On track ✓
- Run ^{12}C NRF Experiment at S-DALINAC → Changed to ^{12}C(e,e') in mid of 2018 ✓

2019

- Analysis of ^{12}C(e,e') data is finished → Possibly at the end of 2019 ?
- ^{12}C Coulomb excitation and ^{12}C(e,e') data are combined → Possibly at the end of 2019 ?

Carbon-14

Carbon-14: Motivation & Recap

Perform (e,e’) on ^{14}C to extract form factors and transition strengths to low-lying excited states @ S-DALINAC:

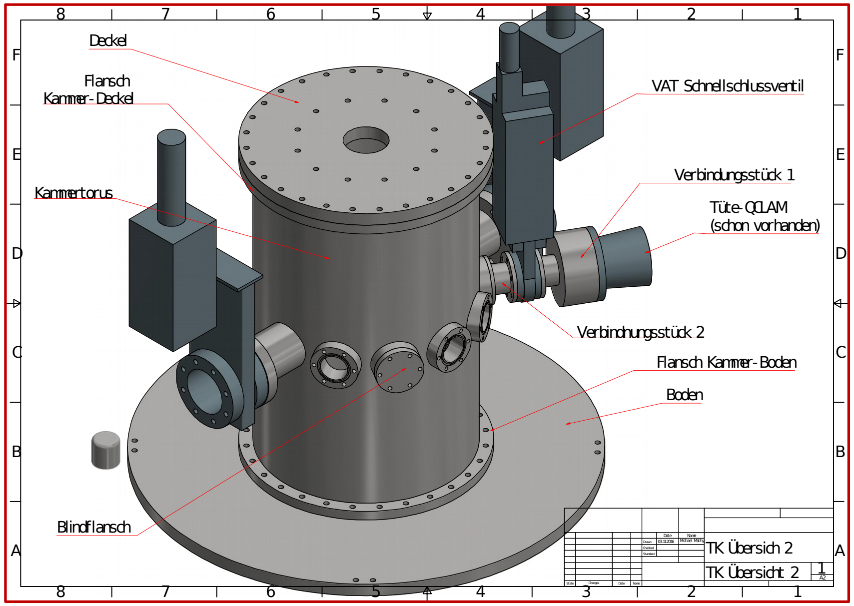
- Many excited states are not described well by theory.
- Challenging to theory due to cluster states.

- ~77mg/cm^2 radioactive ^{14}C target enabling (e,e’) for the first time in 4 decades.
- Measure the strengths for many states with improved precision or for the first time.

Carbon-14: Motivation & Recap

Challenges:

- Need a fast valve system for sudden vacuum failure.
- Fast piezo pressure sensors at top of the QCLAM to trigger valves.
- Designed a new scattering-chamber for QCLAM, which allows to place additional fast valves.



Carbon-14: Latest Progress

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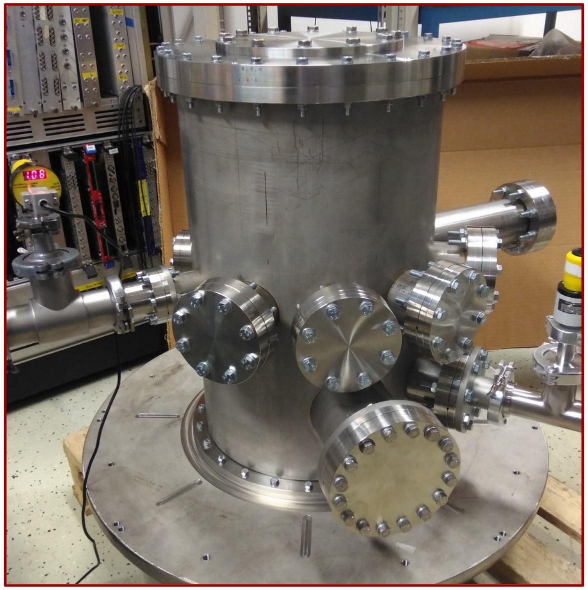
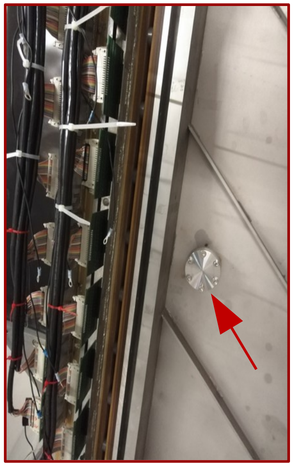
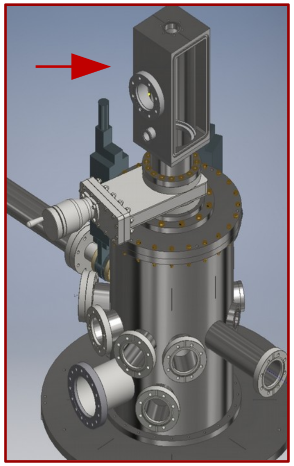
- Lot afford was put in the modernization and recommissioning of the QCLAM vacuum system.
- Scattering-chamber is built now and ready soon.
- All vacuum parts and sensors are at the institute and ready.
- Successfully installed an additional vacuum port at a crucial spot @QCLAM.
- The target seems to be activated at its surface → A new target-chamber/ladder with sewer port is necessary.
- Experiment scheduled for the beginning of 2019.







Carbon-14: Time-Line

SFB Milestones for the ^{14}C Experiment:

2016

- Design scattering-chamber in the first half of 2016 → Done in the beginning 2017 ✅

2017

- Scattering-chamber completed and tested → Done mid 2018 ✅

2018

- Run of $^{14}C(e,e')$ experiment at QCLAM → Scheduled for Spring 2019

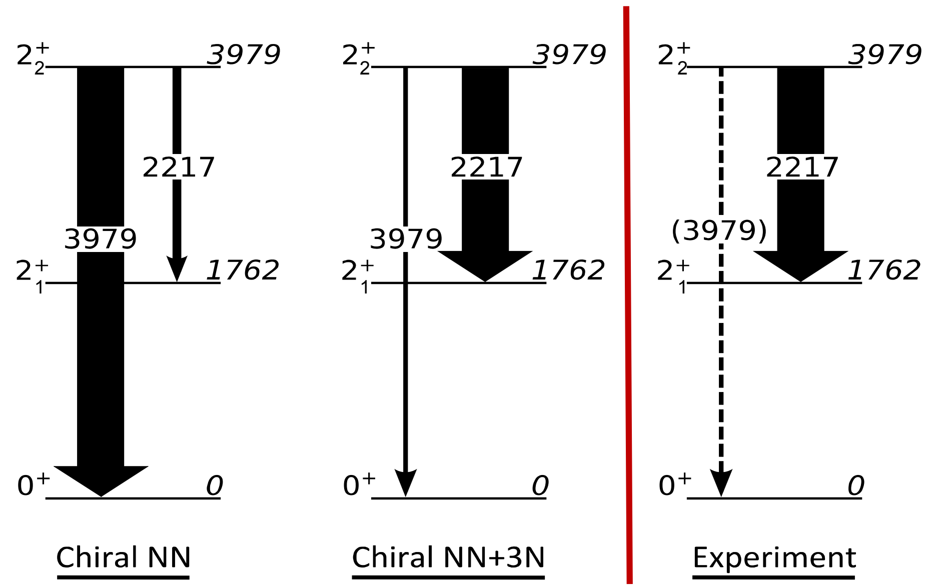
2019

- Analysis of $^{14}C(e,e')$ data is finished → Possibly at the end of 2019
- Results of $^{14}C(e,e')$ data are published → Possibly at the end of 2019

Thank you for your attention!

Appendix: Carbon-16

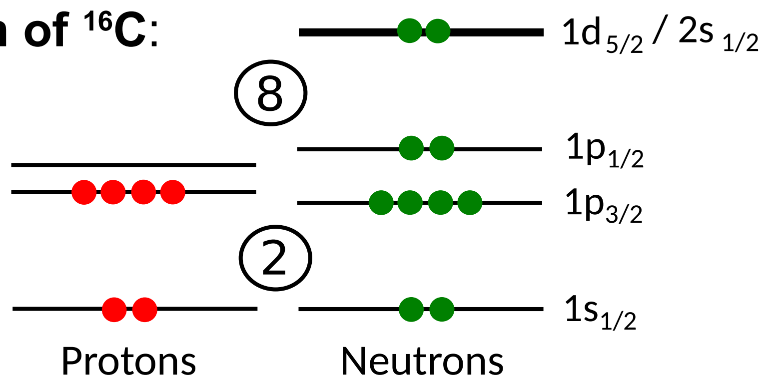
- Electromagnetic observables in **^{16}C** are strongly sensitive to the details of the nuclear Hamiltonian.
- Large changes in **lifetimes** and **branching ratios** if Hamiltonian uses **NN** or **NN+3N** interactions.



(C. Forssén, J. Phys. G: Nucl. Part. Phys. ***40****, 055105 (2013) & M. Petri et al., Phys. Rev. C* ***86*** *044329 (2012))*

Appendix: Carbon-16

- **Particle configuration of ^{16}C**:



(M. Stanoiu et al., Phys. Rev. C 78, 034315 (2008))

- Also strongly pronounced changes in **transition strengths / lifetimes** for different theoretical models!

- E.g.: For the transition strength $B(2_2^+ \rightarrow 0^+)$ in ^{16}**C** one founds**:**

$$7 \cdot B_{\text{NN+3NN}}(2_2^+ \rightarrow 0^+) \approx B_{\text{NN}}(2_2^+ \rightarrow 0^+)$$

$$20 \cdot B_{\text{NN+3NN}}(2_2^+ \rightarrow 0^+) \approx B_{\text{CD-Bonn MesonEx.}}(2_2^+ \rightarrow 0^+)$$

(C. Forssén, et al., J. Phys. G: Nucl. Part. Phys. 40, 055105 (2013))

Appendix: Carbon-16

- Re-calibrated all GS detectors using 15 different energies from 245 keV to 6129 keV Sources: Y-88 / O-16 / Eu152 / Co56
  - ➔ Result:
    - ➢ 23 detectors were not active during the experiment.
    - ➢ 3 detectors have a strange response.
    - ➢ 84 detectors can be used → Access to 16 rings.

- For the first analysis (shown last year) the reached statistics were not satisfying:
  - ➔ Redone ***µ*-Ball** 2D proton cuts (for every run file!) and coincidence window.
  - ➔ Result: 30% more counts in C-16 2_1^+ state than before!

- Unfortunately the statistics is much lower than we aimed for! Reasons:
  - ➔ Reached beam intensity is 28% of aim intensity.
  - ➔ 2p efficiency of ***µ*-Ball** 36% of supposed efficiency
    - ➢ Only ~10% of the statistic we aimed for!

Appendix: Carbon-16

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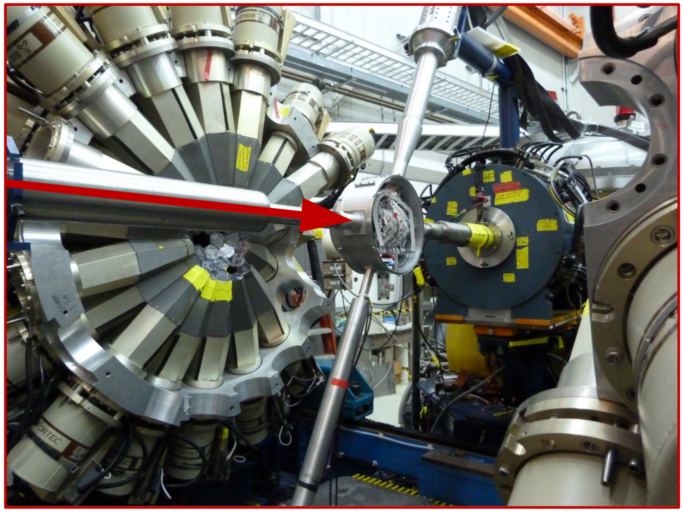
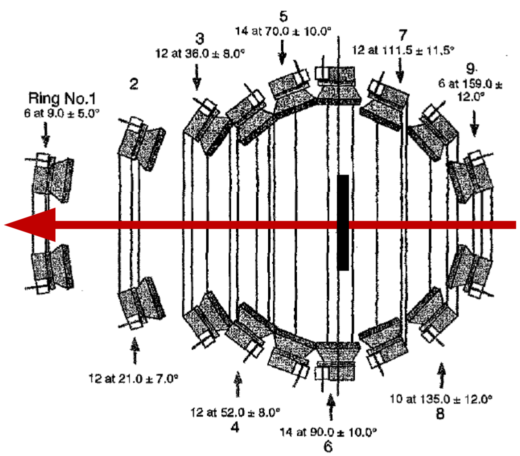


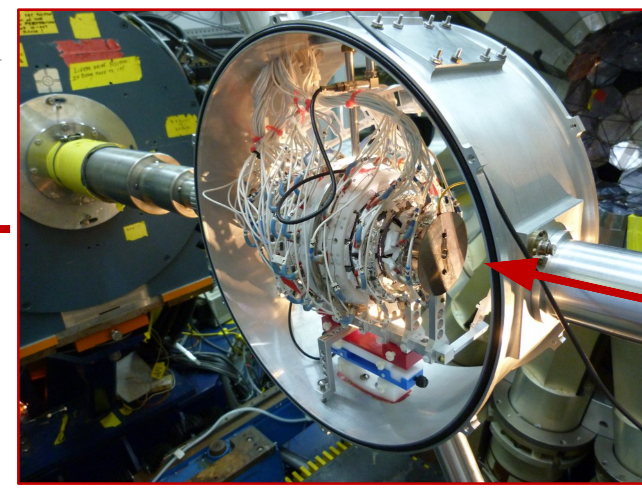
GAMMASPHERE:

- 110 Compton suppressed HPGe detectors.
- ~4π ball.
- Covered angles θ: 17° to 163° with **16 rings**.

***μ*-Ball:**

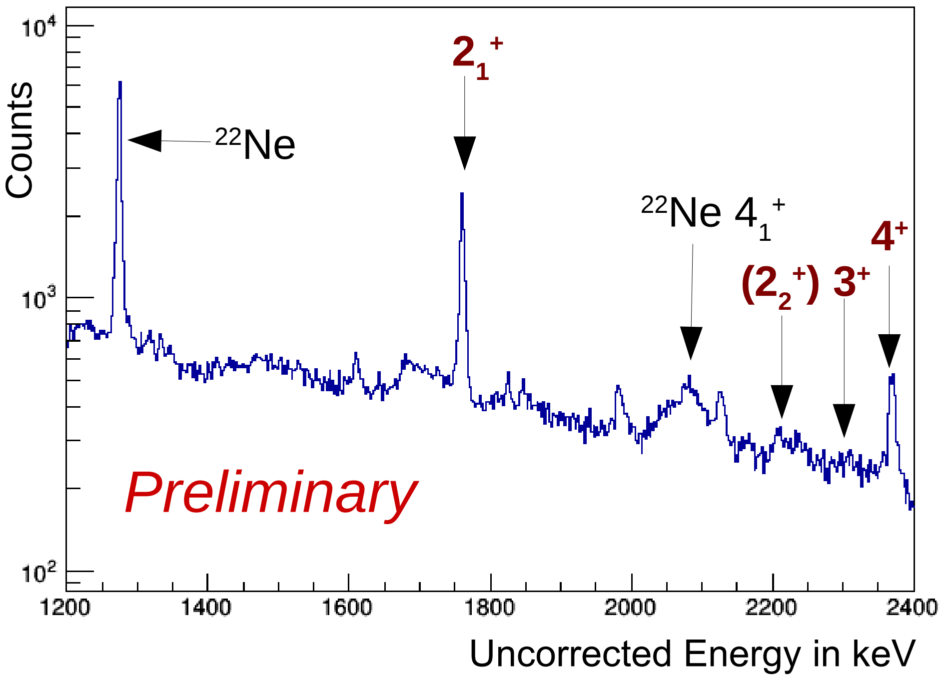
- 96 CsI scintillator detectors.
- ~4π ball.

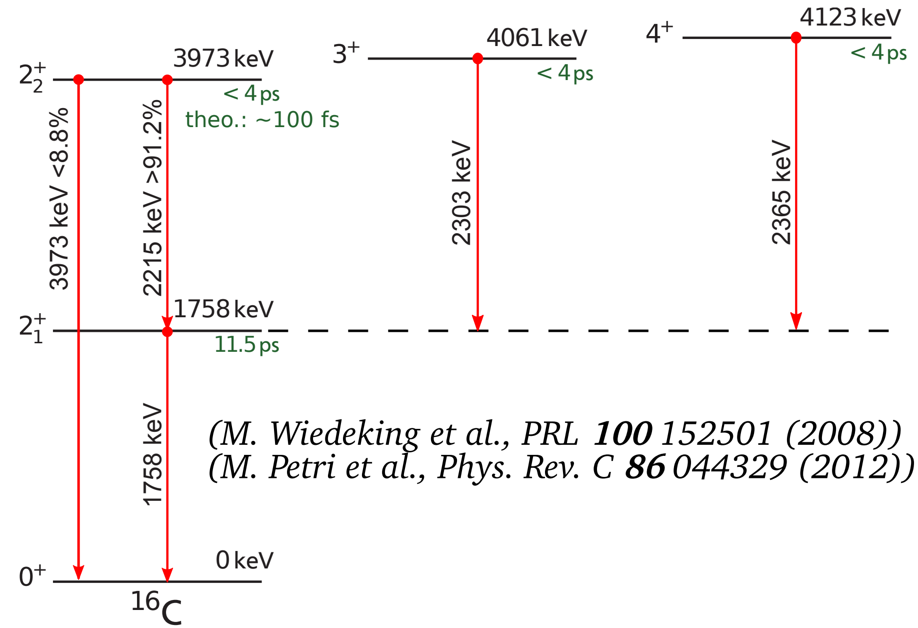




*(D.G. Sarantites et al., Nucl. Instrum. Meth. A **381** (1996))*

Total Uncorrected γ - Spectrum with 2p Cuts:

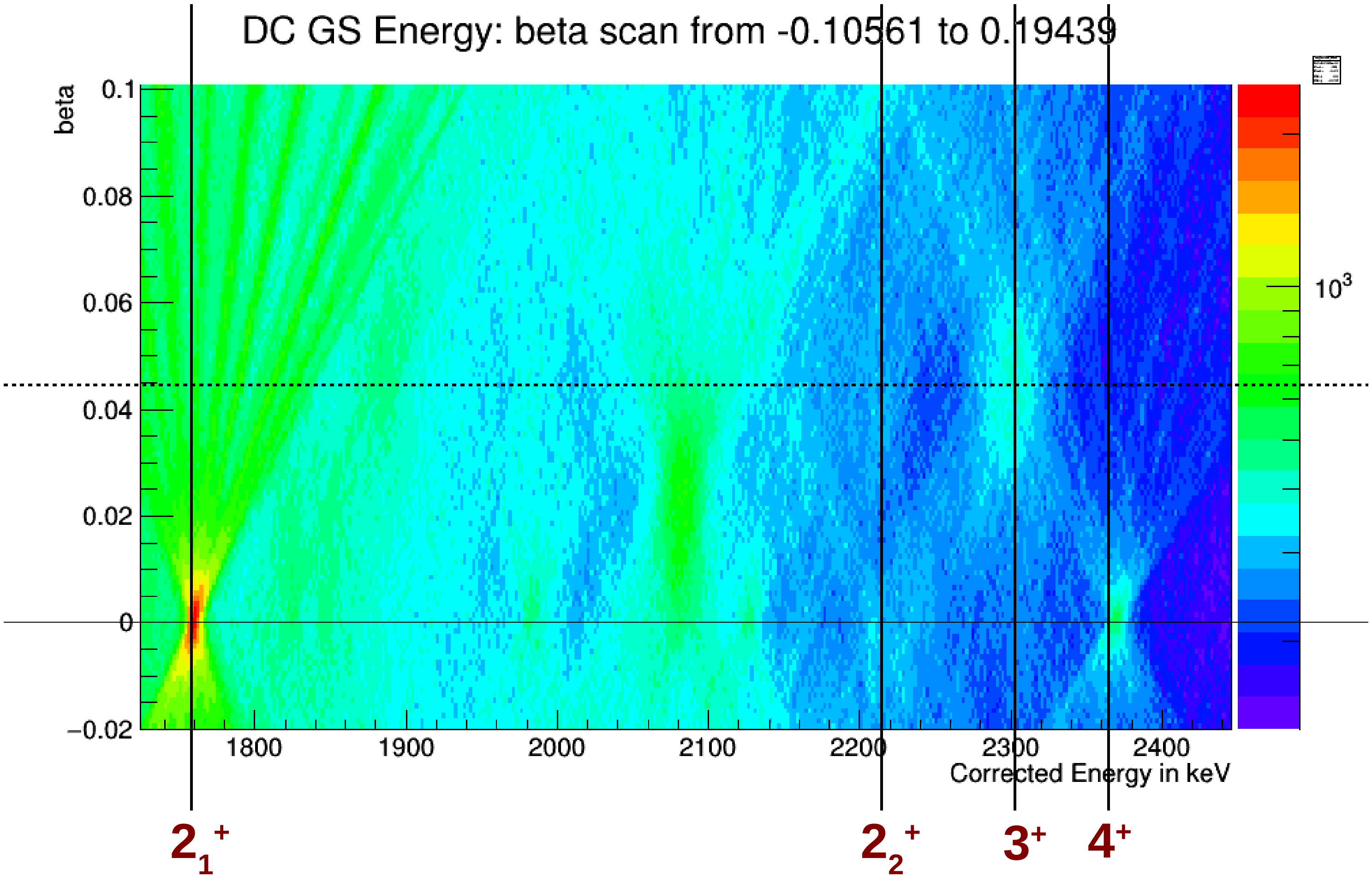




*(M. Wiedeking et al., PRL **100** 152501 (2008))*
*(M. Petri et al., Phys. Rev. C **86** 044329 (2012))*

Appendix: Carbon-16

Beta Scan for Target+Degrader Run:



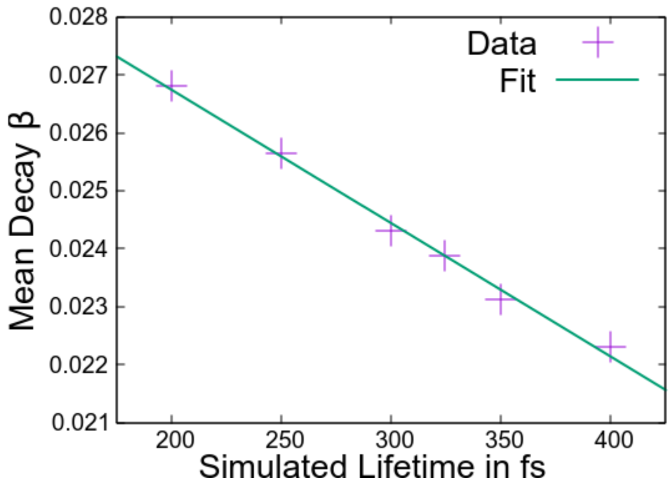
Appendix: Carbon-16

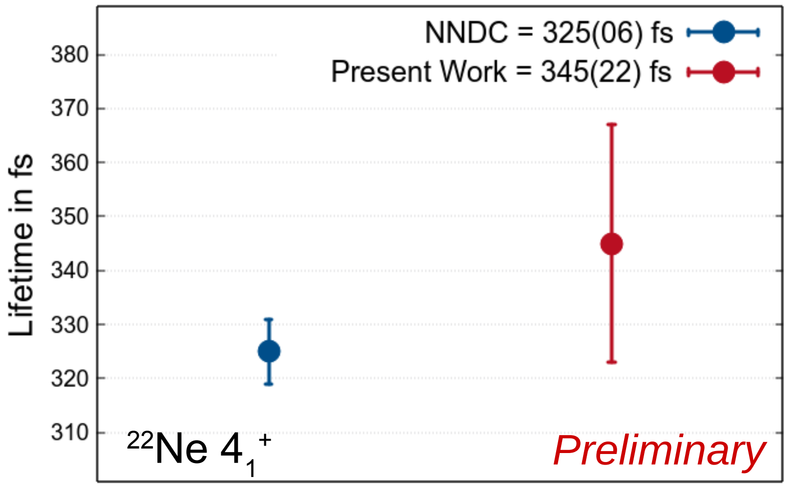
Test realistic Geant4 Simulation with Ne-22 4_1^+:

1) Extract initial beta distribution of Ne-22 mentioned before.

2) **In Geant4:** Generate excited Ne-22 isotope in a thin oxidation layer using the beta distribution from 1).

➔ Do this for several lifetimes & extract mean decay beta.



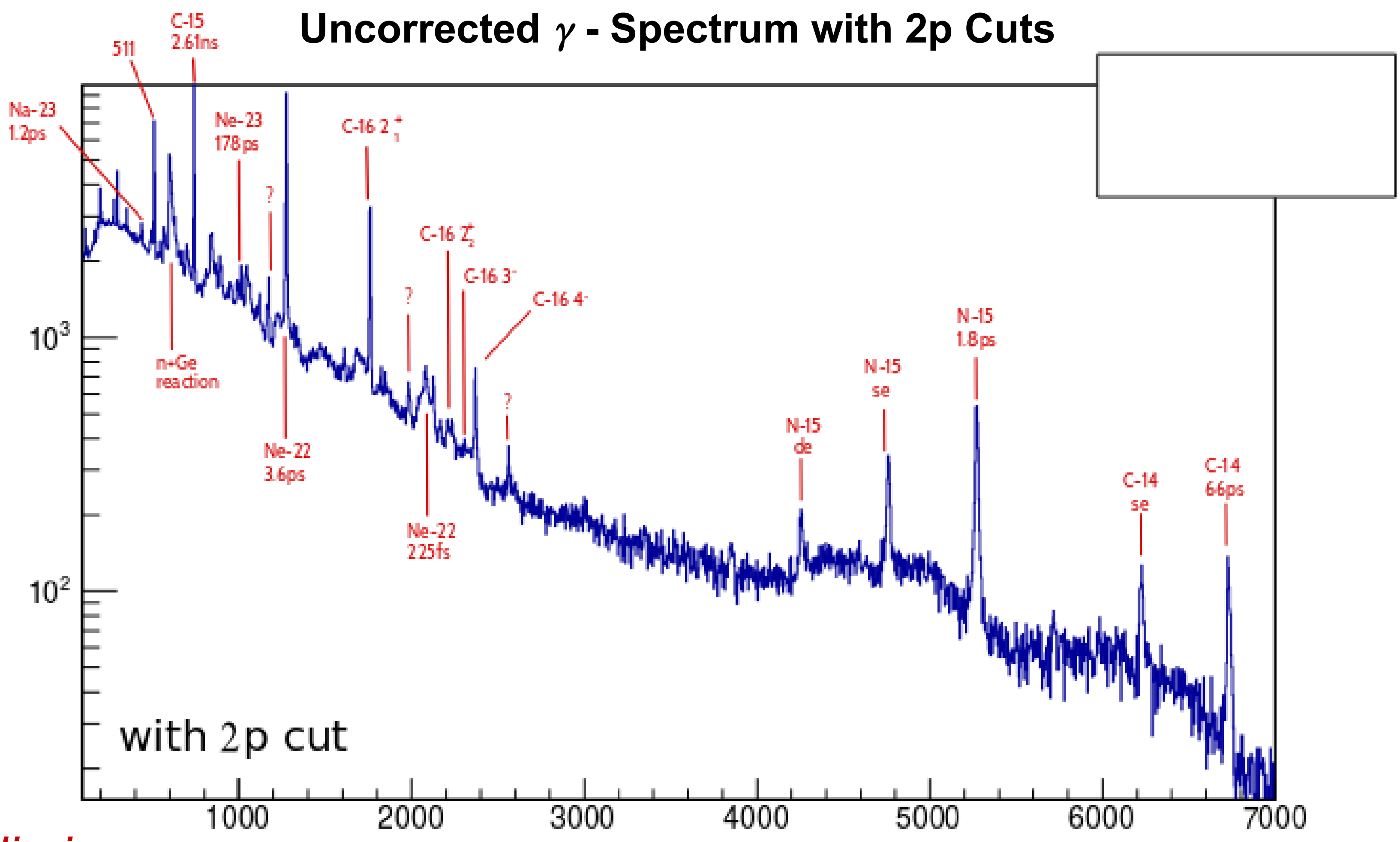


3) Extract experimental mean decay beta:

$$\overline{\beta}_{\mathrm{Exp}} = 0.0234(3)$$

4) Calculate the lifetime for ^{22}Ne 4_1^+ using the results from 3) and 2).

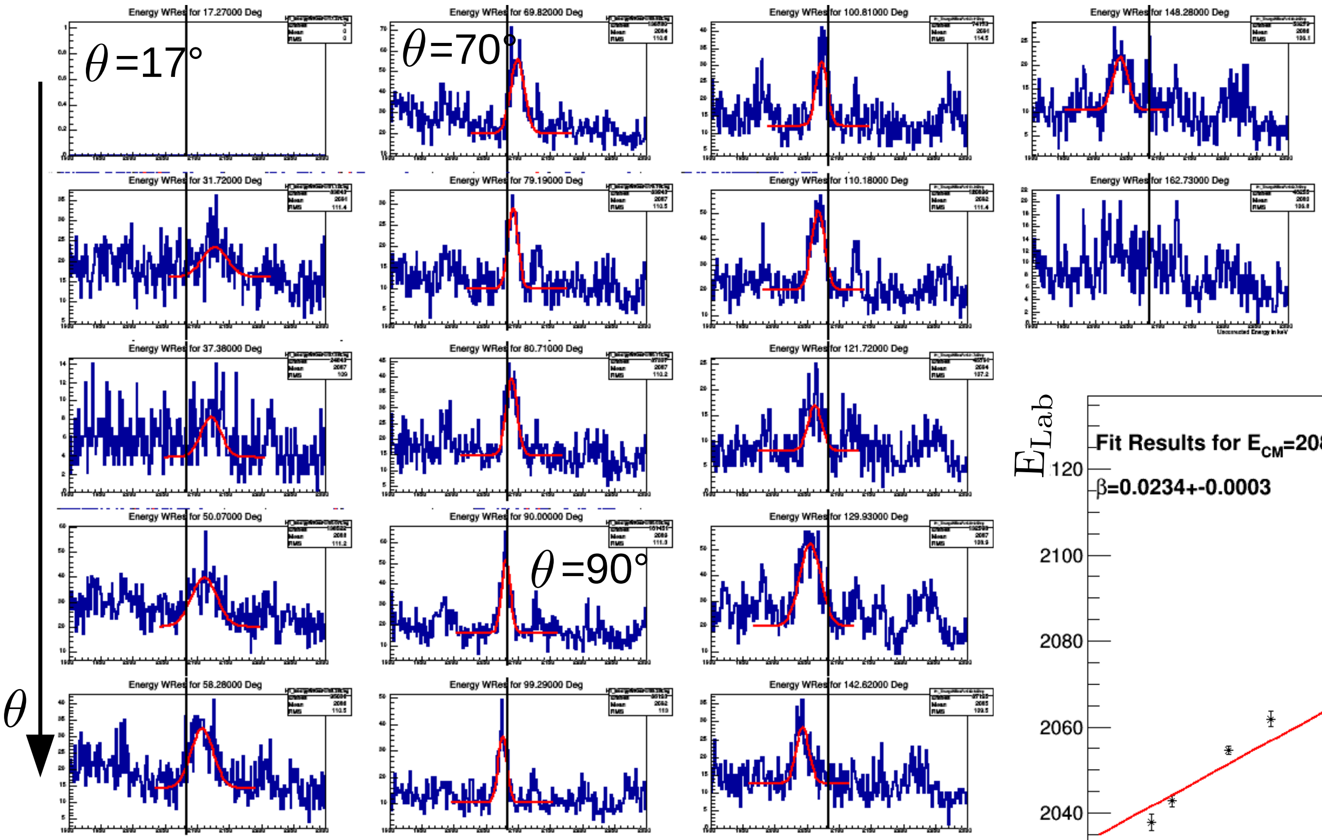
Appendix: Carbon-16



Preliminary

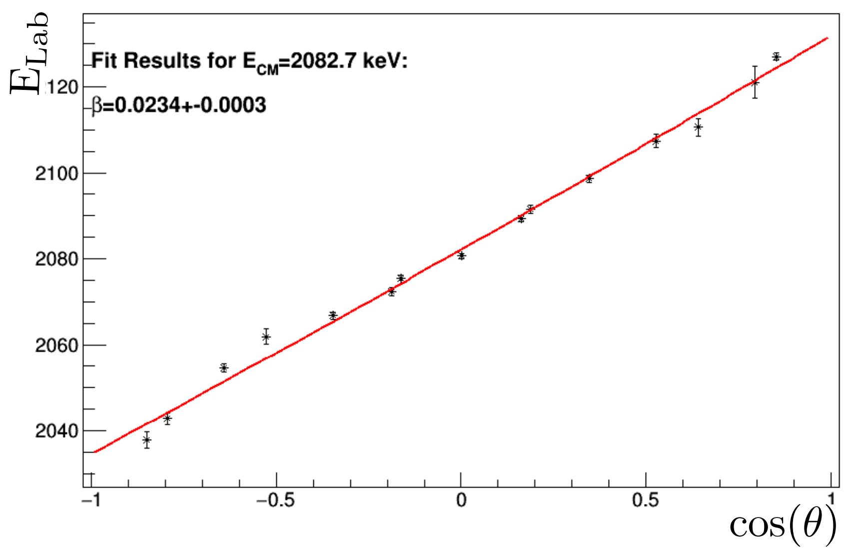
Appendix: Carbon-16

Movement of E_{Lab} for the experimental data for Ne-22 4+:



$$E_{\mathrm{Lab}} = E_{\mathrm{CM}} \frac{\sqrt{1-\beta^2}}{1-\beta\cos(\theta)}$$

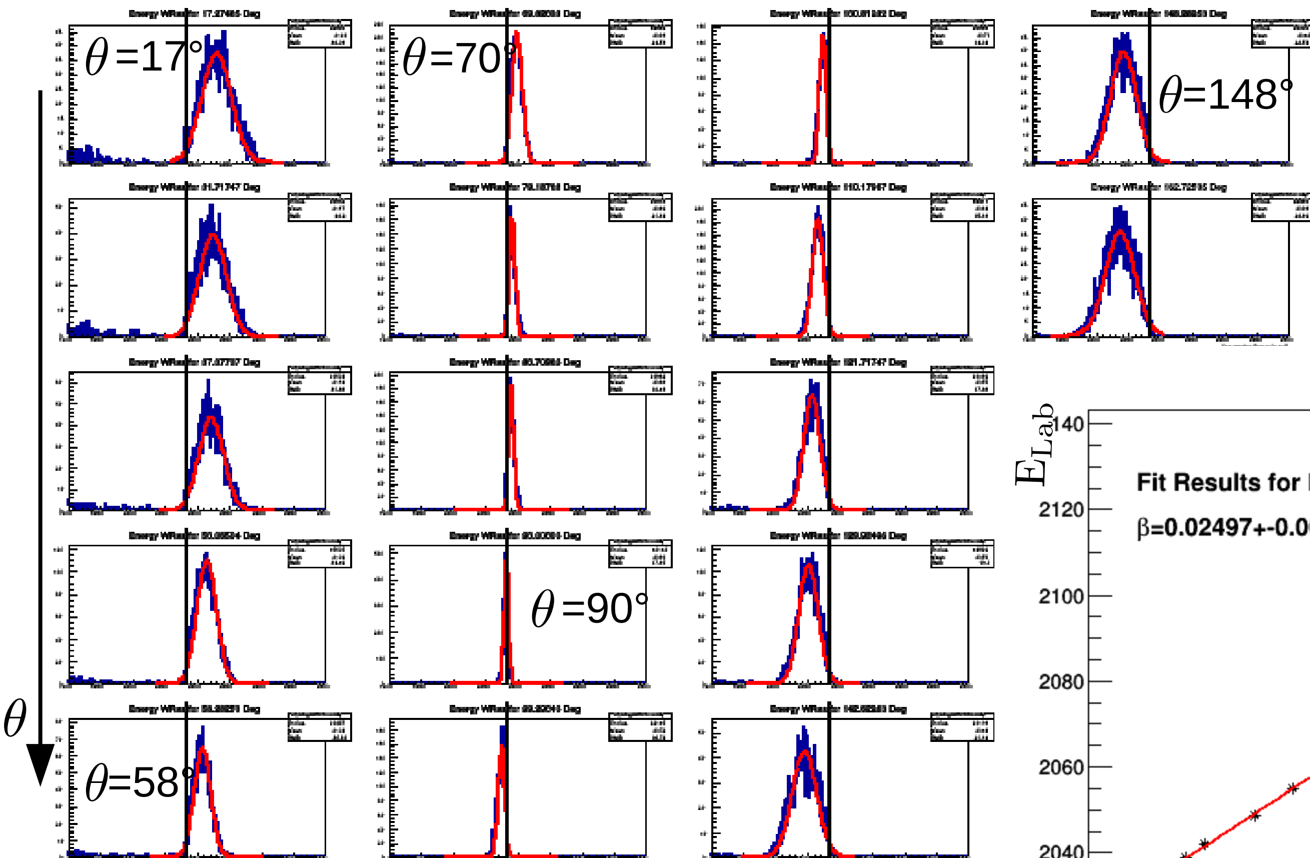
E_{Lab} vs cos(θ)



Preliminary

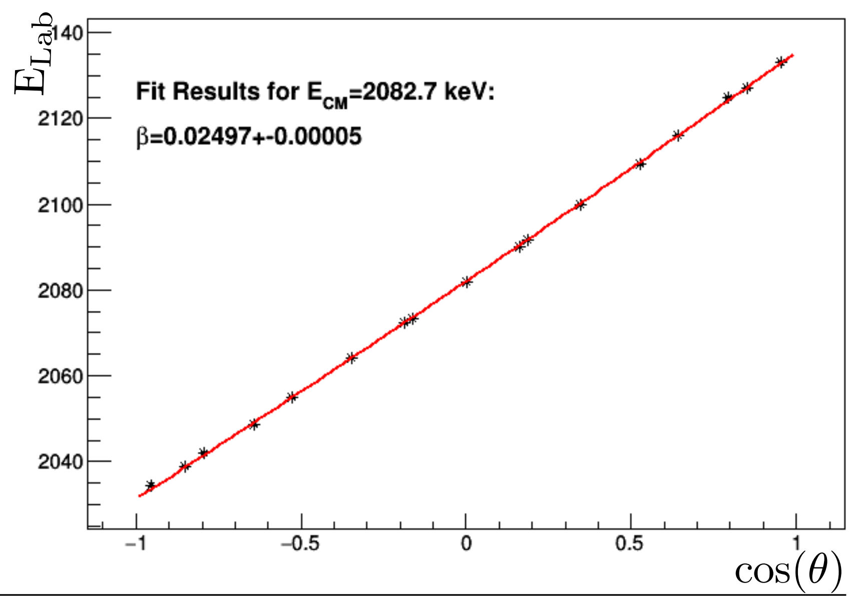
Appendix: Carbon-16

Movement of E_{Lab} for the simulation for Ne-22 4^+:



$$E_{\mathrm{Lab}} = E_{\mathrm{CM}} \frac{\sqrt{1-\beta^2}}{1-\beta\cos(\theta)}$$

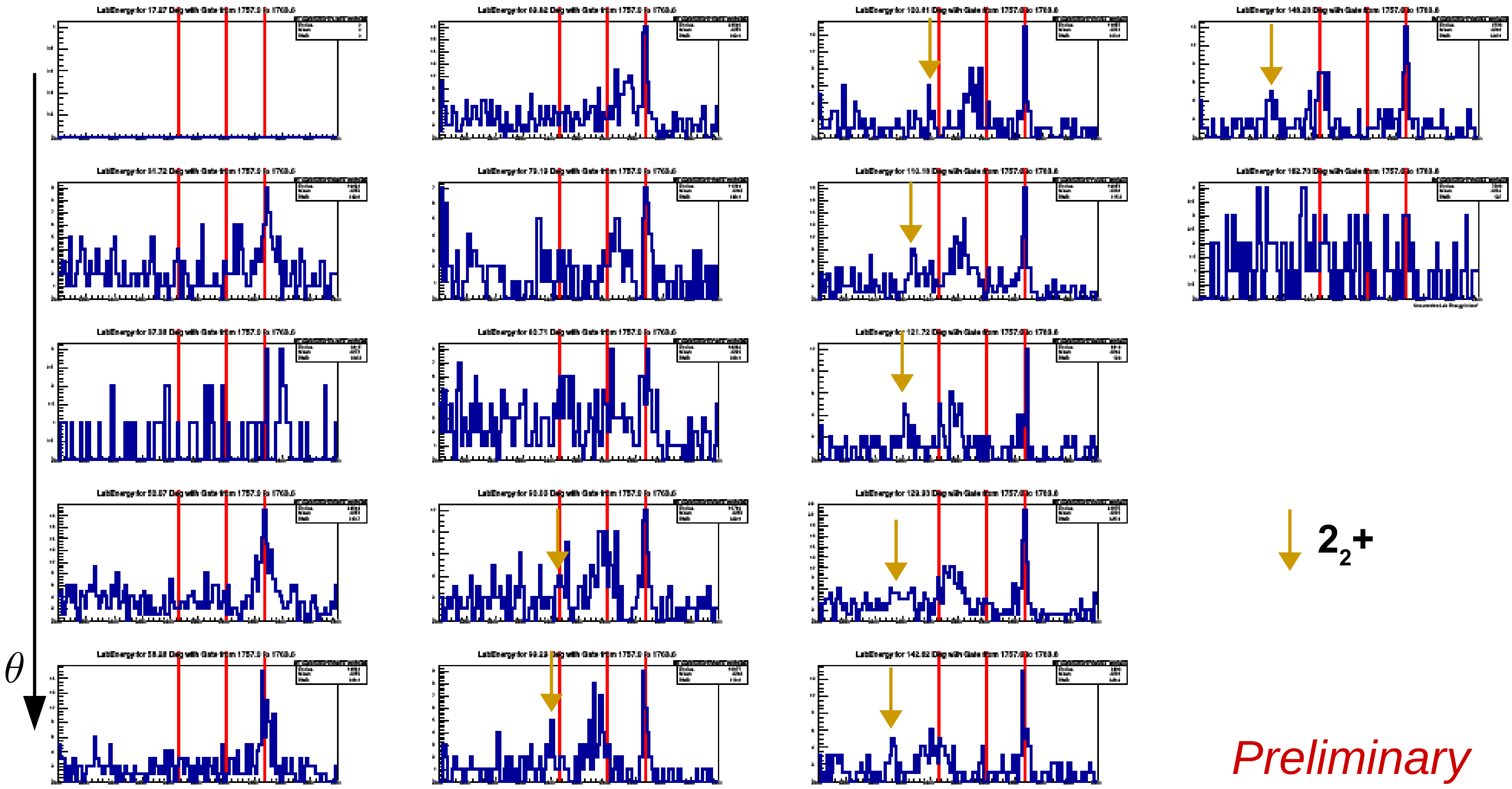
E_{Lab} vs cos(θ)



Preliminary

Appendix: Carbon-16

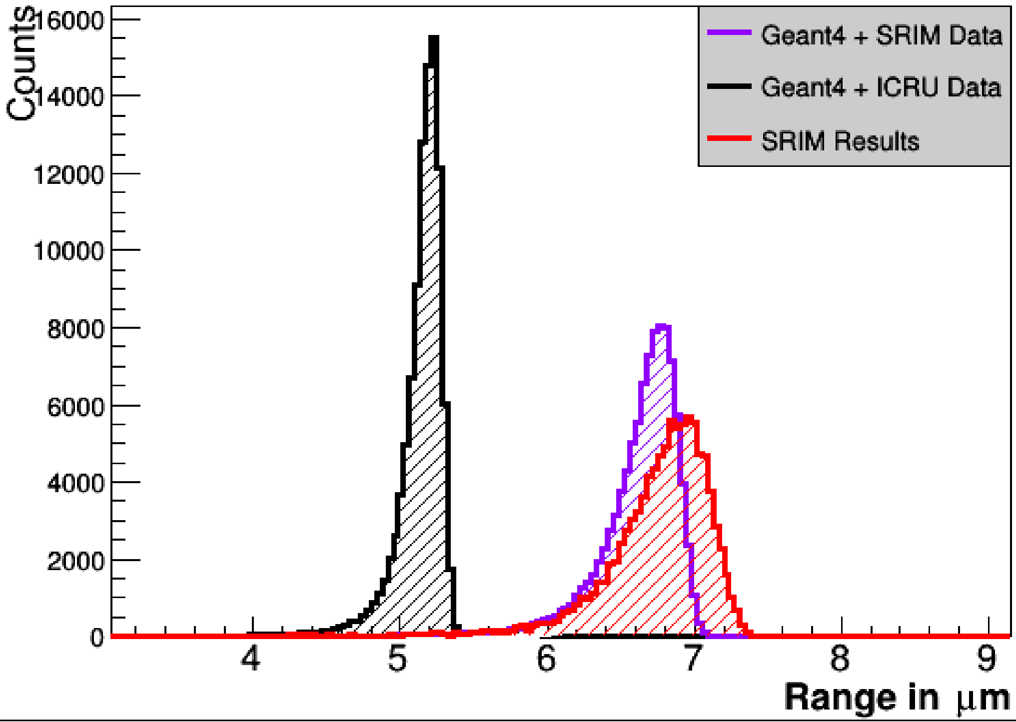
Movement of E_{Lab} for the the experimental data for C-16 2_2+:



Create a realistic Geant4 Simulation: Stopping Power!

- **Problem:** Geant4 is optimized for high energy physics → Is the used stopping power accurate enough?
- **Solution:** Import stopping power from SRIM.

Range-Check:
E.g.: 20 MeV ^{16}C on Gold

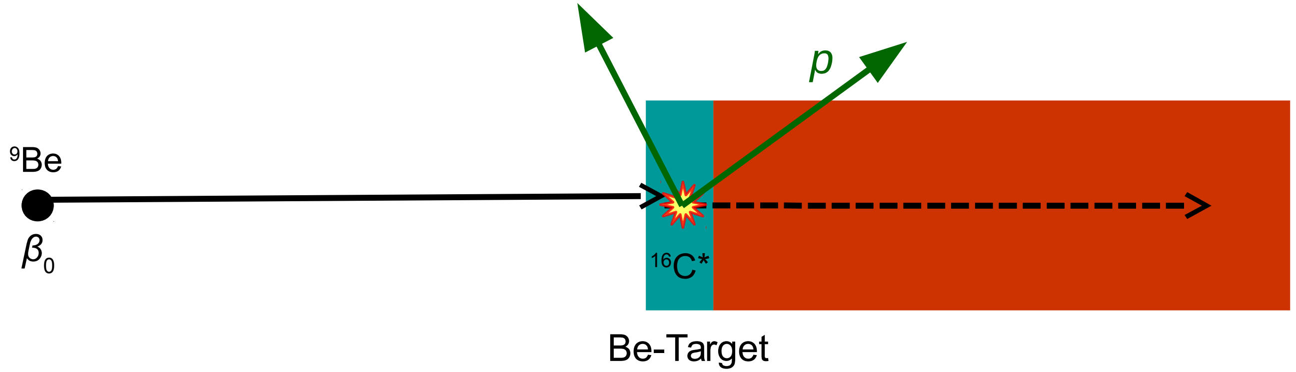


(J. F. Ziegler, J. P. Biersack, M. D. Ziegler: SRIM, the stopping and range of ions in matter. 2008)

Appendix: Carbon-16

Create a realistic Geant4 Simulation: How define incoming particles?

- **Problem 1:** Initial beta distribution of C-16 is important but difficult to implement.
  - ➔ We know nothing about the energy distribution for the 2 protons!
- **Problem 2:** The simulation has to be as close to the experiment as possible.
  - ➔ **Bias in experiment:** - Both protons have to be measured!
    - Protons can stuck in target and degrader!
    - μ-Ball efficiencies varies from detector to detector!



Appendix: Carbon-12

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arXiv:1709.07501v1 [nucl-ex] 21 Sep 2017

Reorientation-effect measurement of the first 2^+ state in ^{12}C: confirmation of oblate deformation

Downsides of this Latest $Q(2^+)$ Measurement:

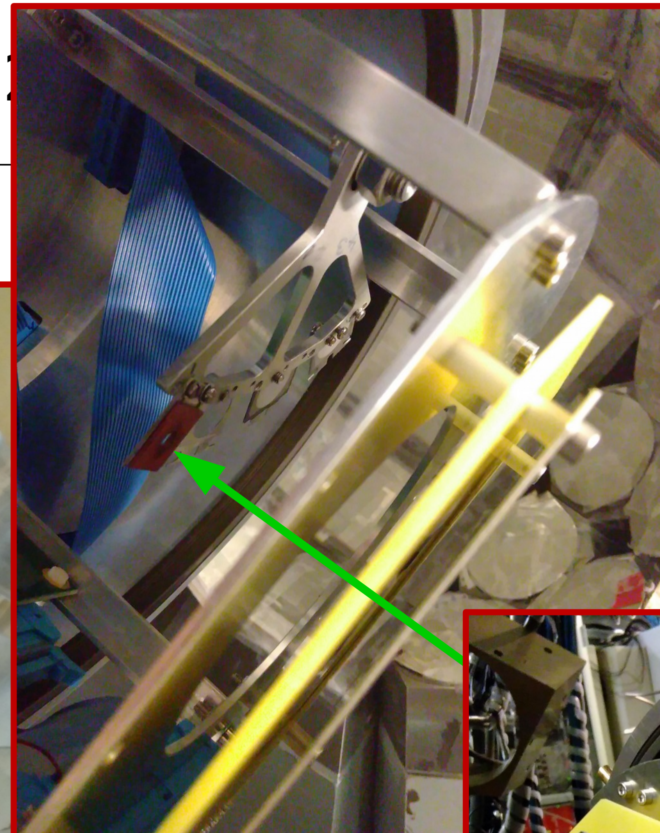
1) Measured C.S. relative to ^{194}Pt → Gamma-ray energy a few keV!
→ Large influence by changes in beam energy.

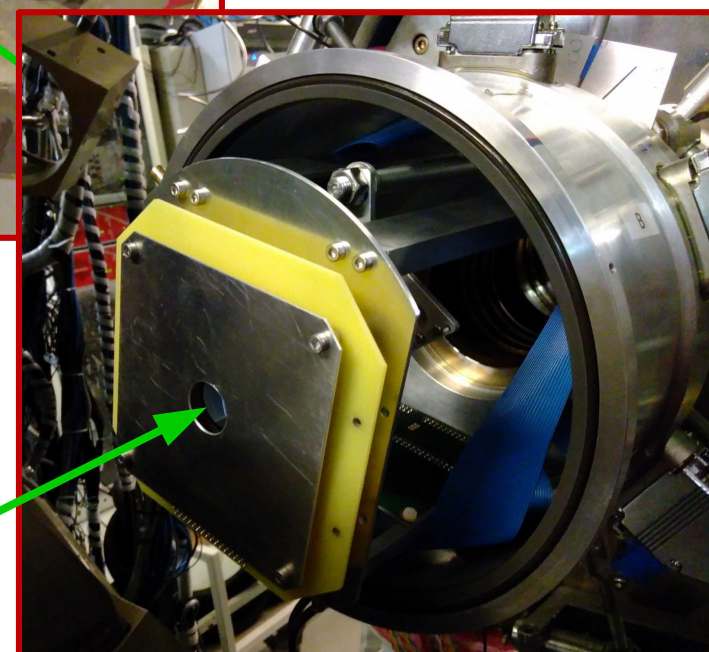
2) No sufficient gamma-ray efficiency calibration at 4 MeV.

3) Measured only under forward angles → No sensitivity for $Q(2^+)$.

Result: $Q_s(2^+) = (+0.053 \pm 0.044)\,\mathrm{eb}$ 83% uncertainty

Appendix: Carbon-1





Carbon-12: The Experiment at JYFL

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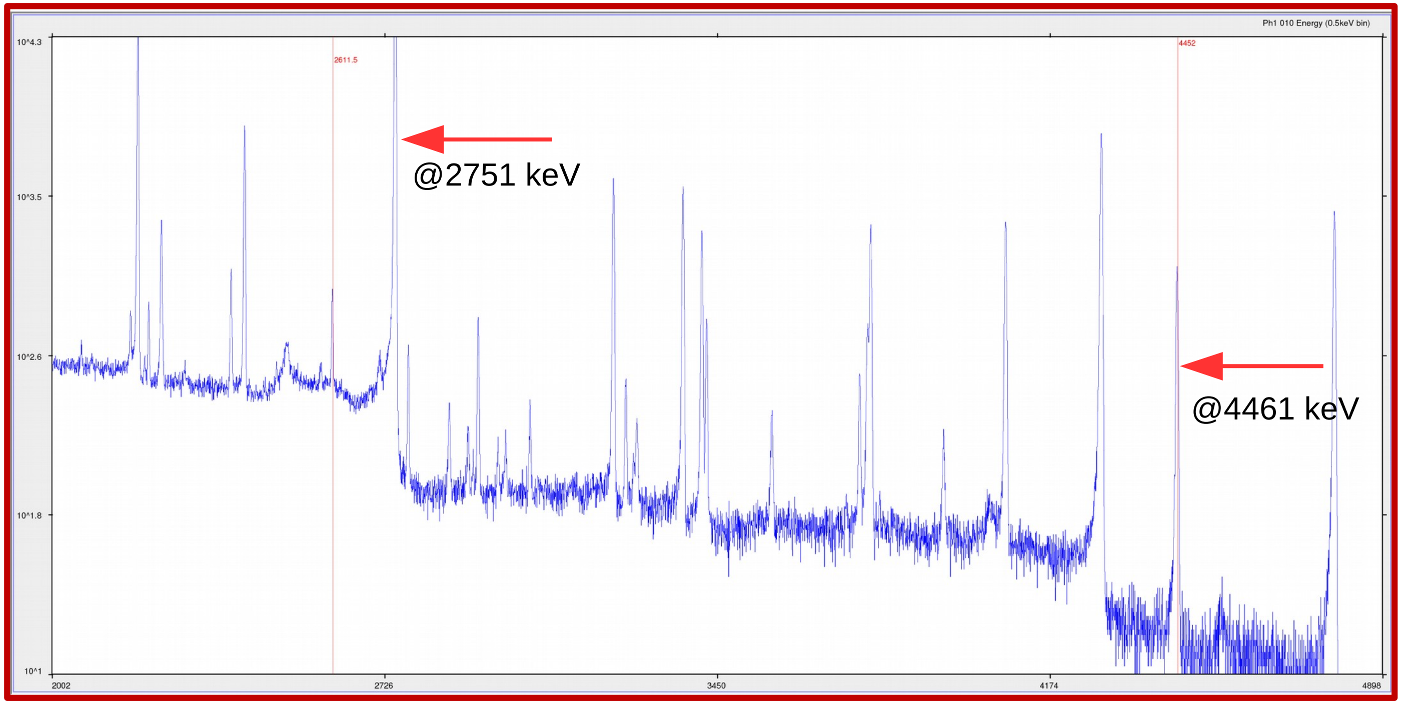
Important: Efficiency Calibration of JurogamII

- Low energy range (E<2 MeV) with “standard” sources:

Co-60, Eu-152, Ba-133

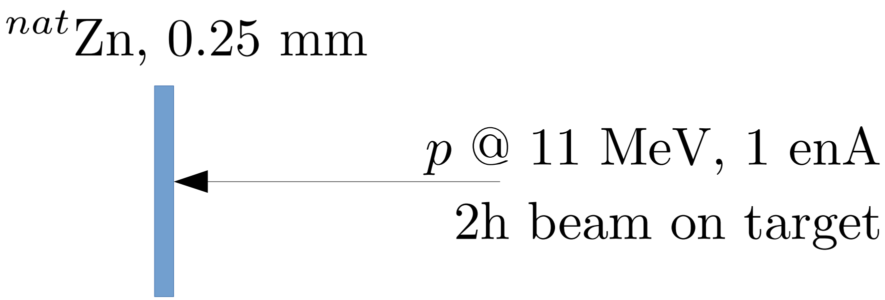
- **Special:** High energy range (E=0.8 to 5 MeV) using $^{nat}\mathrm{Zn(p,xn)}^{66}\mathrm{Ga}$



- 18 different gamma energies with precisely known intensity.

(Baglin et.al., Nucl. Instrum. Methods A, 481, 2002)

Appendix: Carbon-12



E_γ (keV) Helmer [16]	I_γ (rel.) Recommended
833.5324 (21)	15.93 (5)
1039.220 (3)	100.0 (3)
1333.112 (5)	3.175 (12)
1418.754 (5)	1.657 (8)
1508.158 (7)	1.497 (7)
1898.823 (8)	1.051 (8)
1918.329 (5)	5.368 (21)
2189.616 (6)	14.42 (5)
2422.525 (7)	5.085 (22)
2751.835 (5)	61.35 (23)
3228.800 (6)	4.082 (19)
3380.850 (6)	3.960 (19)
3422.040 (8)	2.314 (14)
3791.036 (8)[c]	2.941 (19)
4085.853 (9)	3.445 (18)
4295.224 (10)[c]	10.30 (8)[g]
4461.202 (9)	2.26 (3)
4806.007 (9)	5.03 (3)

Appendix: Carbon-12

- Cleaning the gamma-ray spectra using the ring energy of the SiCD: Example for ^{208}Pb $3^- \rightarrow 0^+$:

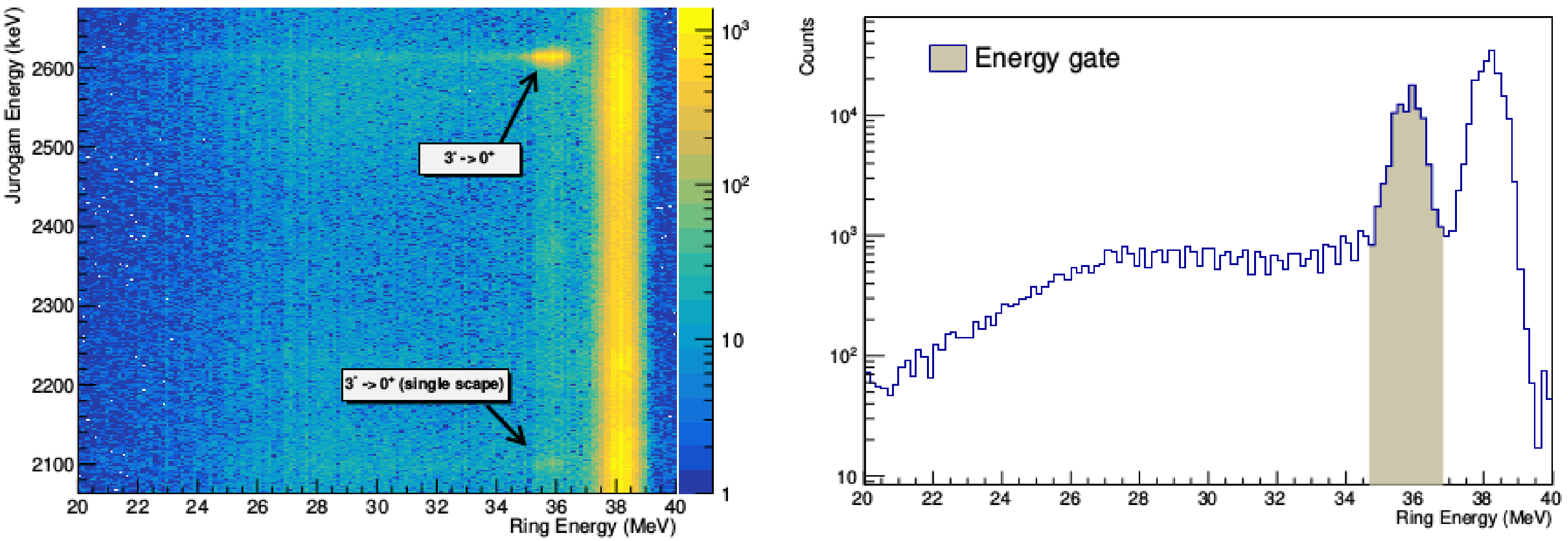


Figure 9: Doppler corrected Jurogam-II energy (keV) vs. ring energy in the SiCD (MeV) (left). Projection of the Jurogam-II energy interval 2595 to 2630 keV along the x-axis (right)