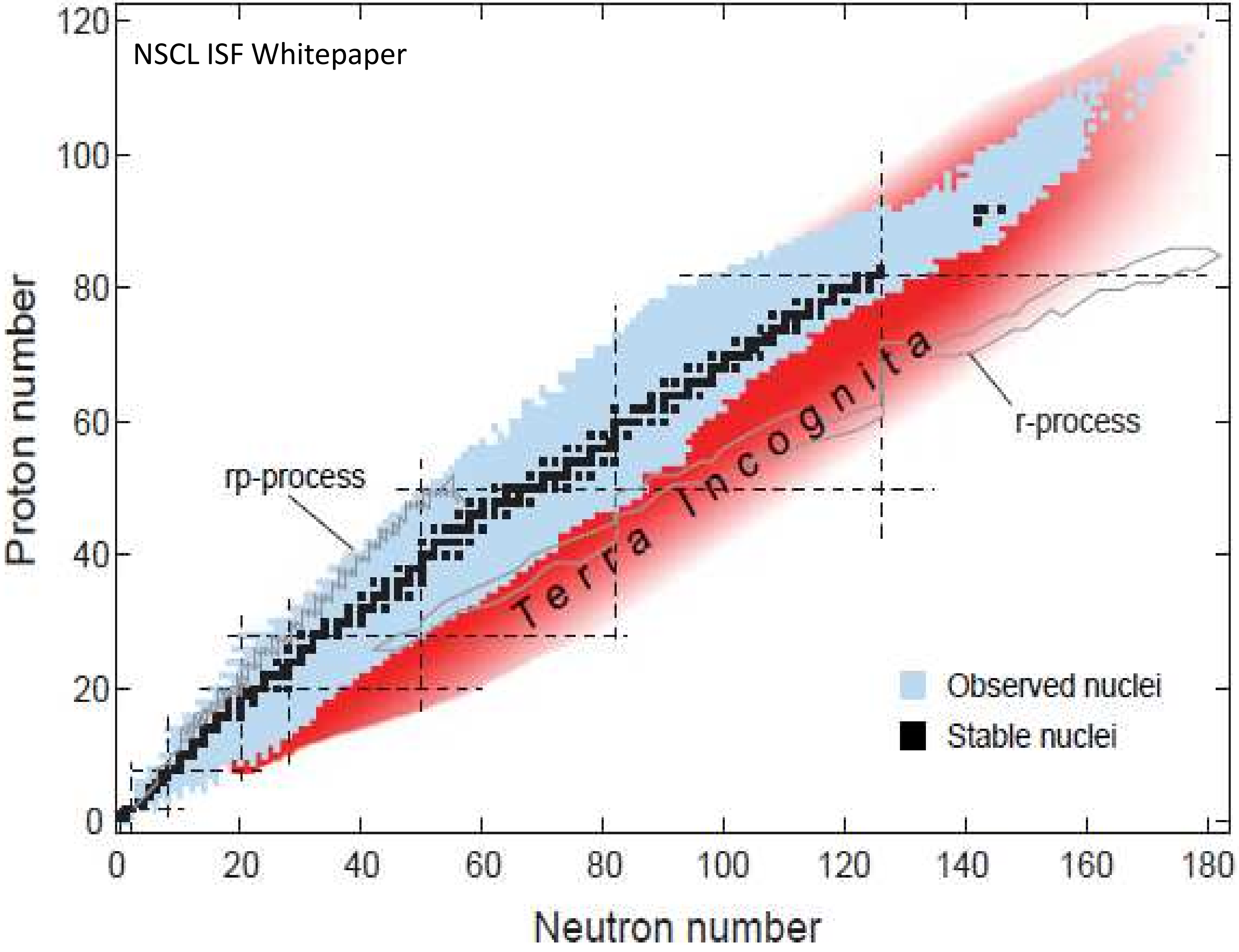
WNPPC 2012
The 49th Winter Nuclear and Particle Physics Conference

Electromagnetic Transition Rate Measurements Far from Stability With Radioactive Beams

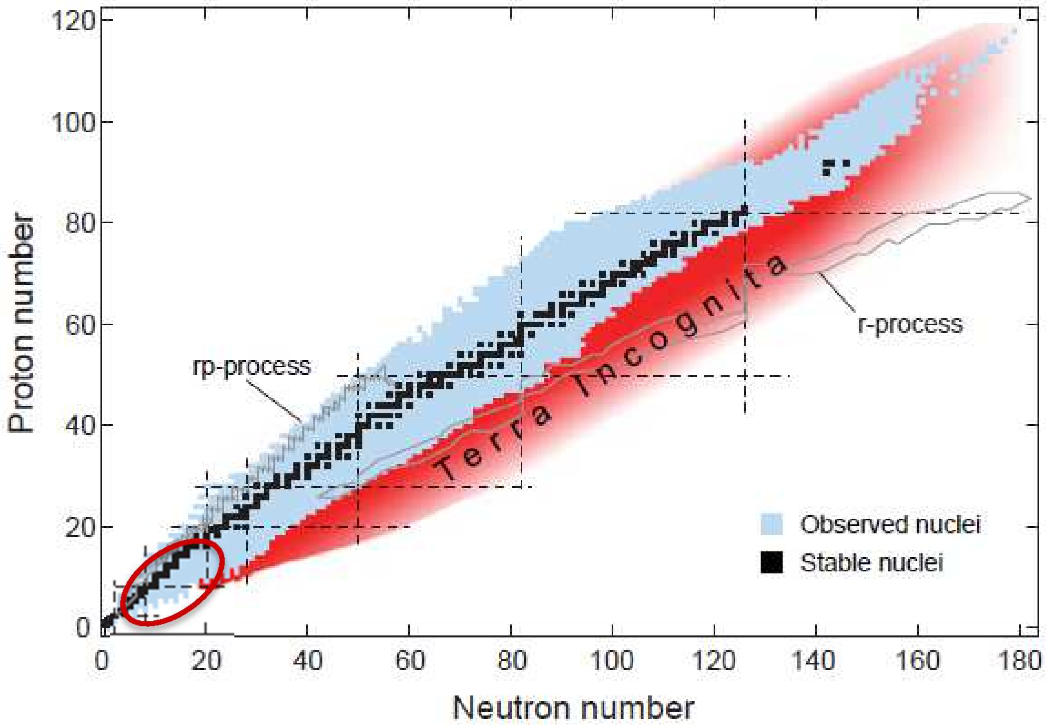
Philip J. Voss
Simon Fraser University

Friday, February 24th 2012

The Nuclear Physics Landscape

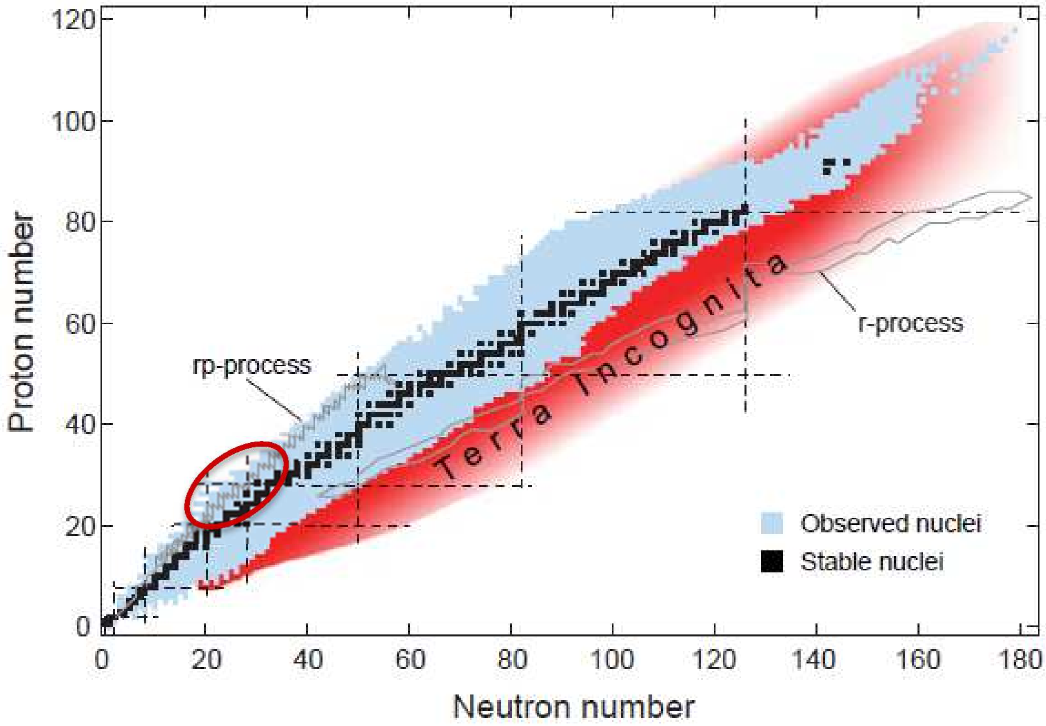


Select Major Questions in Nuclear Physics



- How does an increasing proton-neutron asymmetry impact the evolution of nuclear structure?
- Can the properties of light atomic nuclei be described entirely from first principles, or an *ab initio*, approach?

Select Major Questions in Nuclear Physics



- What mechanisms drive the changes in nuclear shape for radioactive medium-mass N=Z nuclei? How do they impact the proton-rich nucleosynthesis?
- What are the best approximations and approaches for developing an accurate theoretical description of heavy (A > 20) nuclei?

The Importance of Transition Rate Measurements

Measuring electromagnetic observables is ideal as they:

- Impart a negligible perturbation on the nuclear system governed by the strong force.
- Provide a variety of model-independent probes of nuclear structure.

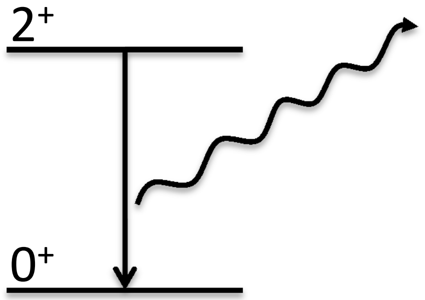
Studies at the extreme limits of nuclear existence require:

- Radioactive beam facilities capable of delivering intense and pure beams of nuclear species.
- Highly efficient detector arrays for gamma-ray spectroscopy.
- A variety of charged particle detector setups for reaction residue and charged particle tagging to decrease background.

The Importance of Transition Rate Measurements

Electromagnetic transition rate measurements lend insight into the evolution of nuclear structure and provide a sensitive test of theoretical models.

Lifetime Measurements



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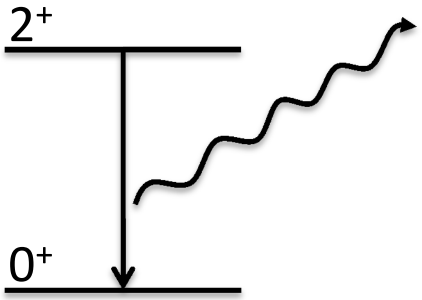


$$\tau(E2; 2_1^+ \to 0_{gs}^+) = \frac{1}{\lambda(E2; 2_1^+ \to 0_{gs}^+)}$$

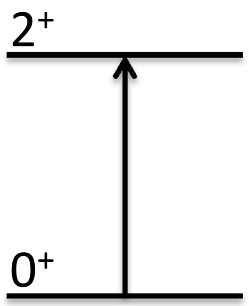
$$\lambda(E2; 2_1^+ \to 0_{gs}^+) \propto E(2_1^+)^5 B(E2; 2_1^+ \to 0_{gs}^+)$$

$$B(E2; I_i \to I_f) = \frac{1}{2J_i + 1} \langle I_f || E2 || I_i \rangle^2$$

The Importance of Transition Rate Measurements

Electromagnetic transition rate measurements lend insight into the evolution of nuclear structure and provide a sensitive test of theoretical models.

Coulomb Excitation



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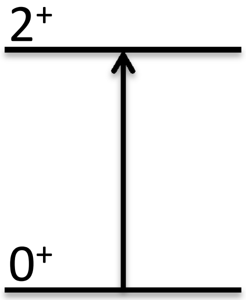
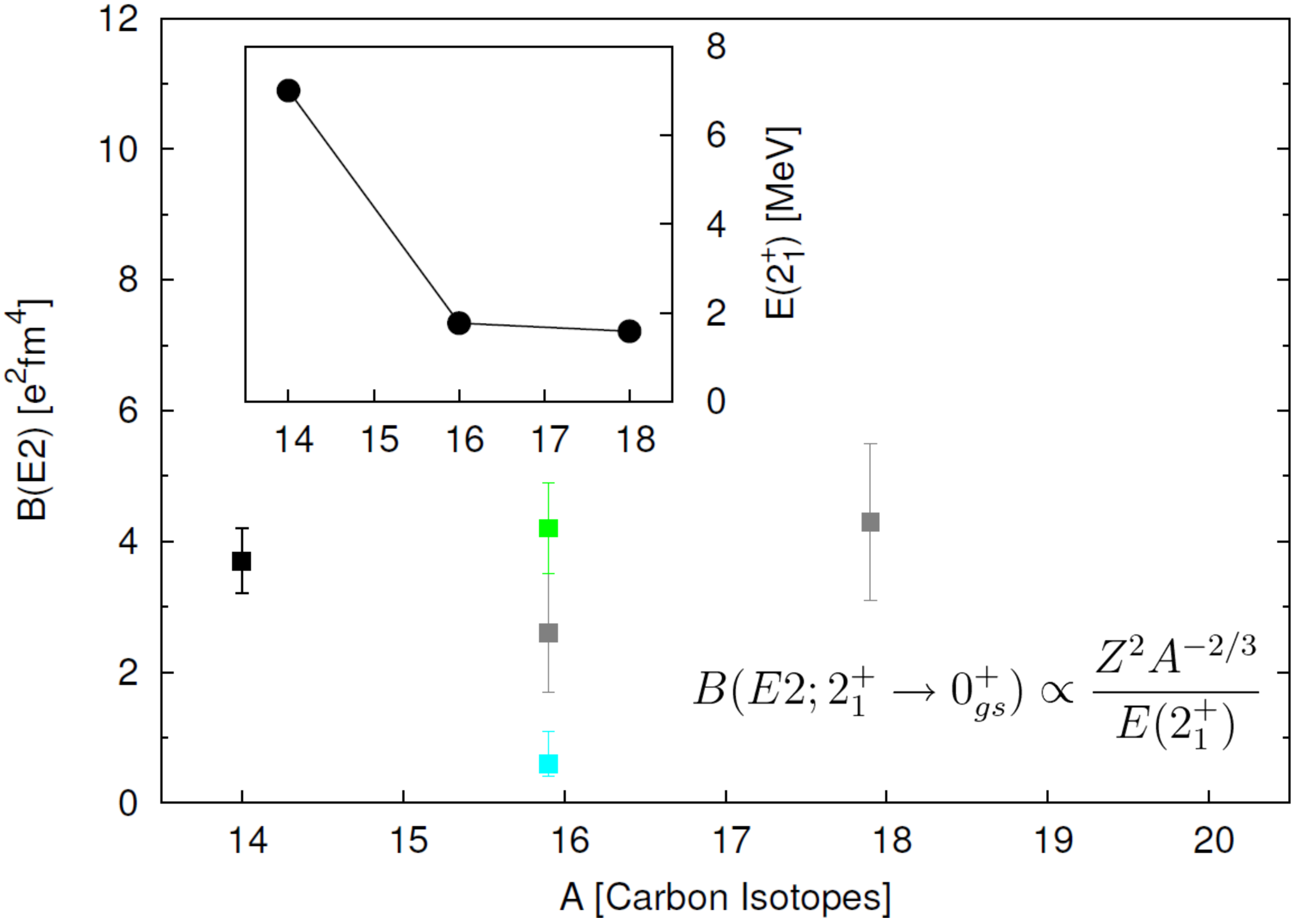


$$P_{0_1^+\rightarrow 2_1^+} \propto B(E2;0_1^+ \rightarrow 2_2^+)[1+\alpha Q(2_1^+)]$$

$$Q(2^+) \propto \langle 2^+||E2||2^+\rangle$$

Anomalous Neutron-Rich Carbon Isotopes?



$$B(E2; 2_1^+ \rightarrow 0_{gs}^+) \propto \frac{Z^2 A^{-2/3}}{E(2_1^+)}$$

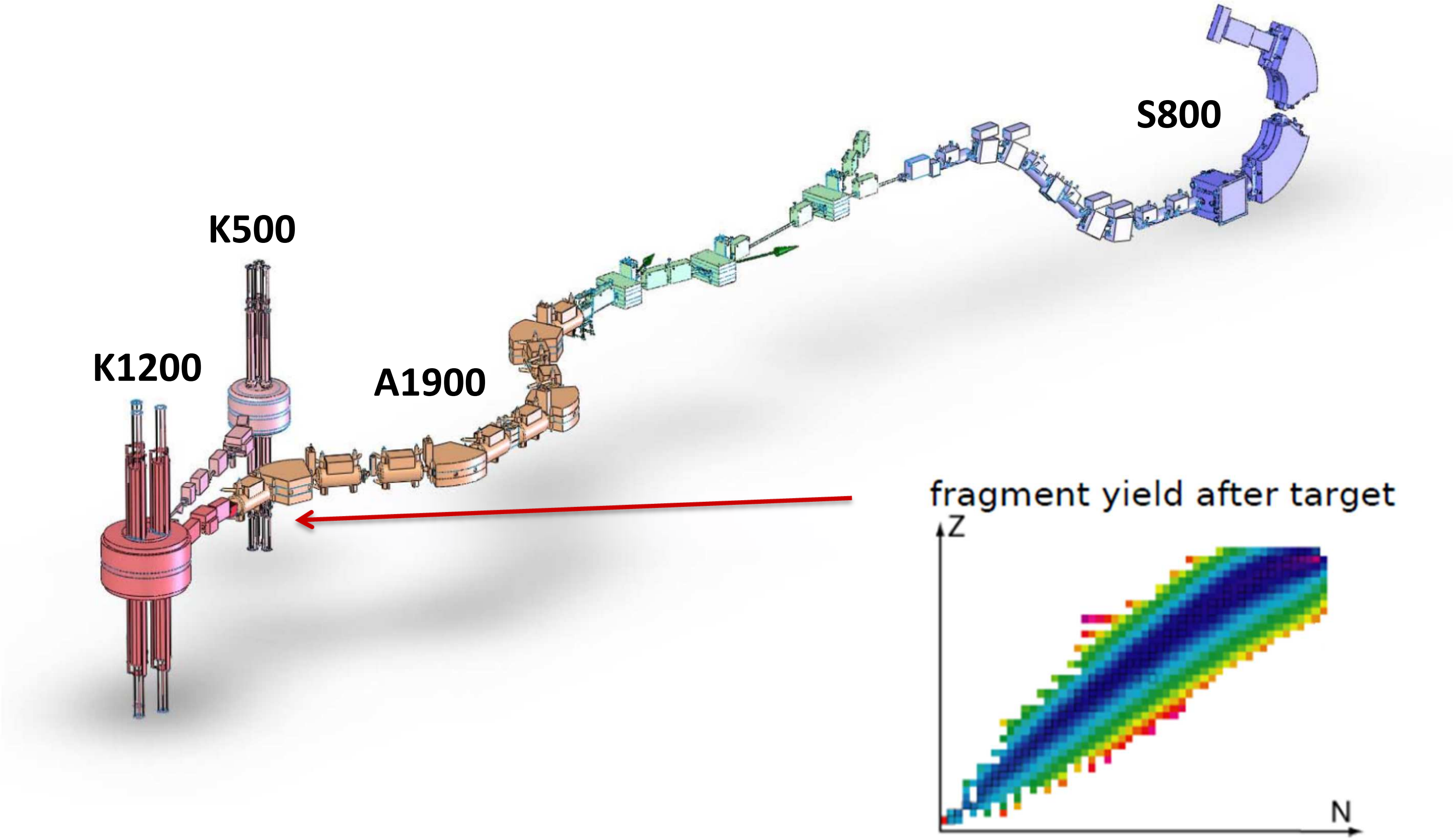
S. Raman et al., Nuclear Data Tables, **36** 1 (1987).

H.J. Ong et al., PRC, **78** 014308 (2008).

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

N. Imai et al., PRL **92**, 062501 (2004).

Exotic Isotope Production at NSCL



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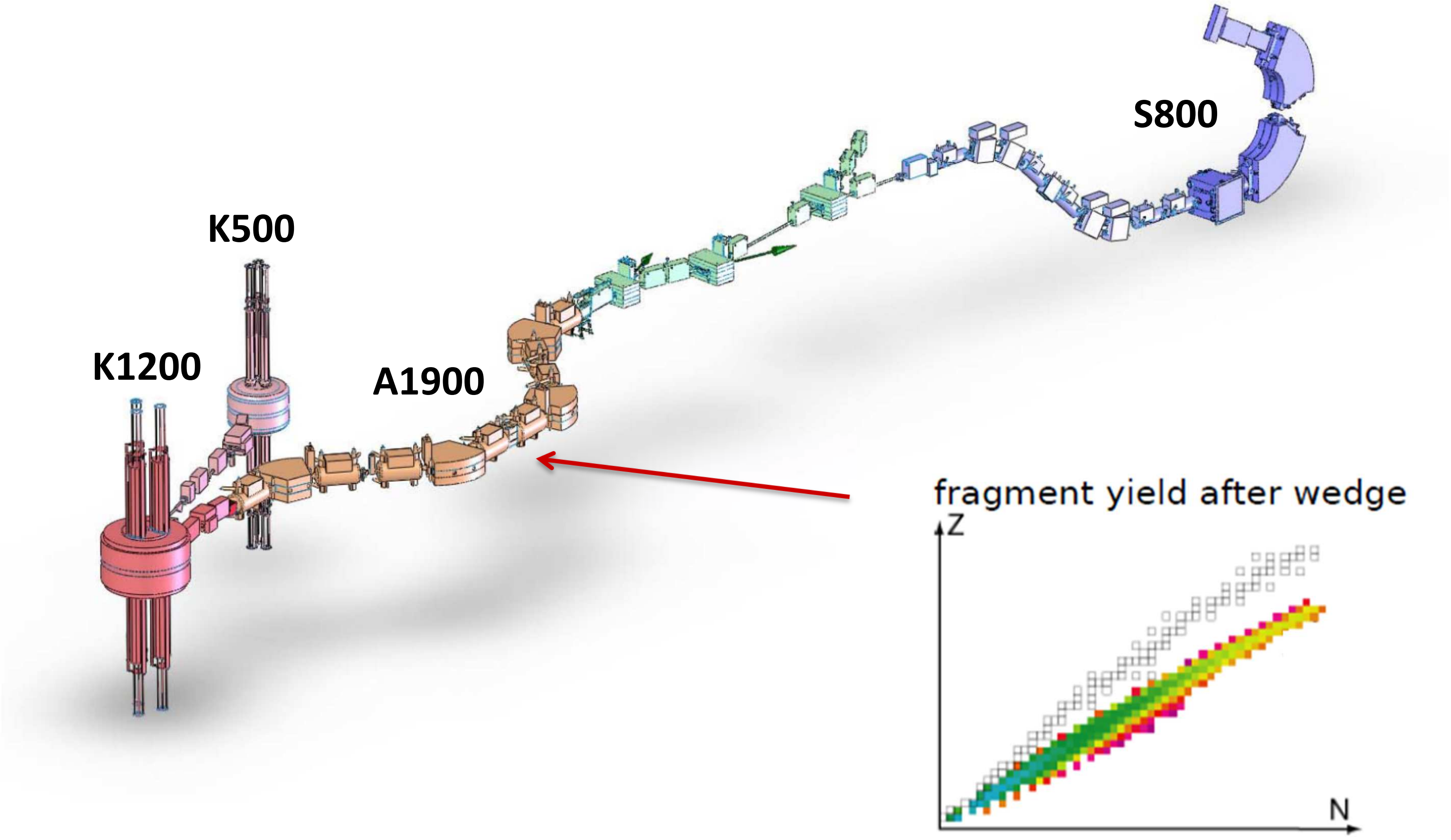
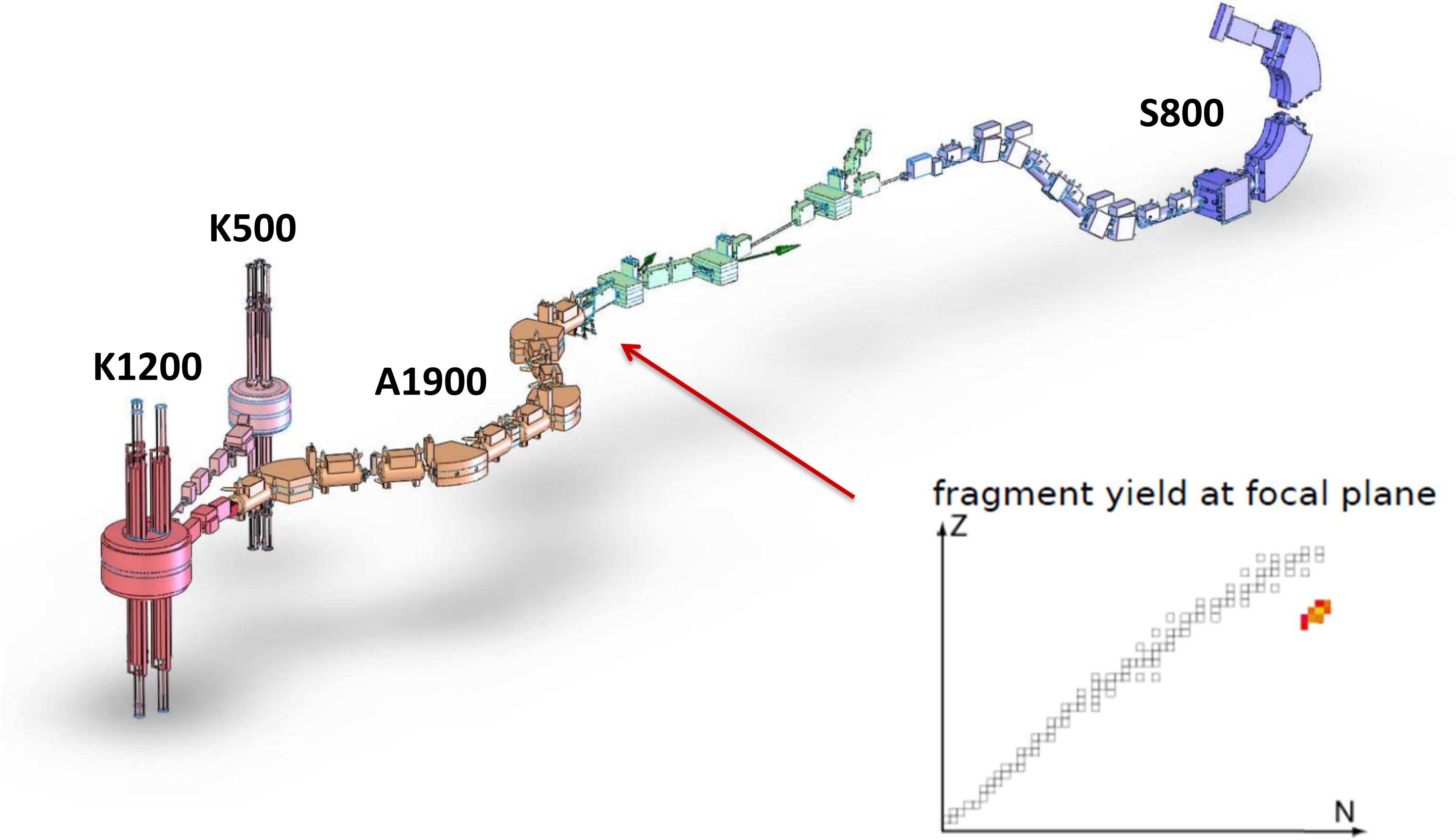
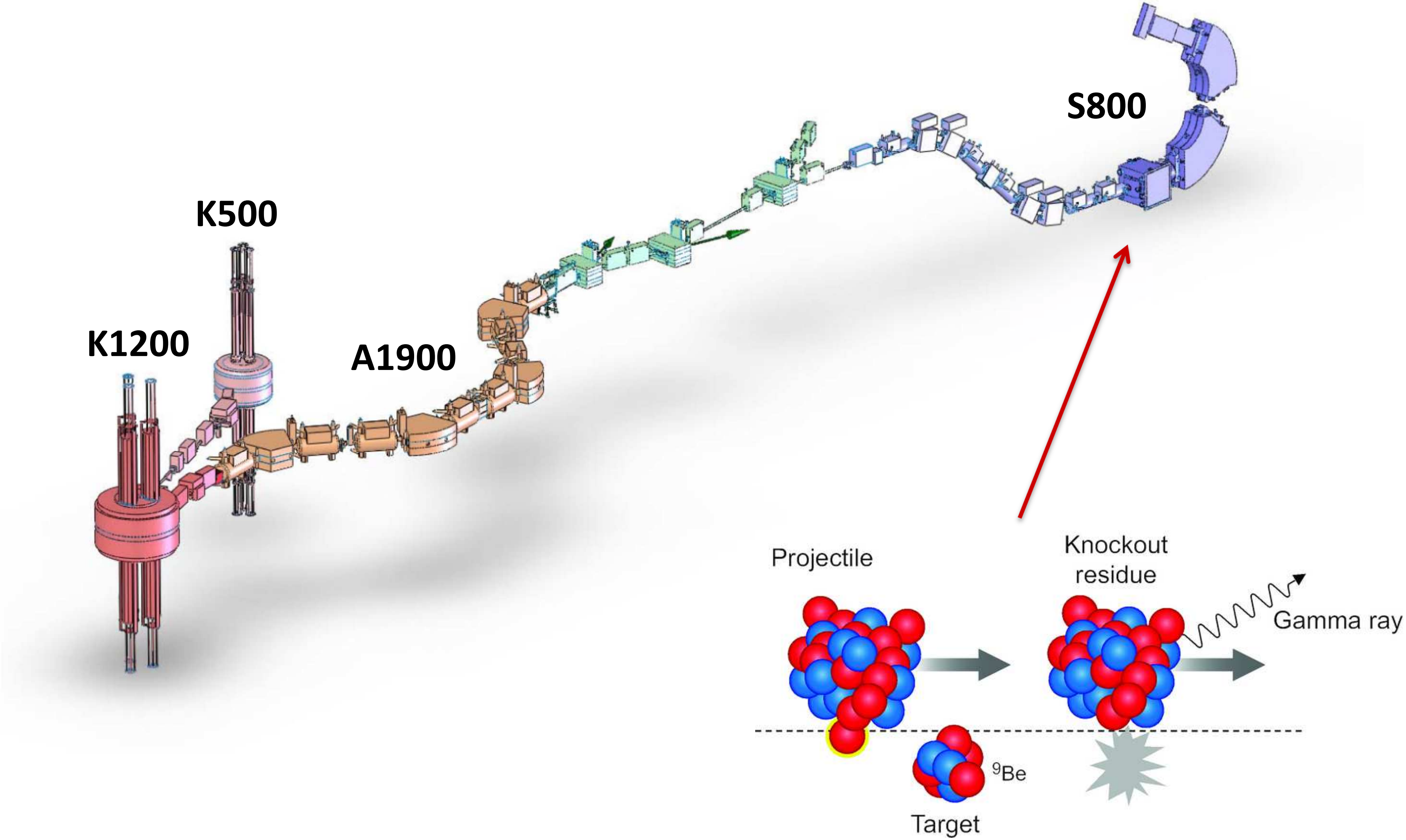


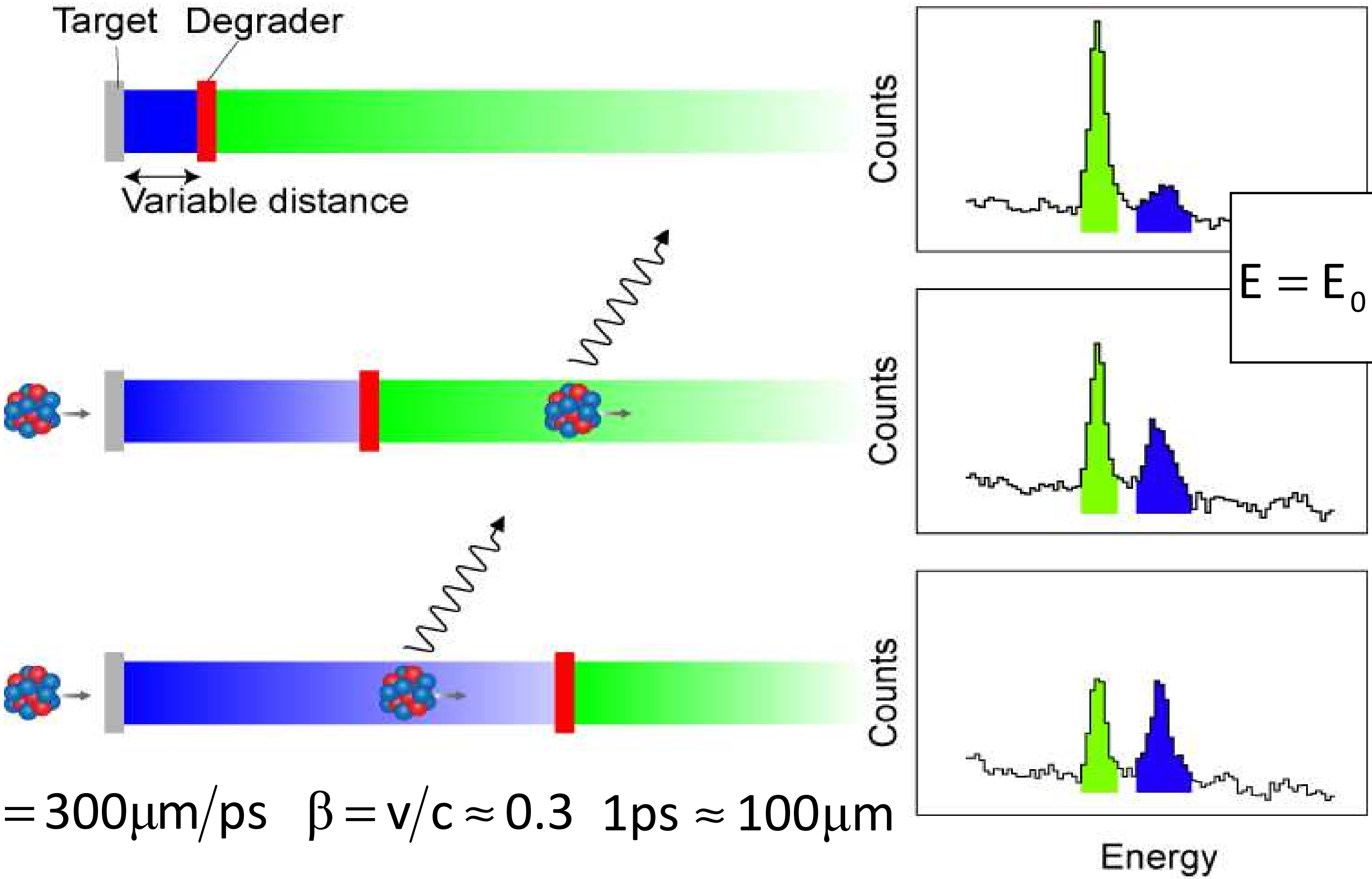
Exotic Isotope Production at NSCL



Exotic Isotope Production at NSCL



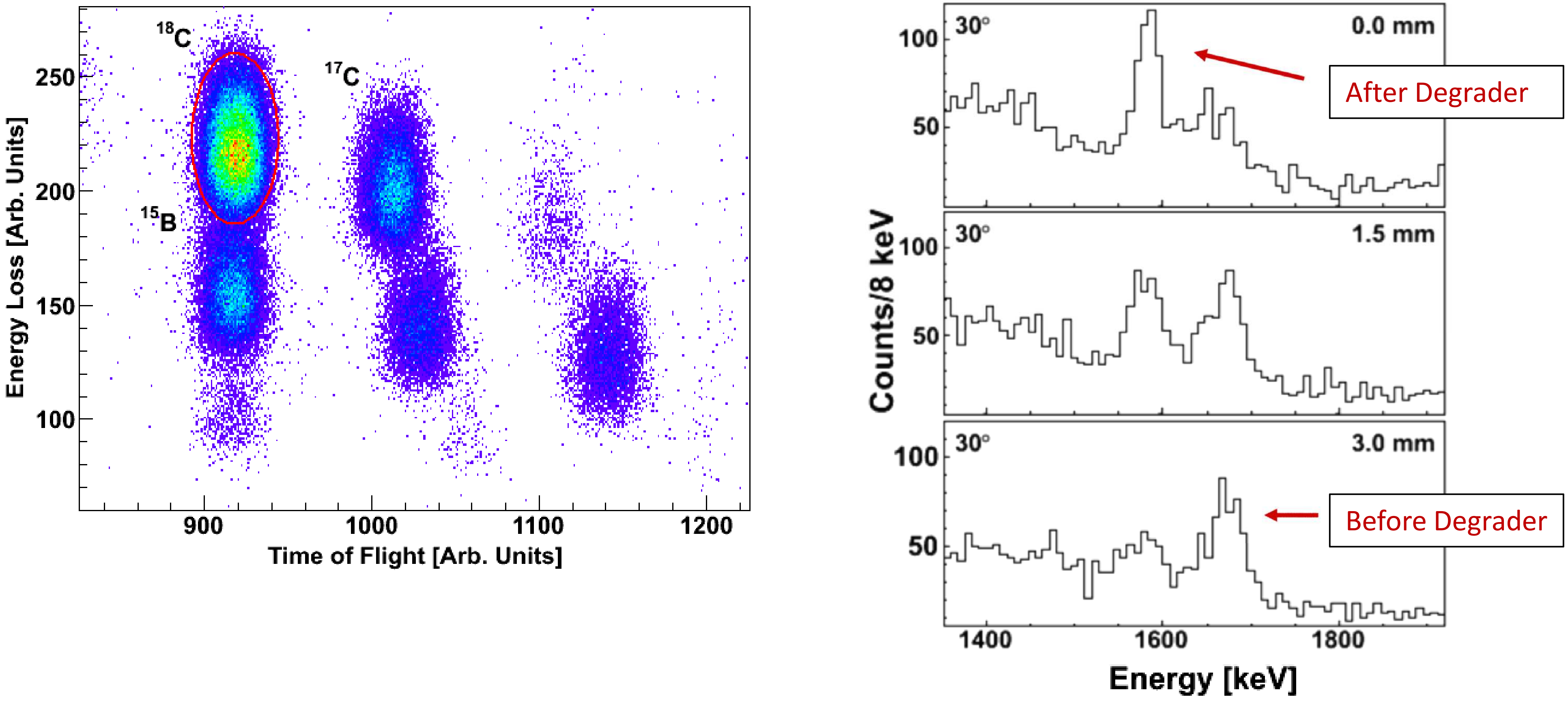
The Recoil Distance Method



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

$$c = 300\mu m/ps \quad \beta = v/c \approx 0.3 \quad 1ps \approx 100\mu m$$

$^{12}C(^{19}N, ^{18}C+\gamma)X$ Experimental Spectra

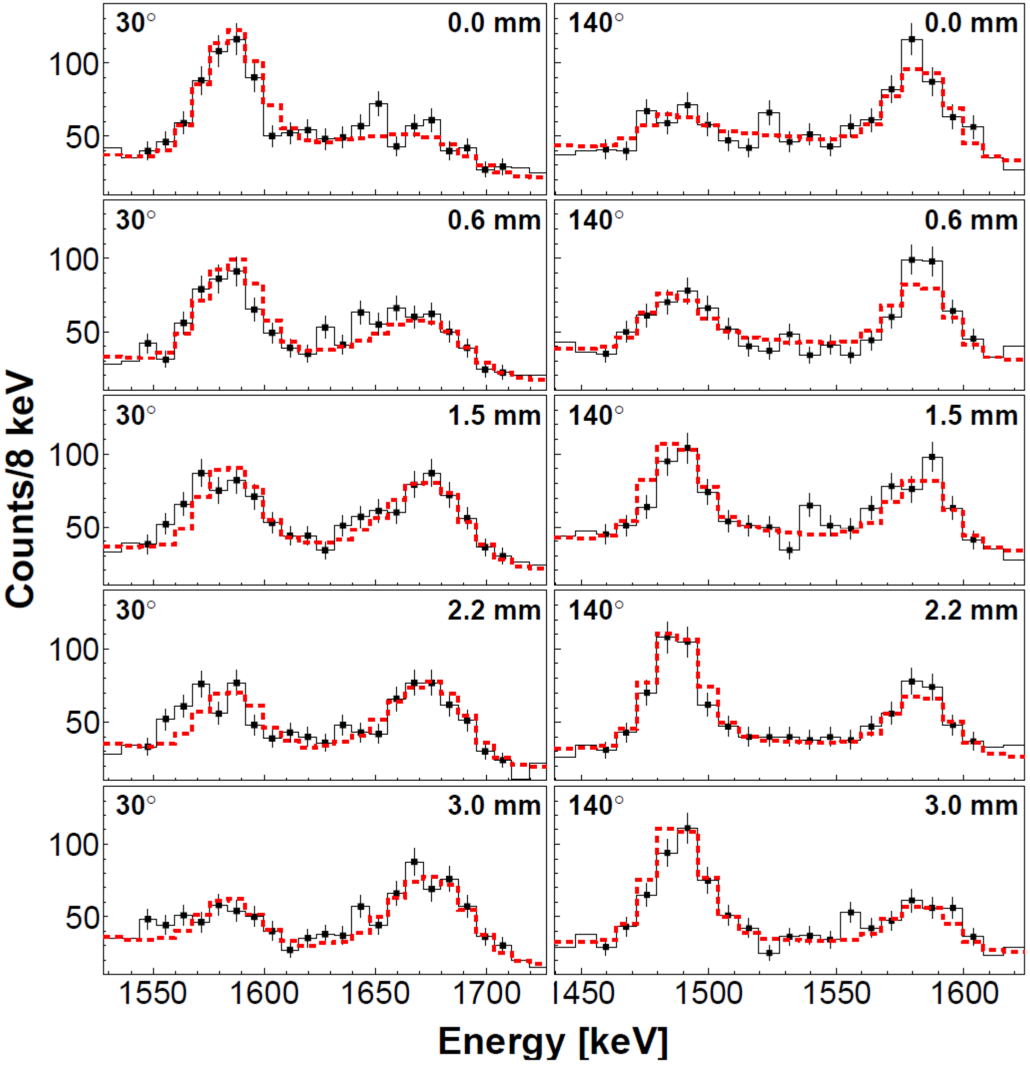


After Degrader

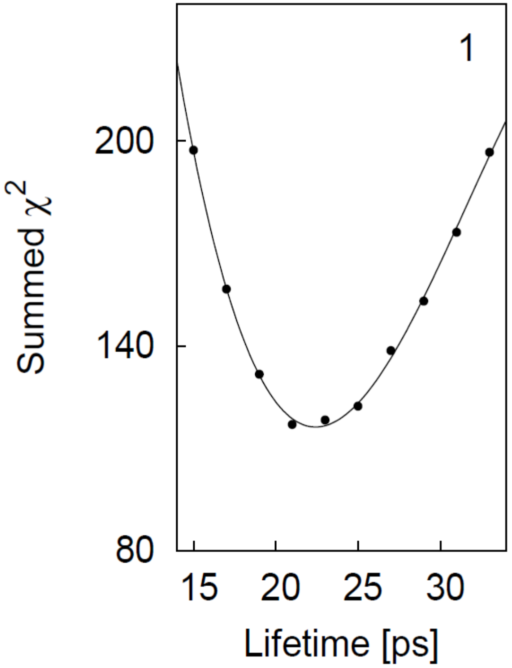
Before Degrader

S800 particle identification and ^{18}C gated gamma-ray energy spectra at three target-degrader distances.

Best Fit Lifetime Results

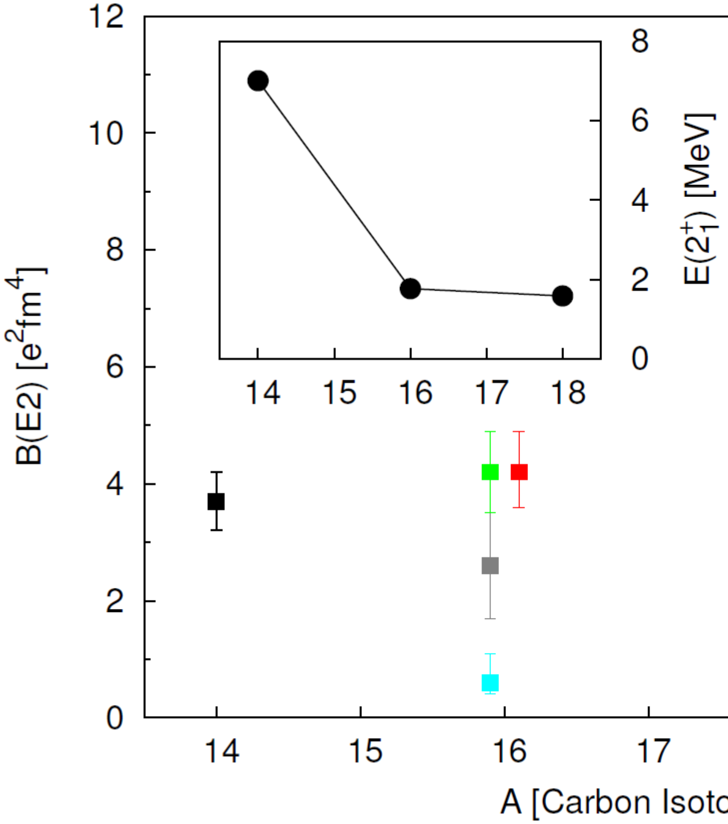


Experimental data and best-fit lifetime **simulated lineshapes** for the 1585 keV transition in ^{18}C.



$$\tau = 22.4 \pm 0.9(\mathrm{stat})^{+2.5}_{-1.6}(\mathrm{syst})\ \mathrm{ps}$$

Results of Neutron-Rich Carbon Lifetime Campaign



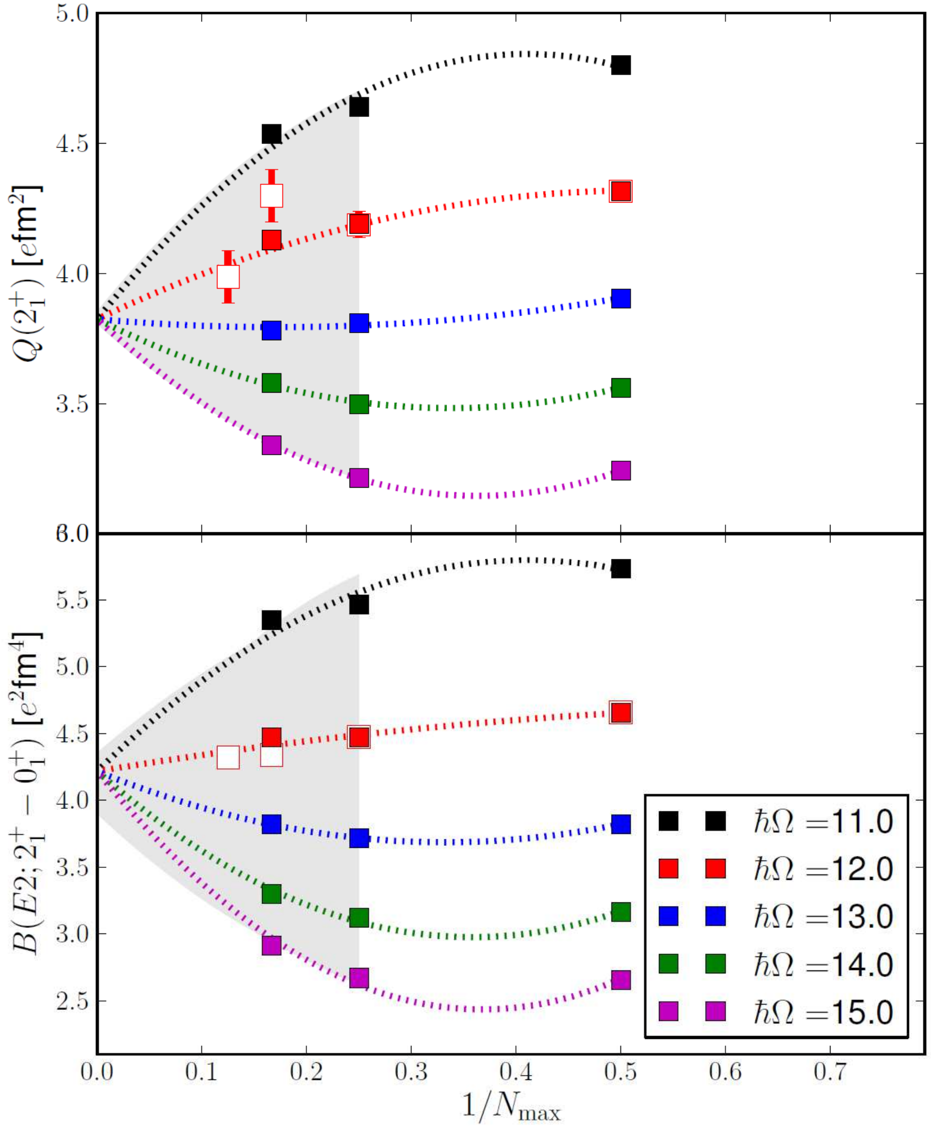
The **present result** reduces the existing fractional uncertainty by a factor of two.

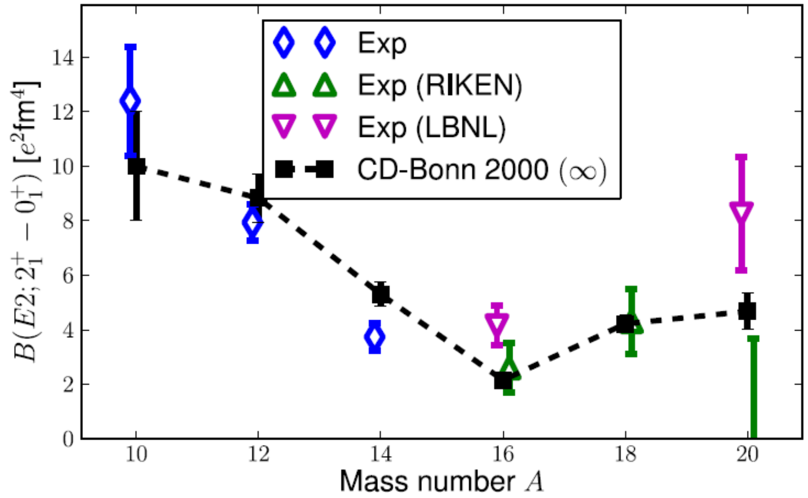
$$B(E2) = 3.64^{+0.46}_{-0.48}\ \mathrm{e^2fm^4}$$

$$B(E2)_{lit} = 4.3 \pm 1.2\ \mathrm{e^2fm^4}$$

S. Raman et al., Nuclear Data Tables, **36** 1 (1987).
H.J. Ong et al., PRC, **78** 014308 (2008).
N. Imai et al., PRL **92**, 062501 (2004).
M. Wiedeking et al., PRL, **100** 152501 (2008).
M. Petri et al., PRL **107** 102501 (2011) and PRC sub.

Ab Initio No-Core Shell Model Calculations



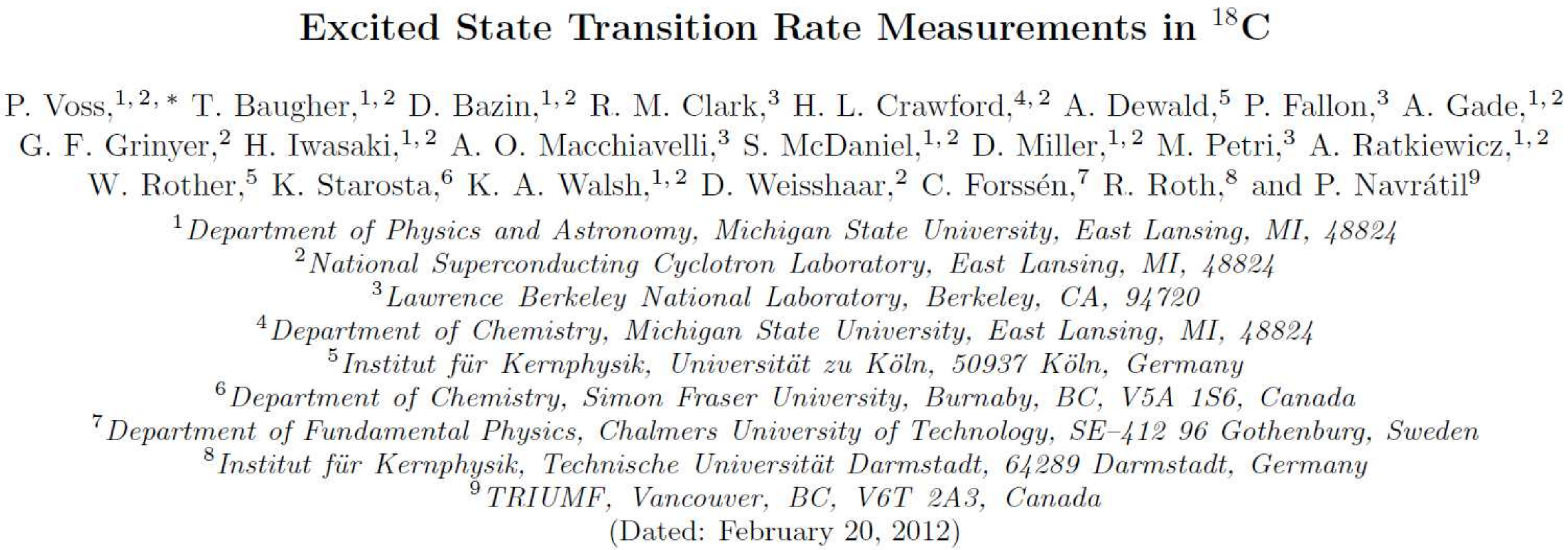


C. Forssén *et al.*, PRC, **arXiv:1110.0634v1** [nucl-th] (2011).

Nucleus	Observable	Experiment	CDB2K
^{18}C	$E(2_1^+)$	1.585(19)	1.8(1)
^{18}C	$B(E2;2_1^+\rightarrow 0_1^+)$	$3.64^{+0.46}_{-0.48}$	4.2(4)
^{18}C	$Q(2_1^+)$		+3.8(4)

The convergence of NCSM calculations employing the importance-truncation scheme is shown to the left.

NSCL Lifetime Group and ^{18}C Collaborators



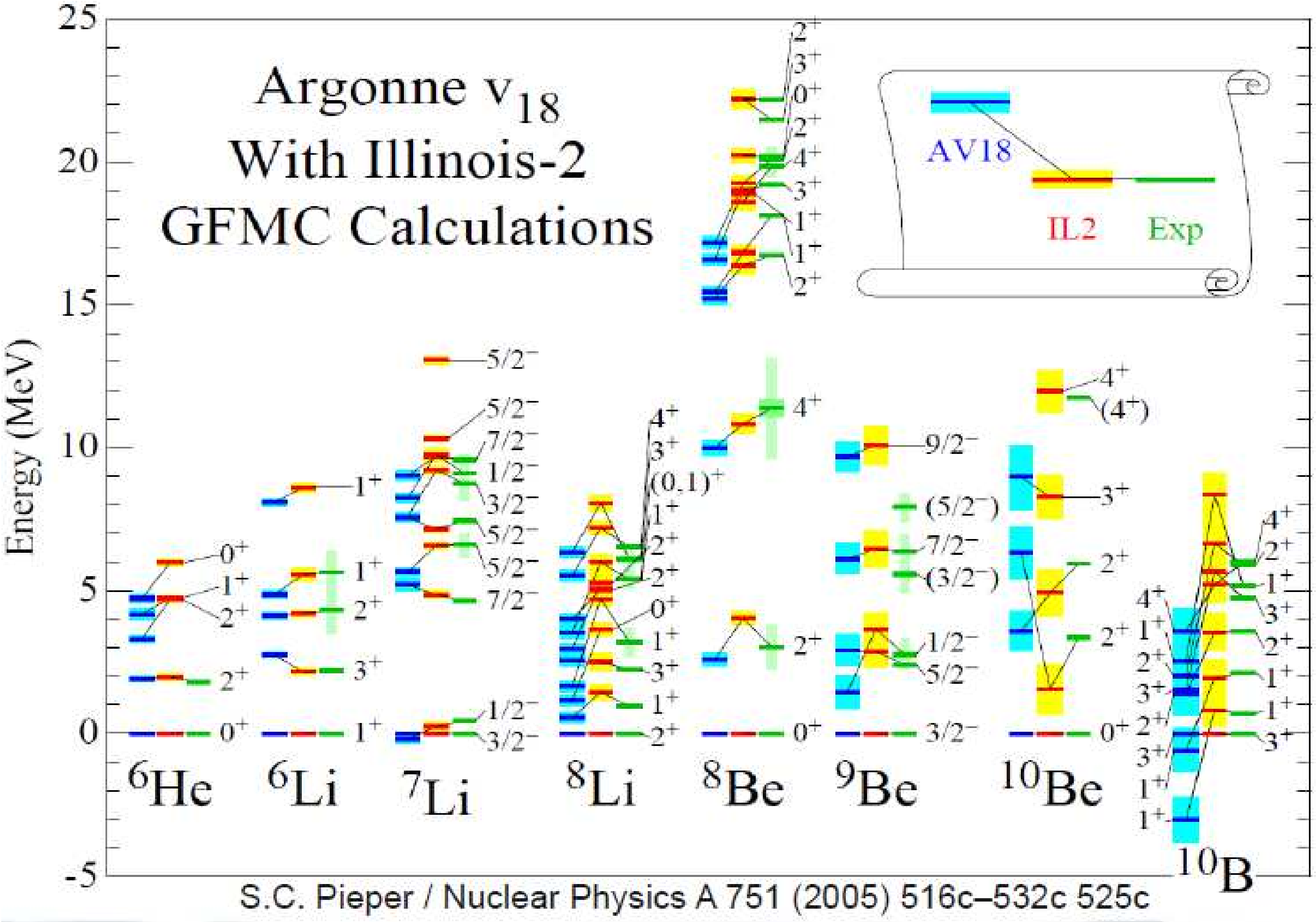
Excited State Transition Rate Measurements in ^{18}C

P. Voss,[1,2,*] T. Baugher,[1,2] D. Bazin,[1,2] R. M. Clark,[3] H. L. Crawford,[4,2] A. Dewald,[5] P. Fallon,[3] A. Gade,[1,2] G. F. Grinyer,[2] H. Iwasaki,[1,2] A. O. Macchiavelli,[3] S. McDaniel,[1,2] D. Miller,[1,2] M. Petri,[3] A. Ratkiewicz,[1,2] W. Rother,[5] K. Starosta,[6] K. A. Walsh,[1,2] D. Weisshaar,[2] C. Forssén,[7] R. Roth,[8] and P. Navrátil[9]

[1] *Department of Physics and Astronomy, Michigan State University, East Lansing, MI, 48824*
[2] *National Superconducting Cyclotron Laboratory, East Lansing, MI, 48824*
[3] *Lawrence Berkeley National Laboratory, Berkeley, CA, 94720*
[4] *Department of Chemistry, Michigan State University, East Lansing, MI, 48824*
[5] *Institut für Kernphysik, Universität zu Köln, 50937 Köln, Germany*
[6] *Department of Chemistry, Simon Fraser University, Burnaby, BC, V5A 1S6, Canada*
[7] *Department of Fundamental Physics, Chalmers University of Technology, SE–412 96 Gothenburg, Sweden*
[8] *Institut für Kernphysik, Technische Universität Darmstadt, 64289 Darmstadt, Germany*
[9] *TRIUMF, Vancouver, BC, V6T 2A3, Canada*

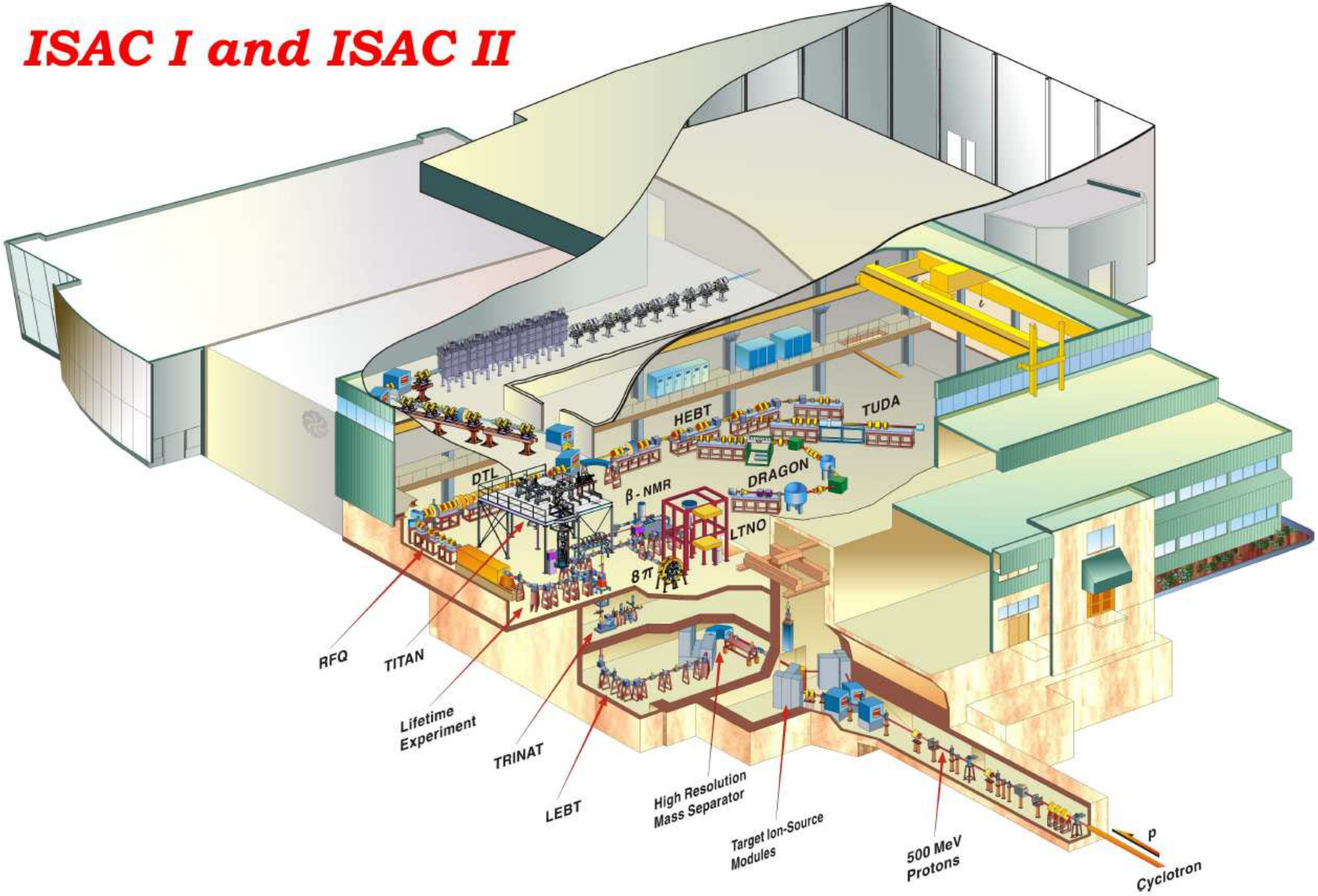
(Dated: February 20, 2012)

The Importance of 3N Forces in *Ab Initio* Calculations

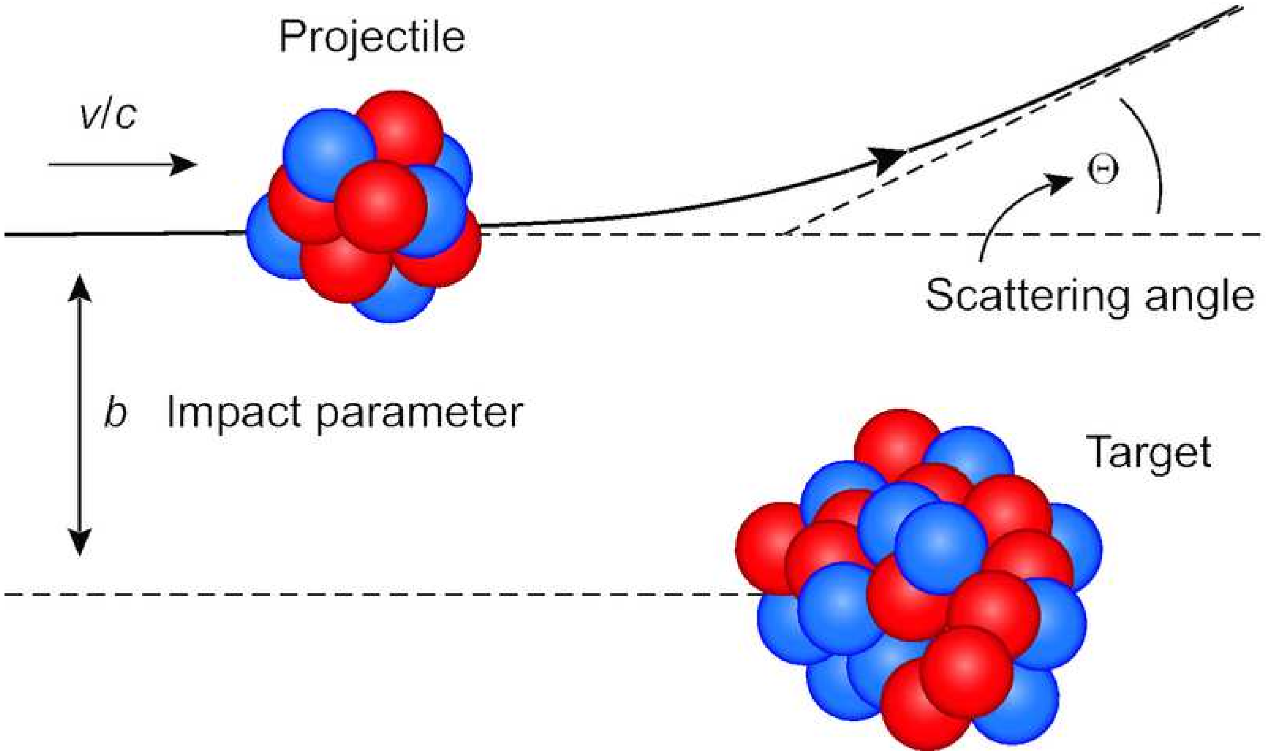


S.C. Pieper / Nuclear Physics A 751 (2005) 516c–532c 525c

Transition Rate Studies at TRIUMF

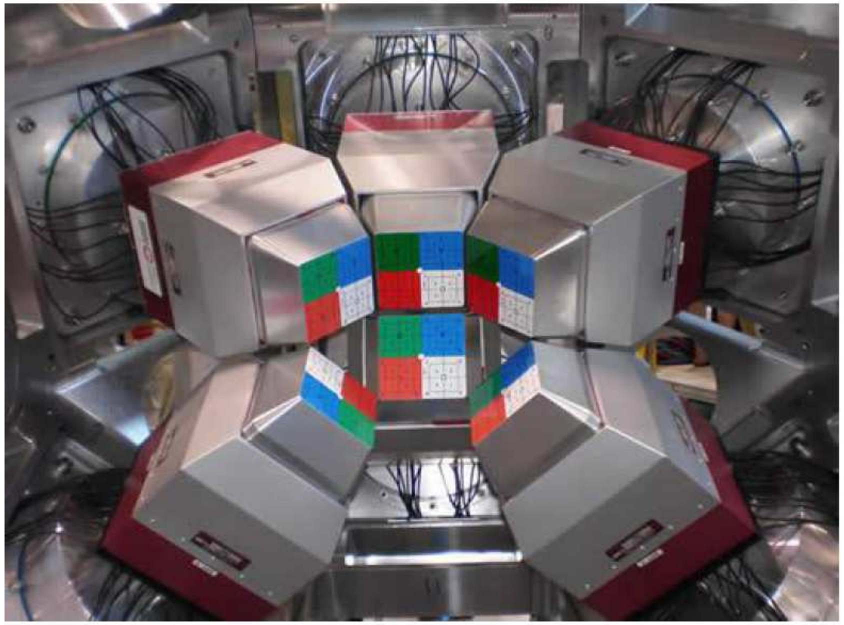


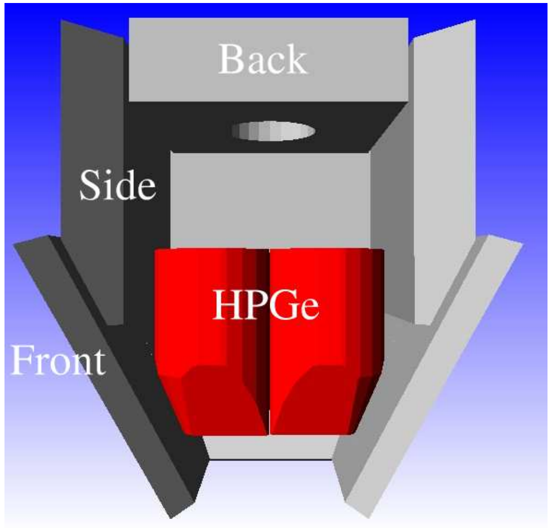
Coulomb Excitation Measurements

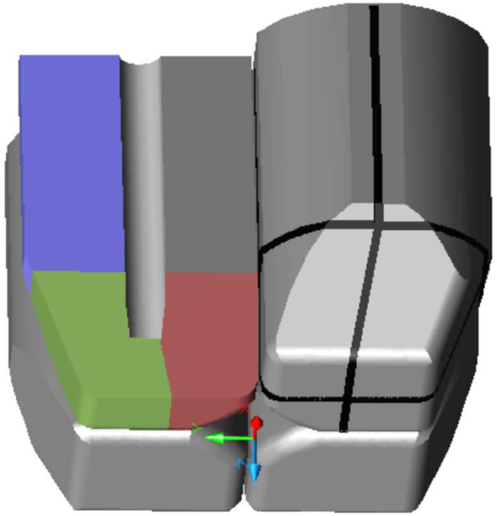


- Highly-segmented silicon (BAMBINO) for scattered particle detection.
- High-efficiency HPGe (TIGRESS) for de-excitation photon detection.

TRIUMF ISAC Gamma-Ray Escape Suppressed Spectrometer





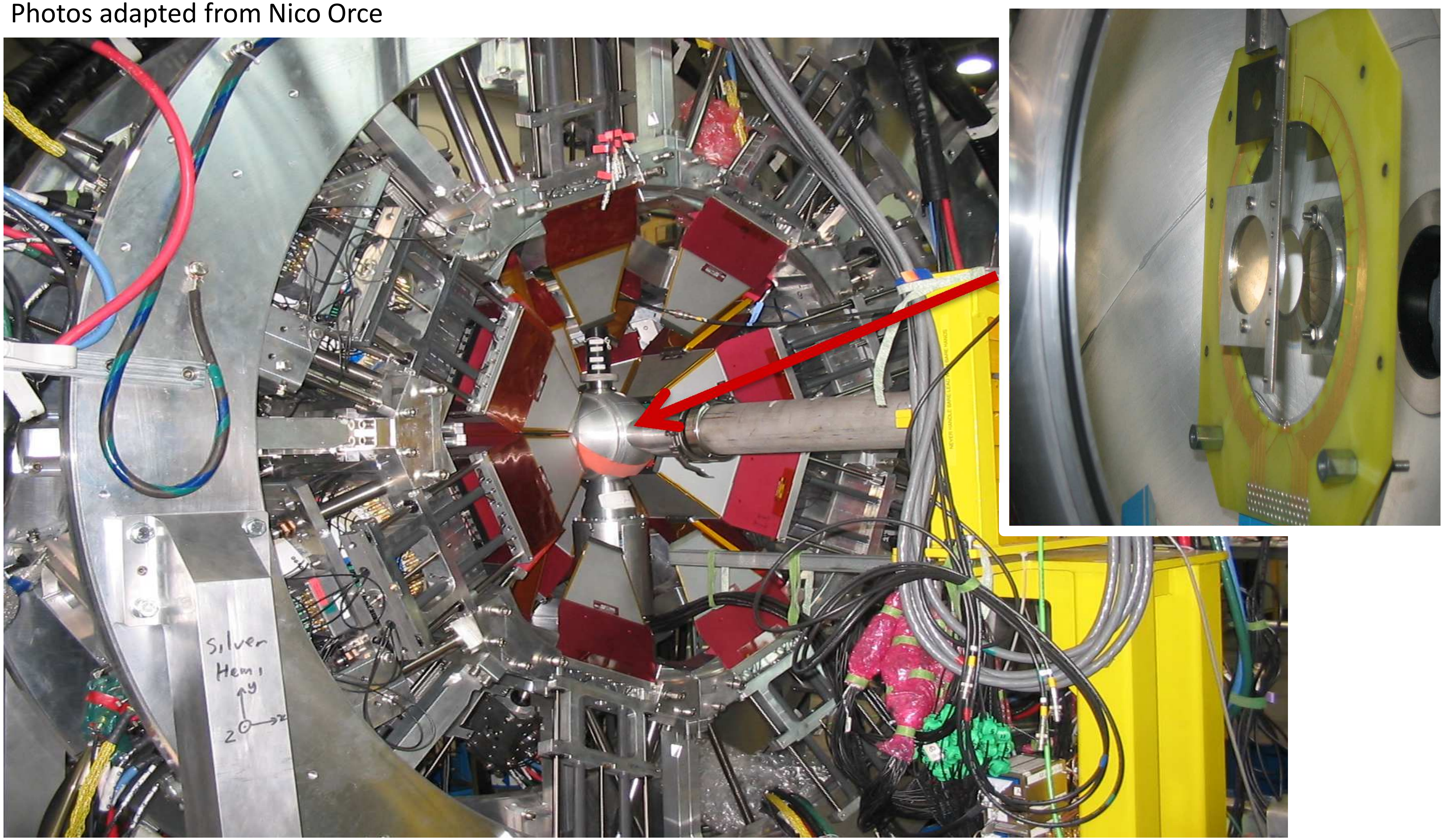


TIGRESS is an array of 16 high-purity germanium clover detectors with 32-fold segmentation per clover for enhanced position resolution.

The array is fully instrumented with fast digital electronics and reconfigurable BGO suppressors to meet a variety of experimental needs.

^{194}Pt(^{10}Be, ^{10}Be*)^{194}Pt* Experimental Equipment

Photos adapted from Nico Orce



^{194}Pt(^{10}Be, ^{10}Be*)^{194}Pt* Gamma-Ray Energy Spectra

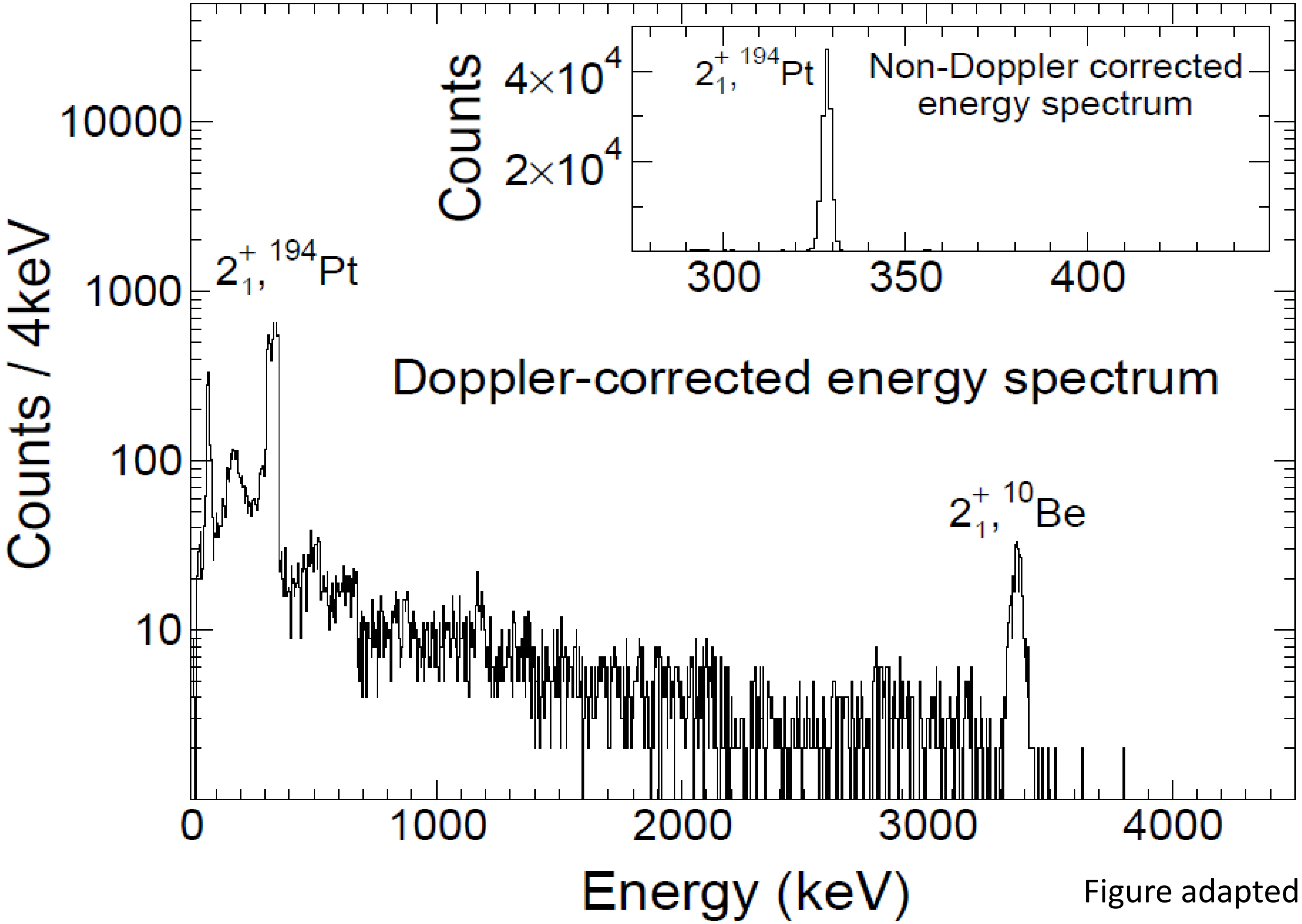
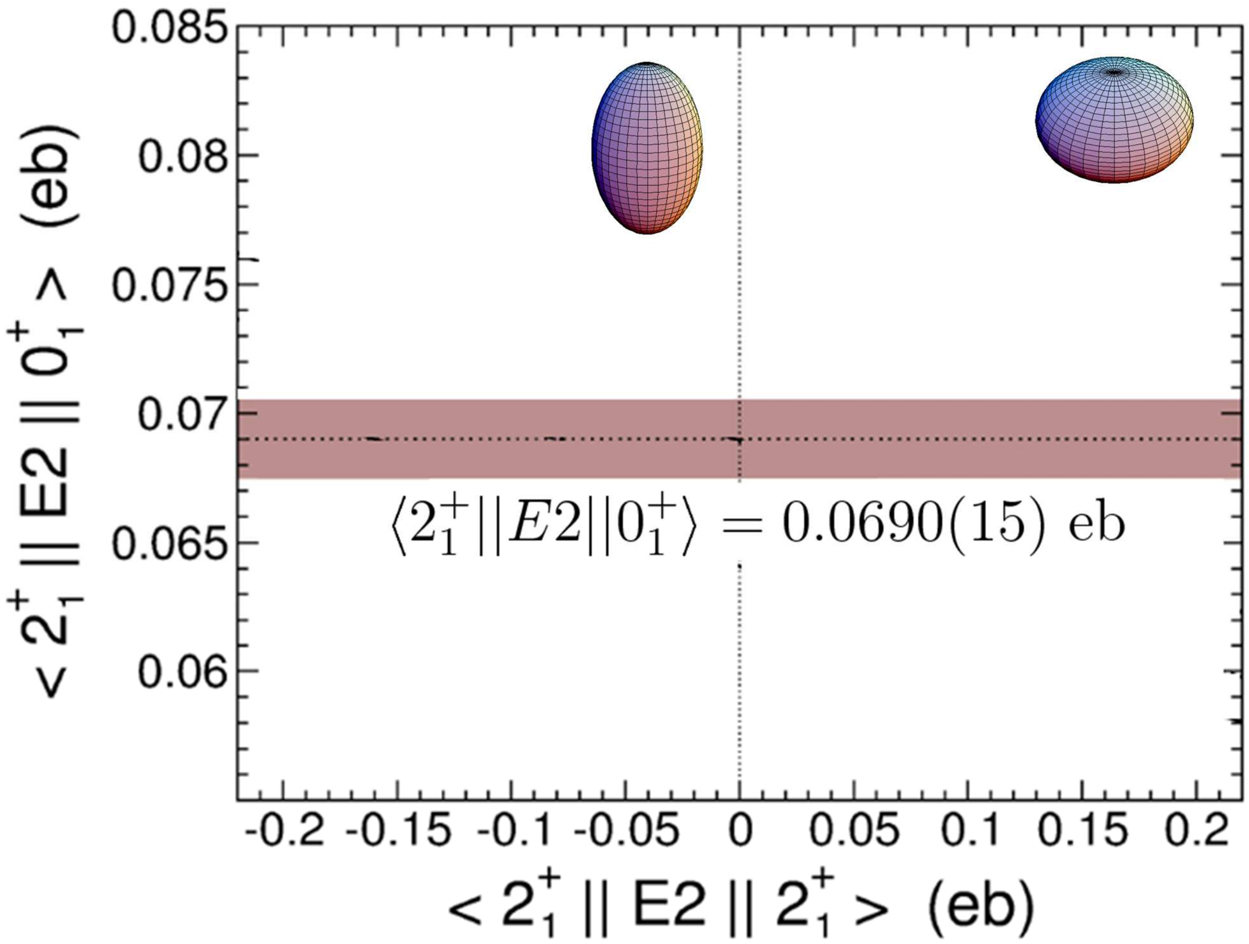


Figure adapted from Nico Orce

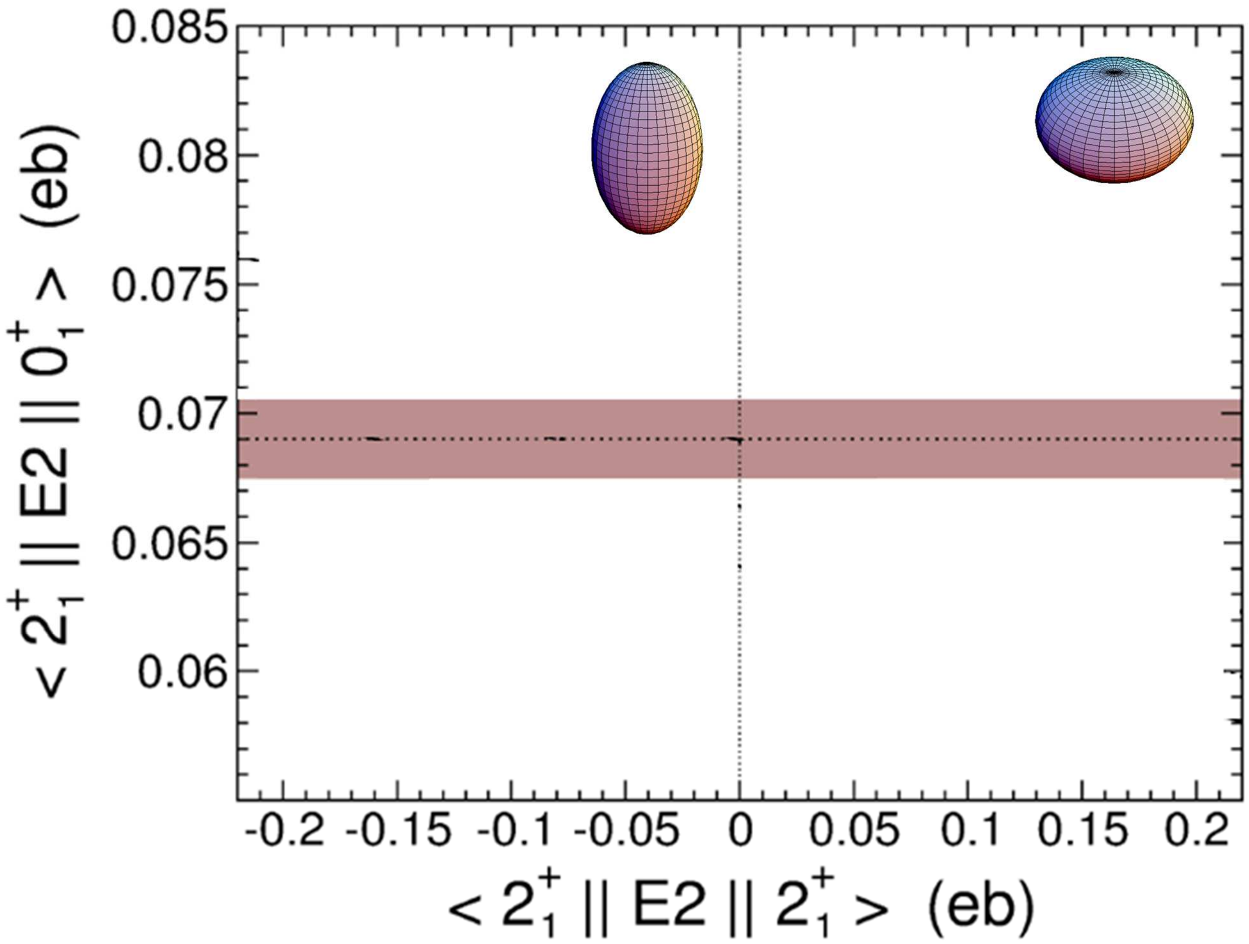
Doppler-corrected gamma-ray energy spectra in coincidence with inelastically scattered 10Be.

Coulomb Excitation Analysis



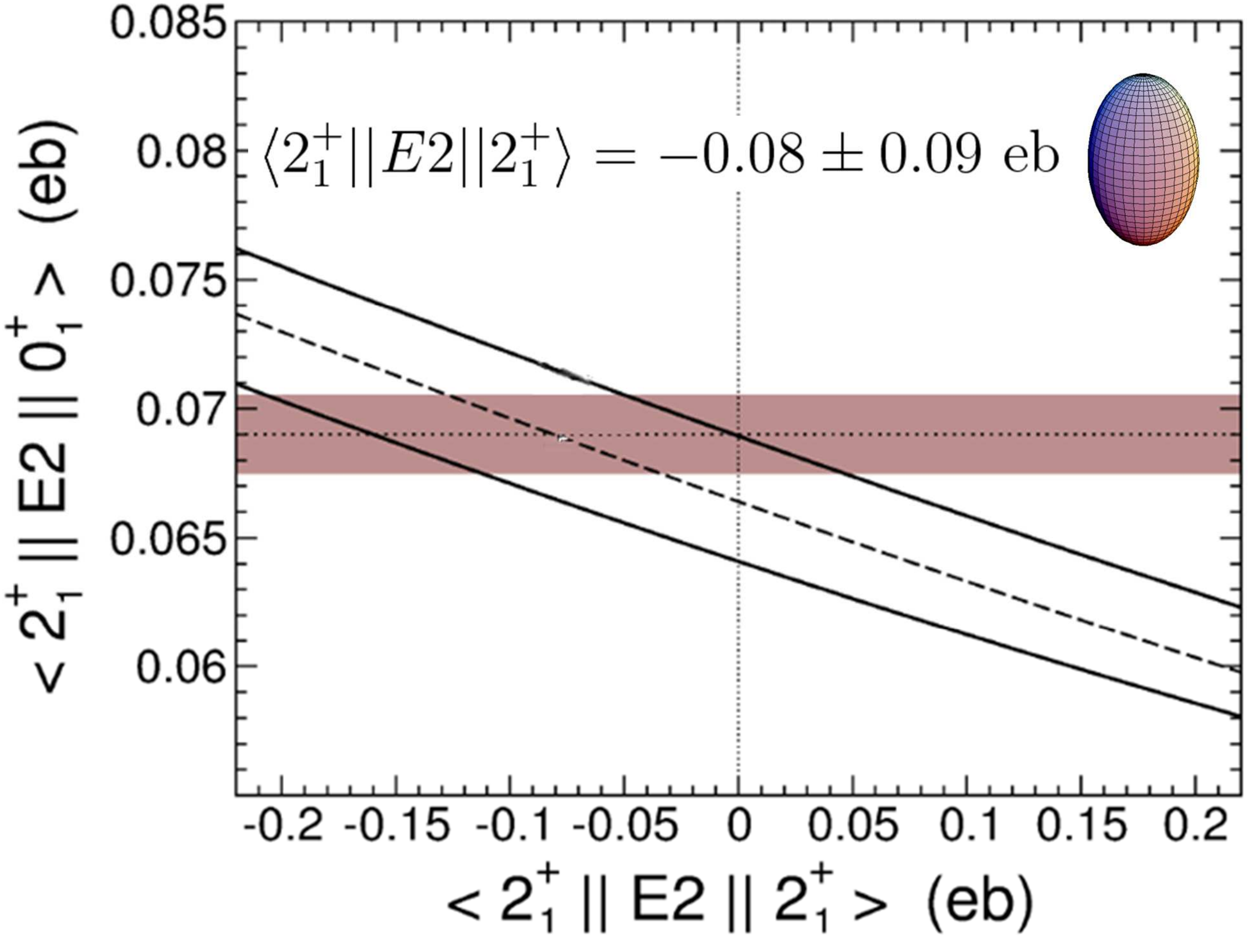
E.A. McCutchan et al., PRL 103, 192501 (2009).
E.K. Warburton et al., Phys. Rev. **148**, 1072 (1966).
T.R. Fisher et al., Phys. Rev. **176**, 1130 (1968).

Coulomb Excitation Analysis

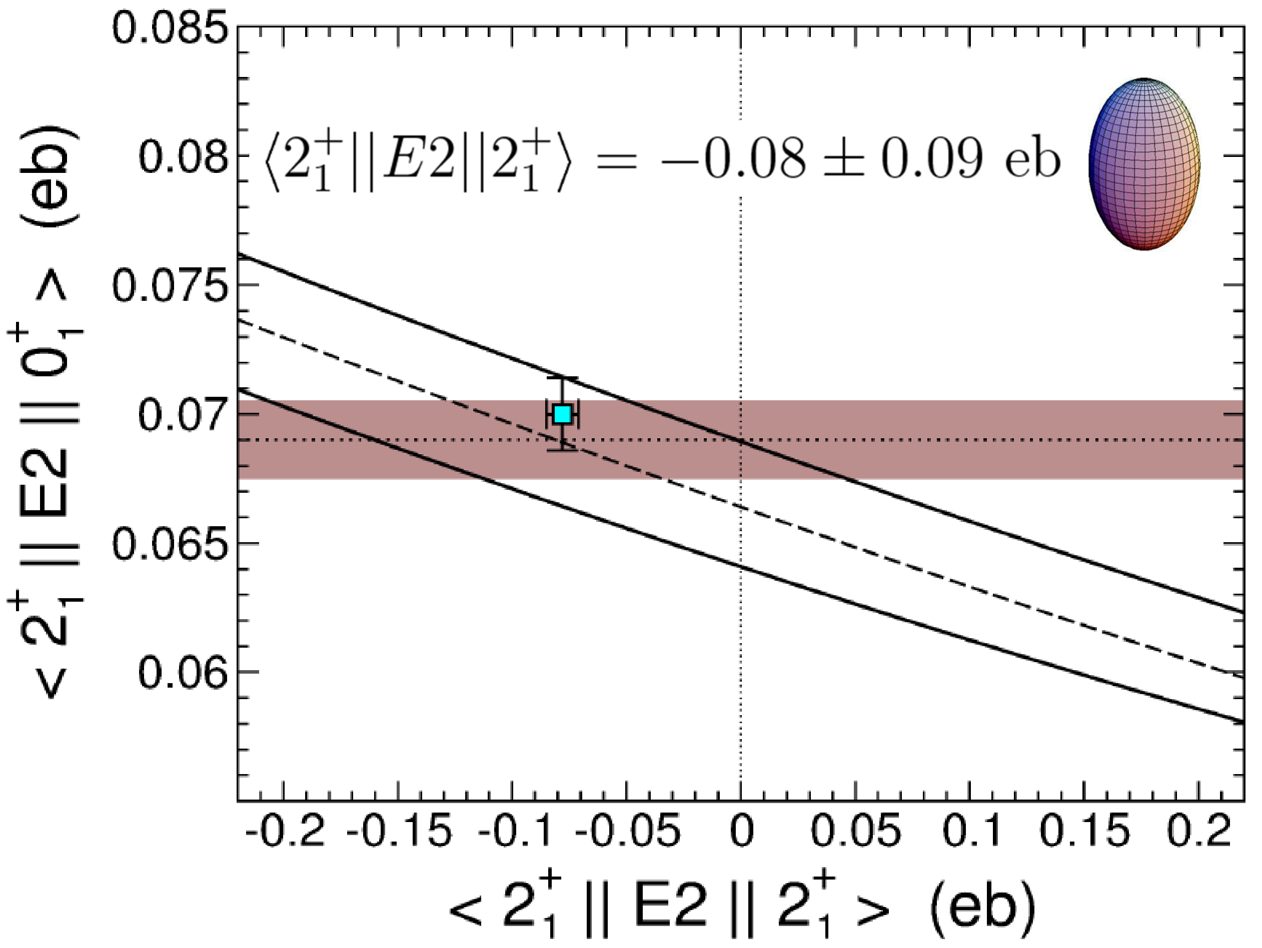


$$P_{0_1^+ \to 2_1^+} \propto B(E2; 0_1^+ \to 2_2^+)[1 + \alpha Q(2_1^+)]$$

Coulomb Excitation Analysis

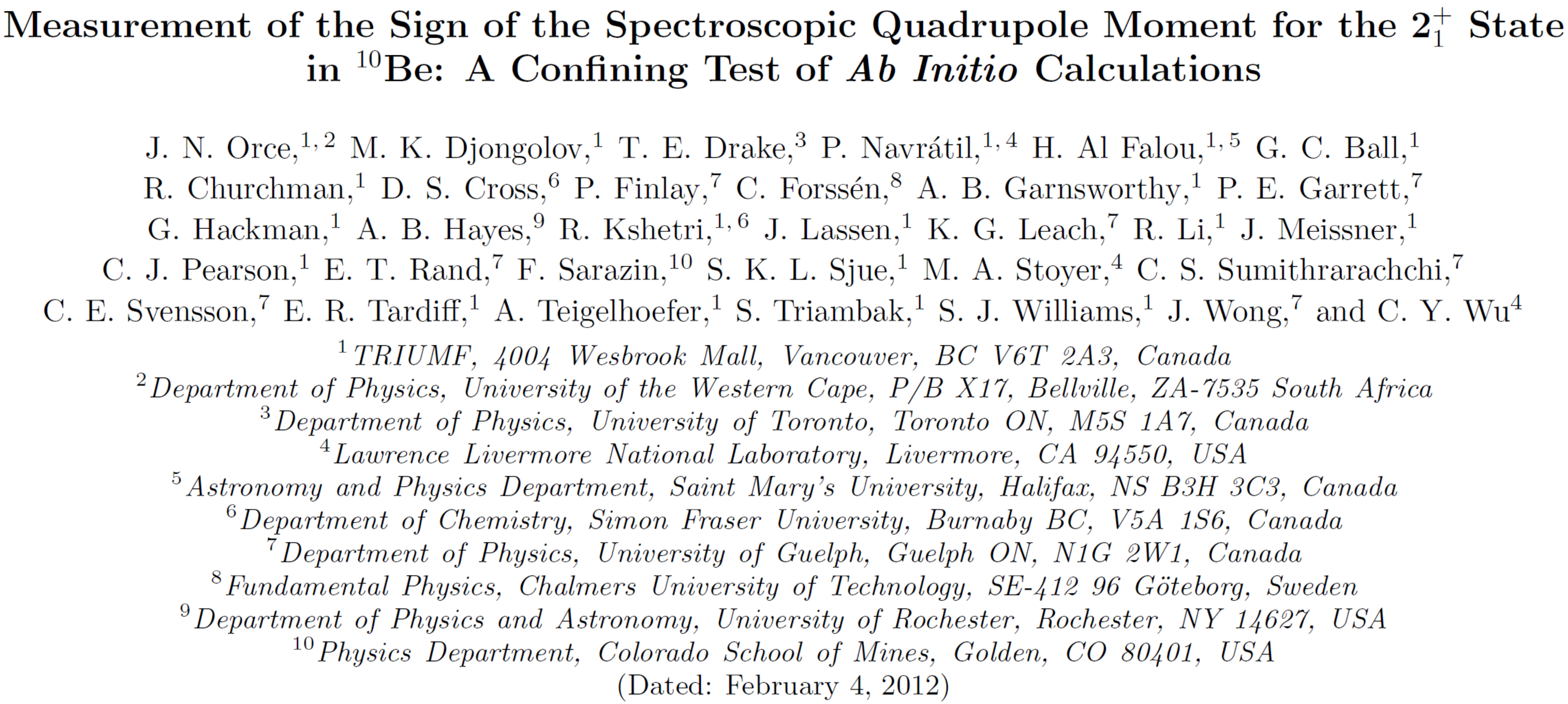


Coulomb Excitation Analysis



Result in excellent agreement with *2N* NCSM and *3N* GFMC *ab initio* calculations.

The ^{10}Be Collaboration



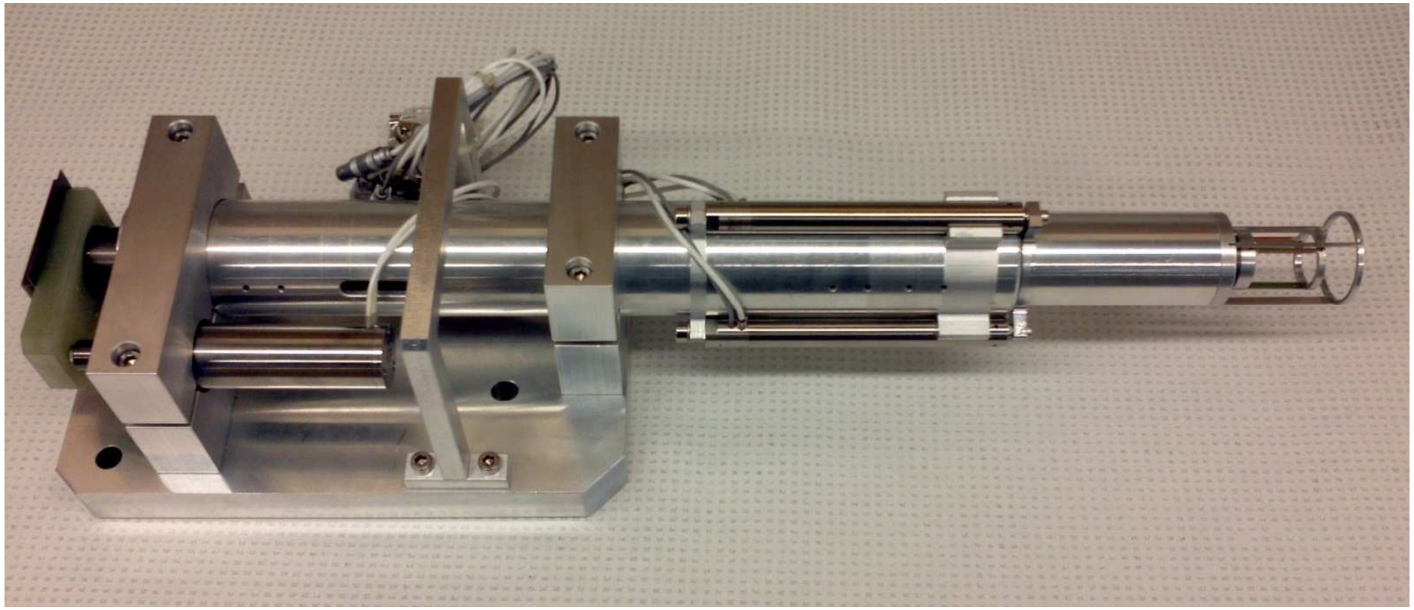
Measurement of the Sign of the Spectroscopic Quadrupole Moment for the 2_1^+ State in ^{10}Be: A Confining Test of *Ab Initio* Calculations

J. N. Orce,[1,2] M. K. Djongolov,[1] T. E. Drake,[3] P. Navrátil,[1,4] H. Al Falou,[1,5] G. C. Ball,[1]
R. Churchman,[1] D. S. Cross,[6] P. Finlay,[7] C. Forssén,[8] A. B. Garnsworthy,[1] P. E. Garrett,[7]
G. Hackman,[1] A. B. Hayes,[9] R. Kshetri,[1,6] J. Lassen,[1] K. G. Leach,[7] R. Li,[1] J. Meissner,[1]
C. J. Pearson,[1] E. T. Rand,[7] F. Sarazin,[10] S. K. L. Sjue,[1] M. A. Stoyer,[4] C. S. Sumithrarachchi,[7]
C. E. Svensson,[7] E. R. Tardiff,[1] A. Teigelhoefer,[1] S. Triambak,[1] S. J. Williams,[1] J. Wong,[7] and C. Y. Wu[4]

[1] *TRIUMF, 4004 Wesbrook Mall, Vancouver, BC V6T 2A3, Canada*
[2] *Department of Physics, University of the Western Cape, P/B X17, Bellville, ZA-7535 South Africa*
[3] *Department of Physics, University of Toronto, Toronto ON, M5S 1A7, Canada*
[4] *Lawrence Livermore National Laboratory, Livermore, CA 94550, USA*
[5] *Astronomy and Physics Department, Saint Mary's University, Halifax, NS B3H 3C3, Canada*
[6] *Department of Chemistry, Simon Fraser University, Burnaby BC, V5A 1S6, Canada*
[7] *Department of Physics, University of Guelph, Guelph ON, N1G 2W1, Canada*
[8] *Fundamental Physics, Chalmers University of Technology, SE-412 96 Göteborg, Sweden*
[9] *Department of Physics and Astronomy, University of Rochester, Rochester, NY 14627, USA*
[10] *Physics Department, Colorado School of Mines, Golden, CO 80401, USA*

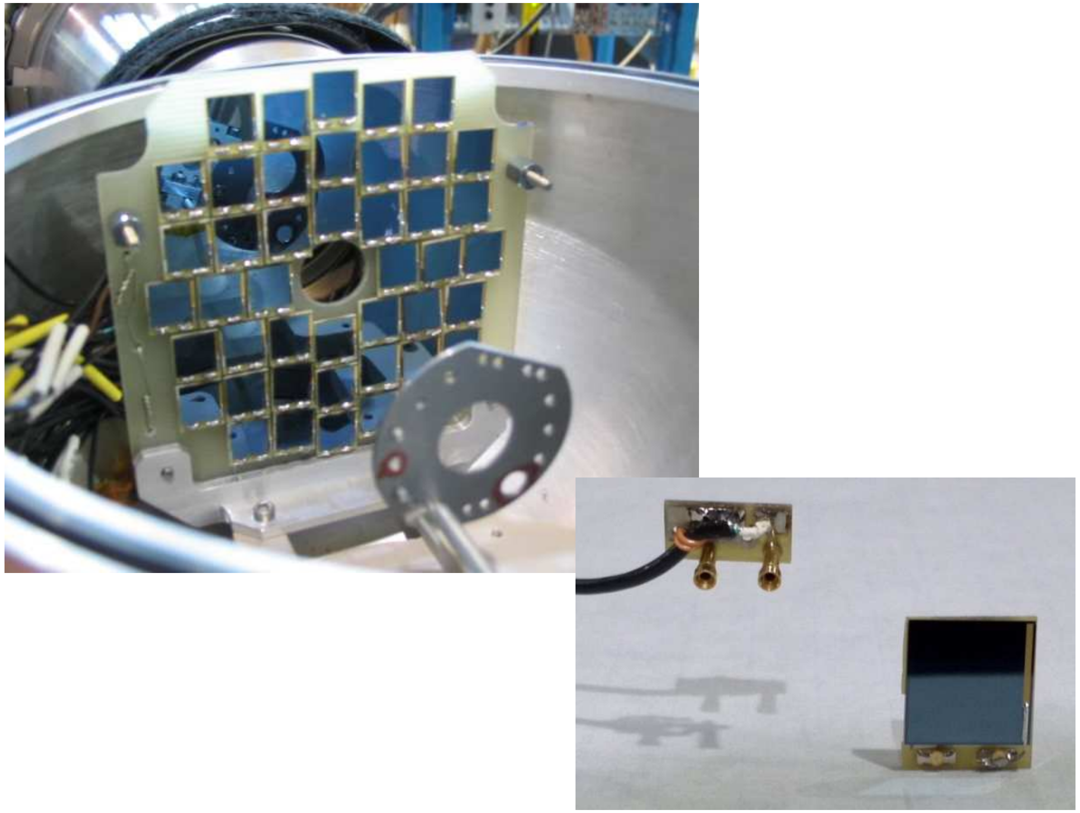
(Dated: February 4, 2012)

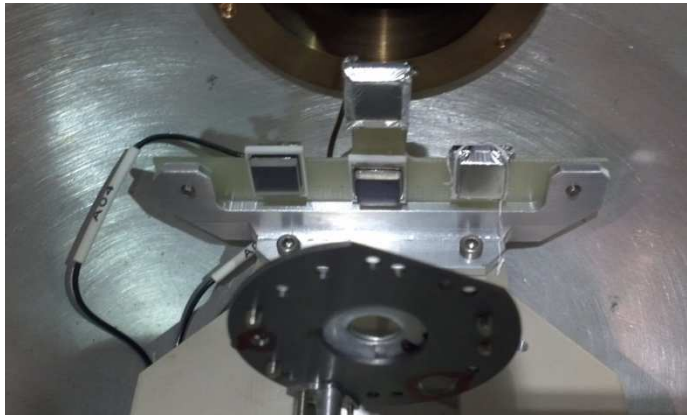
The TIGRESS Integrated Plunger



- TIP delivers a new experimental program at TRIUMF using accelerated beams from ISAC-II and variety of reaction mechanisms for studies of exotic nuclei.
- TIP offers unmatched flexibility for nuclear structure studies via lifetime and Coulomb excitation measurements.
- Recoiling nuclei travel at about 10 μm/ps (compared to 100 μm/ps at NSCL). Lifetime lower limit depends upon achieving the smallest target-stopper gap.

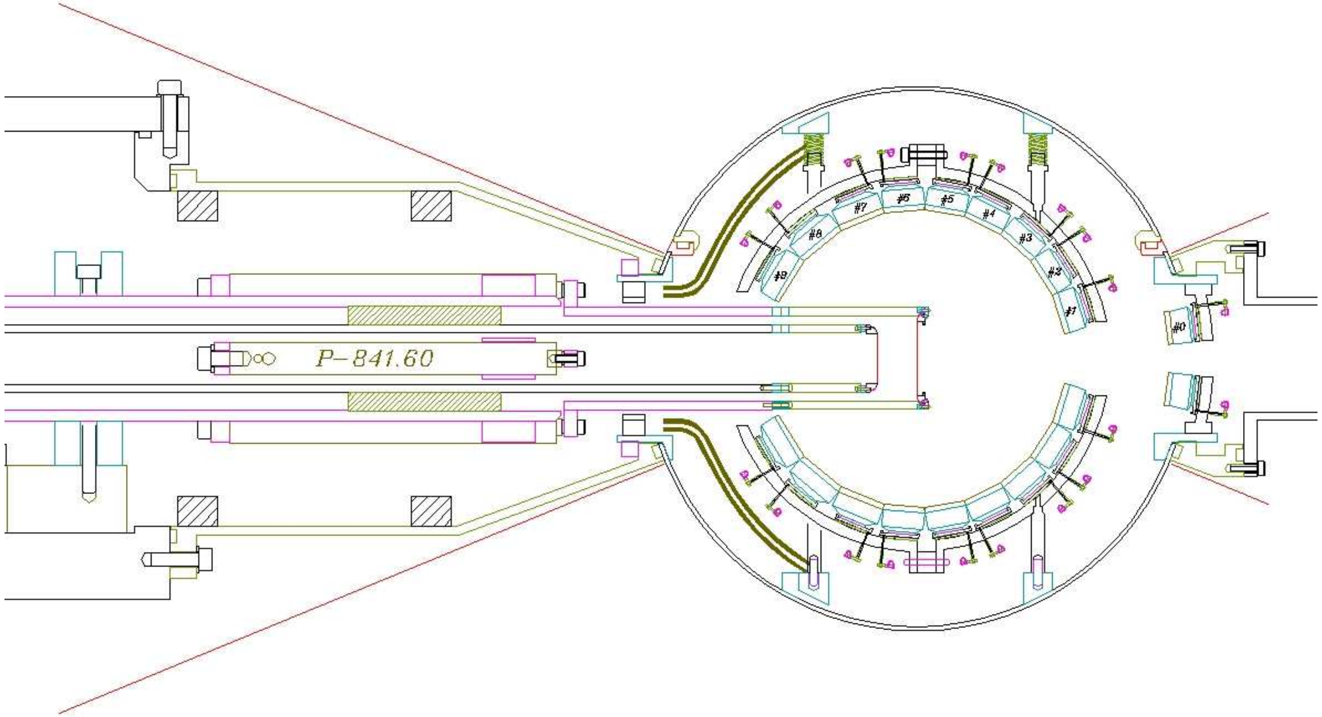
TIP Auxiliary Detector Systems





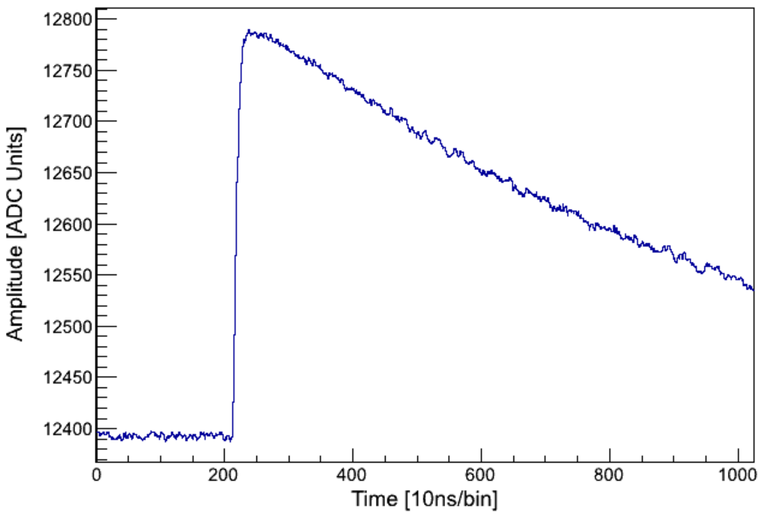
A suite of charged particle detectors has been developed for TIP, including a silicon S3 detector, a silicon PIN diode forward wall, and CsI crystals.

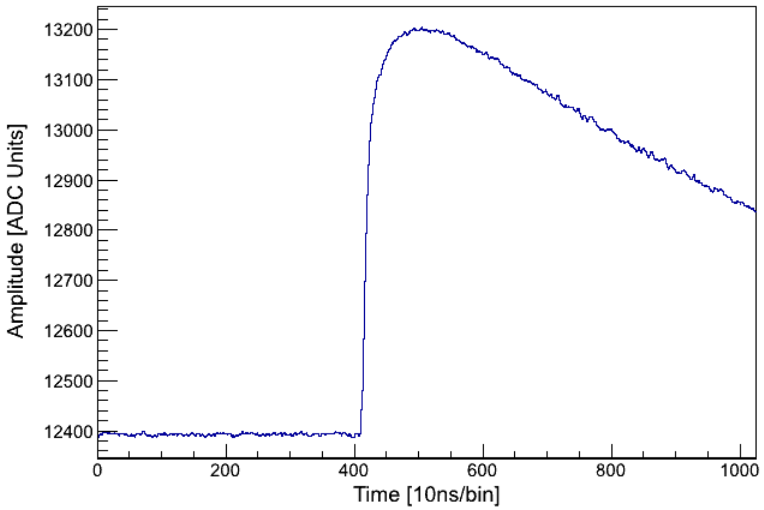
CsI(Tl) Ball for Charged-Particle Tagging



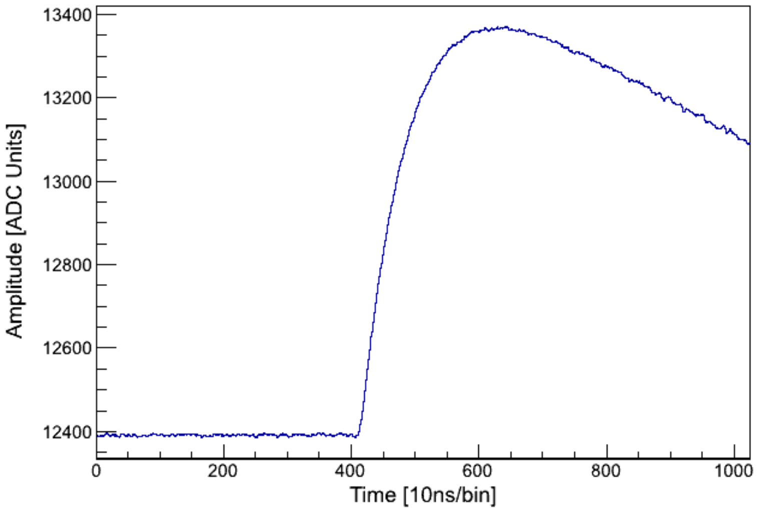
- Commissioning ^{40}Ca(^{36}Ar, 2α)^{68}Se lifetime measurement will use fusion-evaporation reactions.
- Radiation-hard 3π CsI(Tl) scintillator array necessary for reaction channel selection.

$^{40}\mathrm{Ca}(^{36}\mathrm{Ar}, 2\alpha)^{68}\mathrm{Se}$ CsI Pulse Shape Analysis





Preliminary CsI waveform spectra demonstrating particle identification sensitivity.



Summary

- Electromagnetic transition rate measurements with radioactive beams play an important role in our understanding of the nucleus and provide stringent benchmark tests of nuclear models.
- Precision Coulomb excitation measurements with TIGRESS and BAMBINO together with lifetime measurements have demonstrated the capability of directly accessing the shape of nuclear charge distributions.
- The addition of TIP and its suite of charged particle detectors opens the door for precision lifetime measurements with radioactive beams at the ISAC-II facility at TRIUMF.

The TIP Collaboration

K. Starosta, C. Andreoiu, R. Austin, G. Ball, P. Garrett, G. Hackman, C. Svensson,
P. Voss, R. Ashley, A. Chester, D. Cross, J. Pore

The TIGRESS Collaboration

R. Henderson and the TRIUMF Detectors/Engineering Group

The SFU Science Machine and Electronics Shop

Funded by NSERC award SAPIN/371656-2010 and SAPEQ/390539-2010

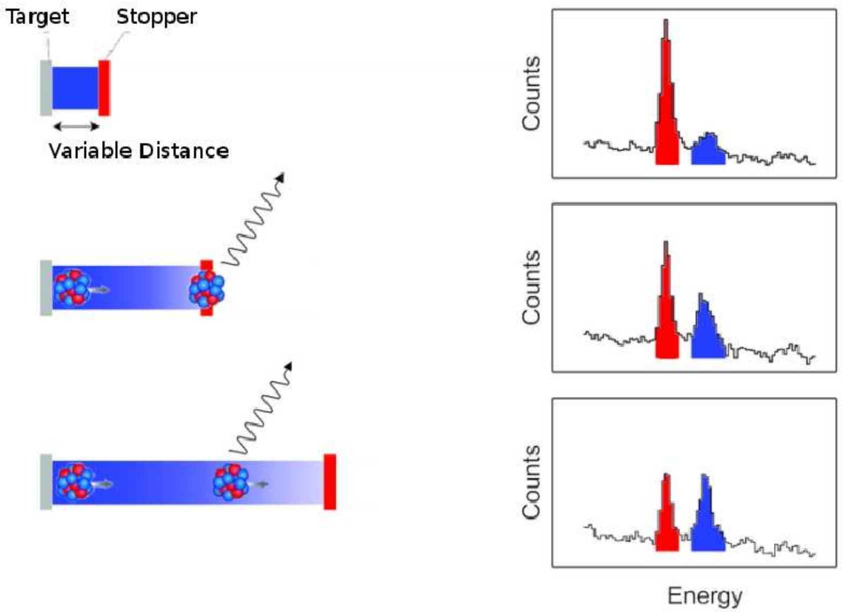
Thank you!

Merci!

Lifetime Measurements at TRIUMF

Recoiling nuclei travel at about 10 μm/ps (compared to 100 μm/ps at NSCL). Lifetime lower limit depends upon achieving the smallest target-stopper gap.

- Foil flatness and uniformity.
- Parallel-alignment and distance stability.
- Sensitive gap control mechanism.



^{10}Be + ^{194}Pt: Experimental Details

Laser-ionized $^{10}Be^{2+}$ radioactive beam properties:

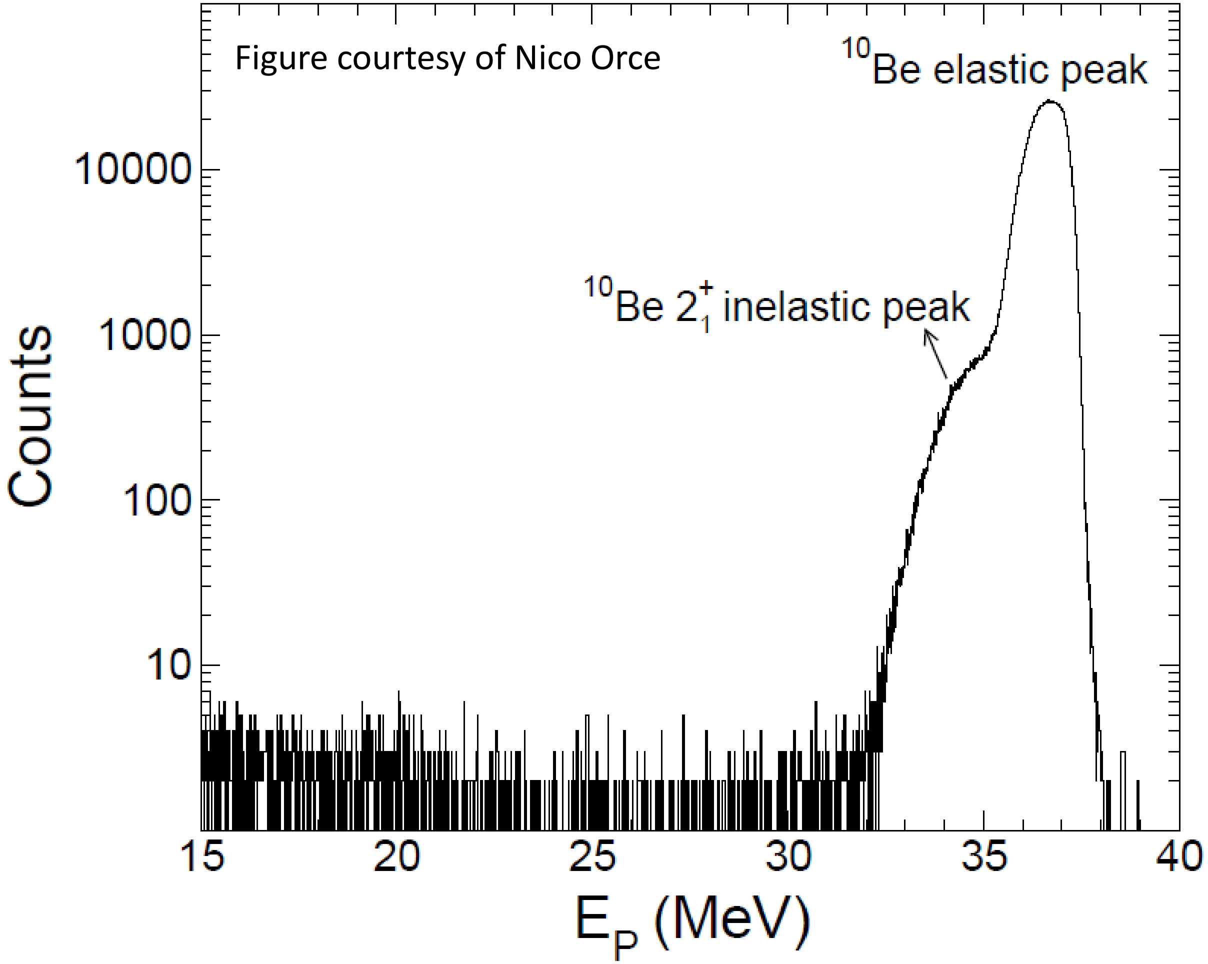
- Accelerated to final energy of 41 MeV
- Intensity on target of approximately 10^7 ions per second
- Beam on target for approximately 100 hours

^{194}Pt target with thickness of 3 mg/cm^2

TIGRESS array properties:

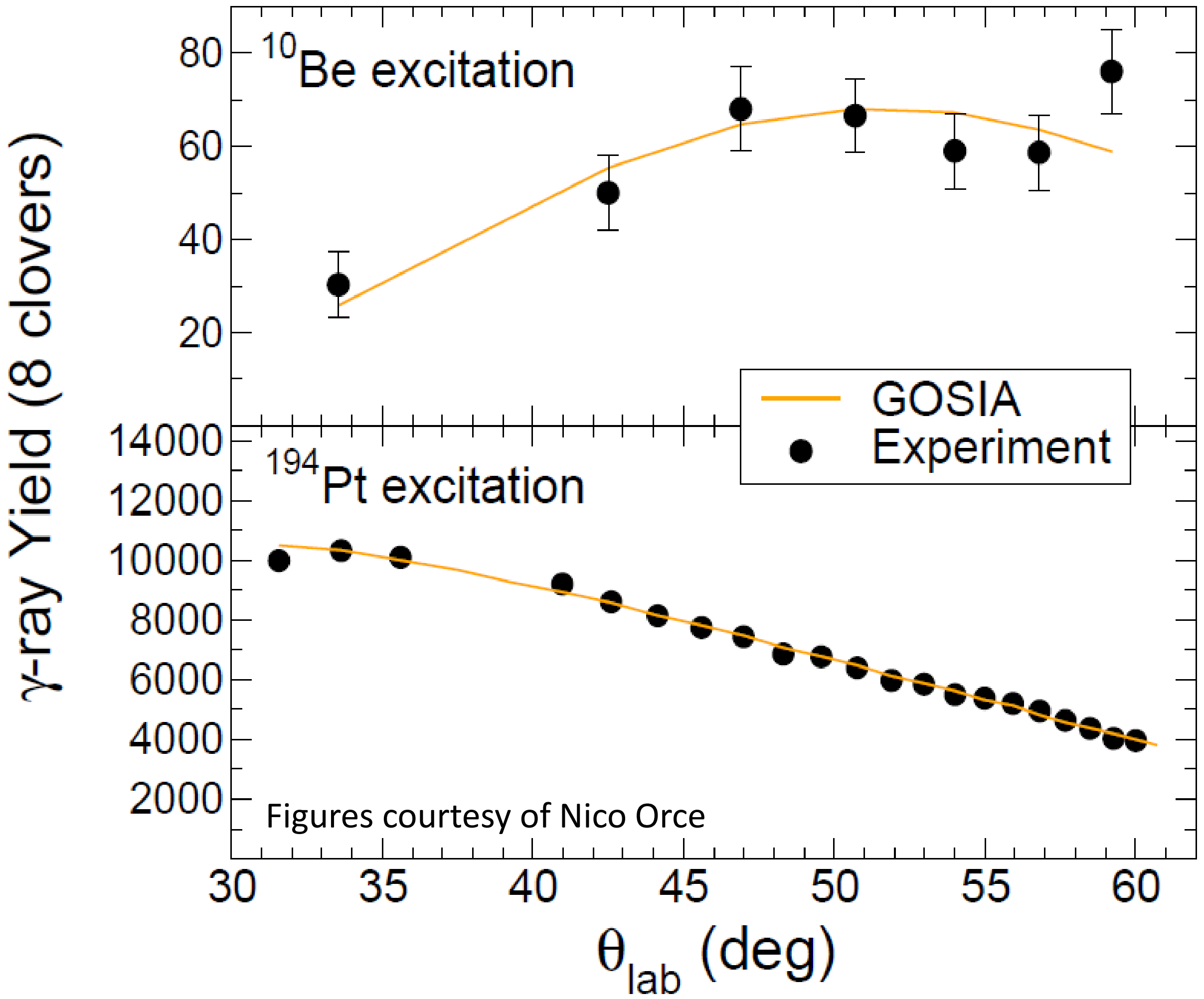
- Eight clovers were used, full Compton suppression
- 9.0% gamma-ray efficiency at the 328 keV excitation energy of ^{194}Pt
- 2.5% gamma-ray efficiency at the 3368 keV excitation energy of ^{10}Be

^{194}Pt(^{10}Be, ^{10}Be*)^{194}Pt* Particle Energy Spectrum



^{10}Be elastic and inelastic scattering peaks detected by BAMBINO.

Coulomb Excitation Analysis



Figures courtesy of Nico Orce

Measured gamma-ray yields well reproduced with GOSIA.

^{10}Be Quadrupole Moment Calculations

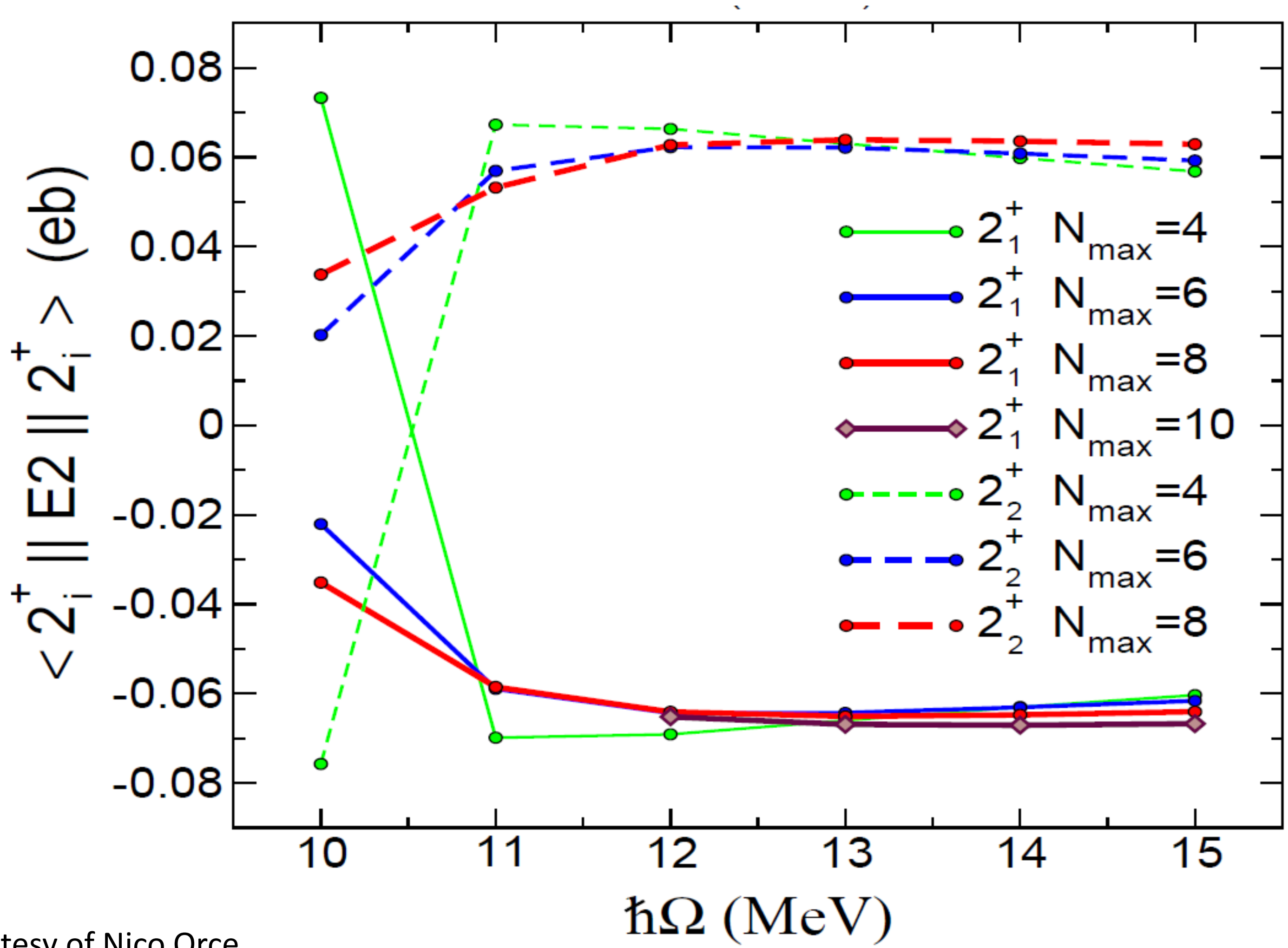
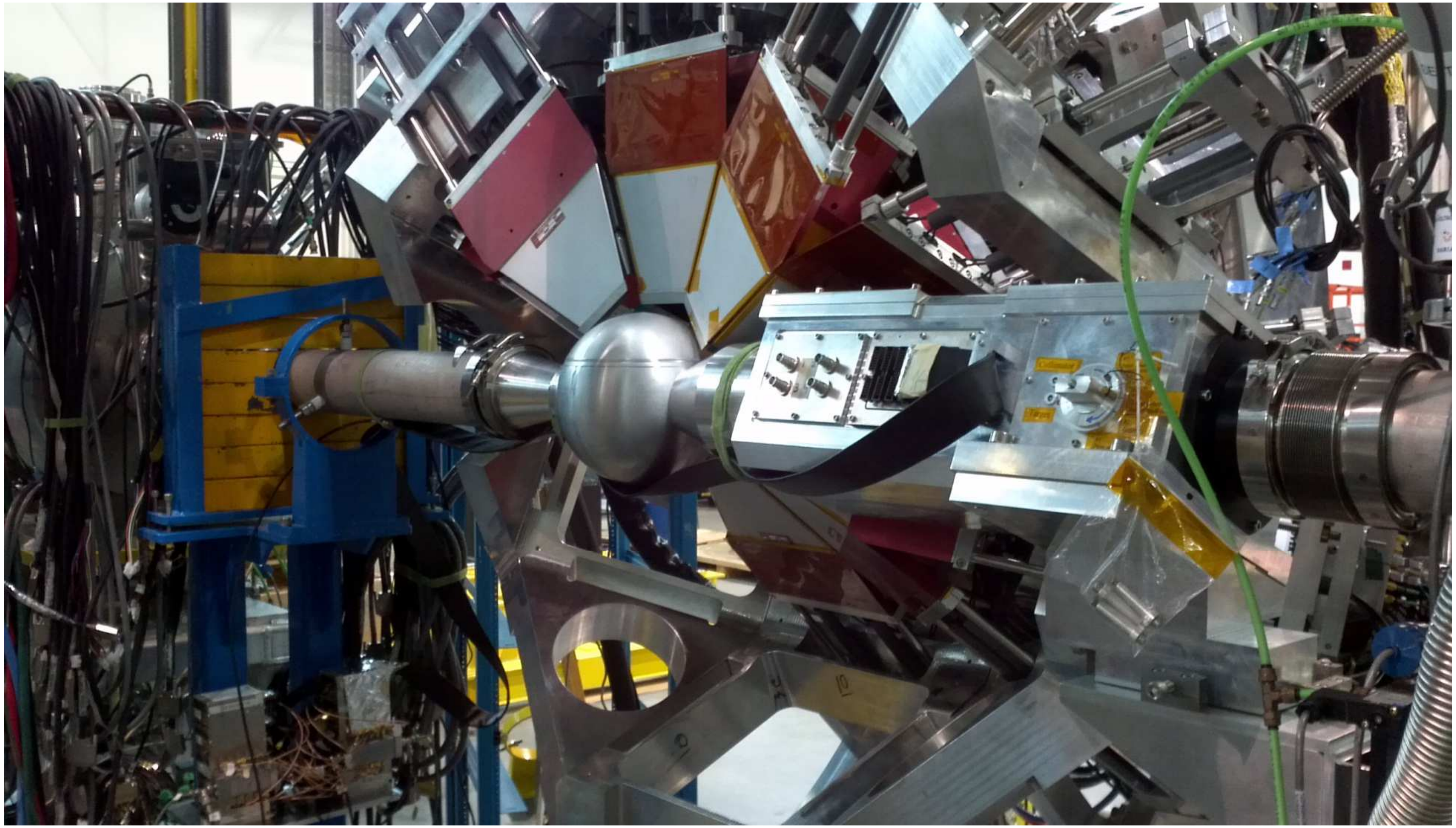
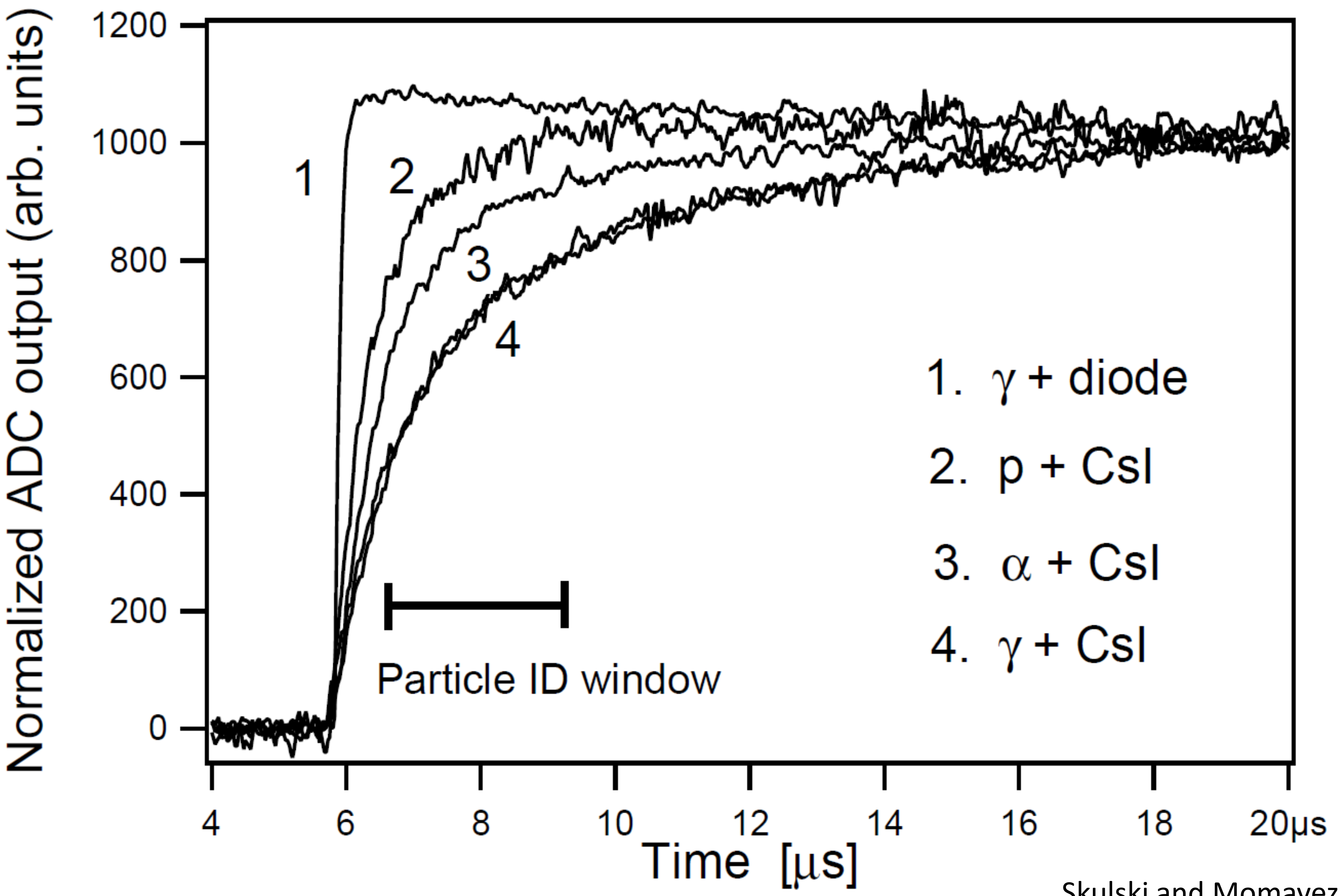


Figure courtesy of Nico Orce

The TIGRESS Integrated Plunger

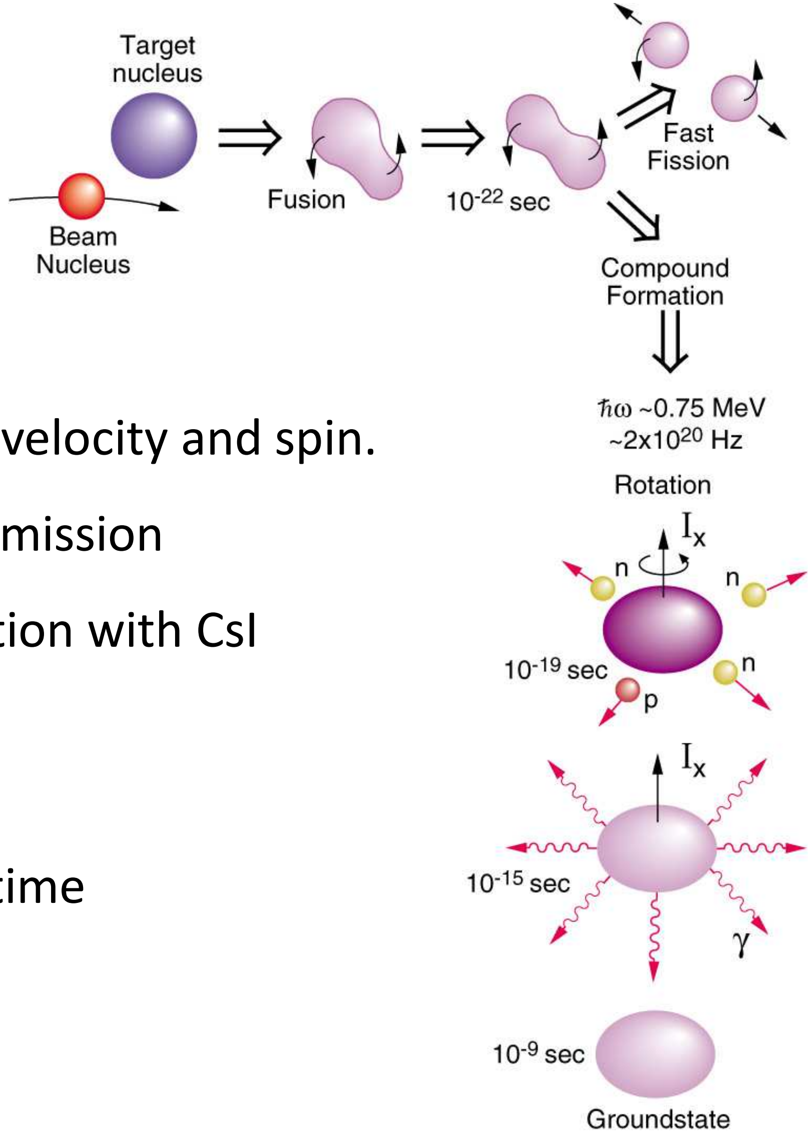


CsI(Tl) Ball: Pulse Shape Analysis



Skulski and Momayezi

Fusion-Evaporation Reactions with TIP



Formation of compound nucleus with high recoil velocity and spin.

Decay to ground state proceeds first by particle emission

- Charged particle detection and identification with CsI array.

And then by gamma-ray emission

- Detection by TIGRESS. DSAM or RDM lifetime measurements can proceed.

Importance of ^{68}Se

Model	Shell Model	Interacting Boson Model	Hartree-Bogoliubov	Self-consistent Collective Coordinate		Vampire
Reference	[1]	[2]	[3]	[4](a)	[4](b)	[5]
$B(E2,2_1^+ \rightarrow 0_1^+)$ [e^2fm^4]	100	280	500	725	834	1048

[1] M. Hasegawa, et. al., Phys. Lett. B 656, 51 (2007).

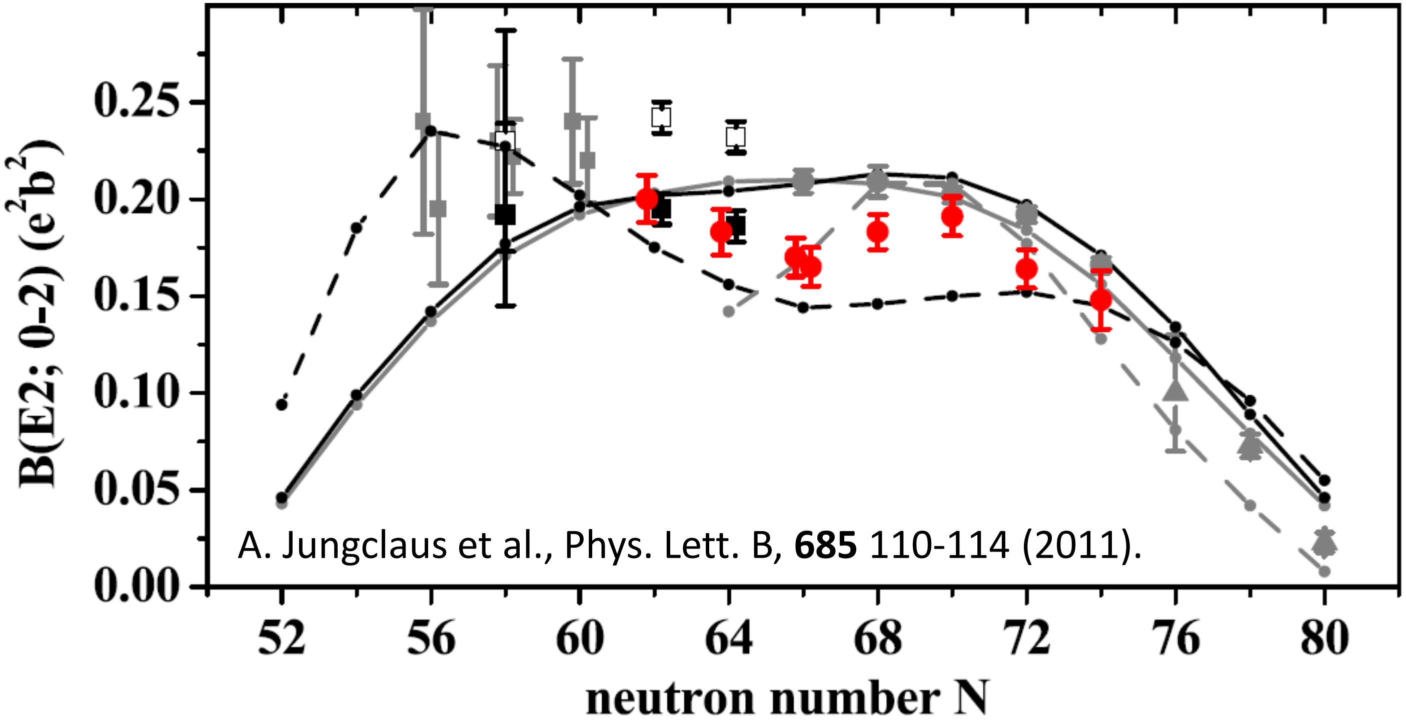
[2] F. Il. Khudair, Y. S. Li, G. L. Long, Phys. Rev. C 75 054316 (2007).

[3] T. A. War et. al., Eur. Phys. J. A 22, 13 (2004).

[4] N. Hinohara et. al., Prog. Theor. Phys. (Kyoto) 119, 59 (2008).

[5] A. Petrovici et. al., Nucl. Phys. A 710, 246 (2002).

Reduced Collectivity in Light Stable Sn



A. Jungclaus et al., Phys. Lett. B, **685** 110-114 (2011).

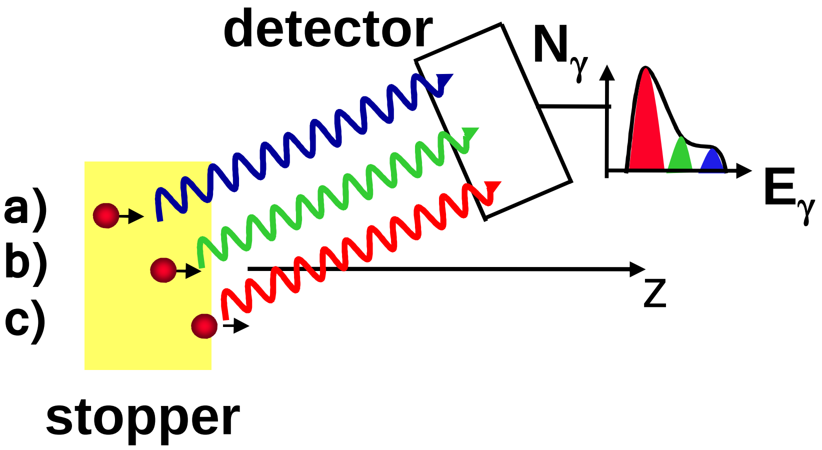
New reported *B(E2)* values in stable even-even tin isotopes (red) present a clear discrepancy with previous measurements and significant revisions to data normalized by these results (black squares).

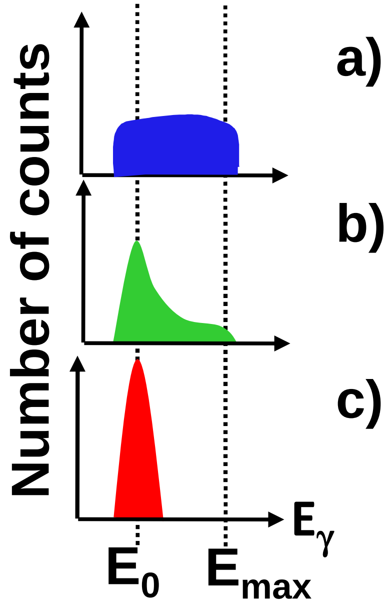
Reduced Collectivity in Light Stable Sn

TIP will address the experimental discrepancies in $^{112-118}$Sn using the complimentary approaches of sub-barrier Coulomb excitation and lifetime studies.

- For proper kinematic reconstruction and event-by-event Doppler correction to obtain the Coulex cross section and thus the *B(E2)* value.
- To separate contaminant Coulomb excitation within the heavy DSAM stopping material via light target recoil detection in coincidence with gamma rays.

Doppler Shift Attenuation Method





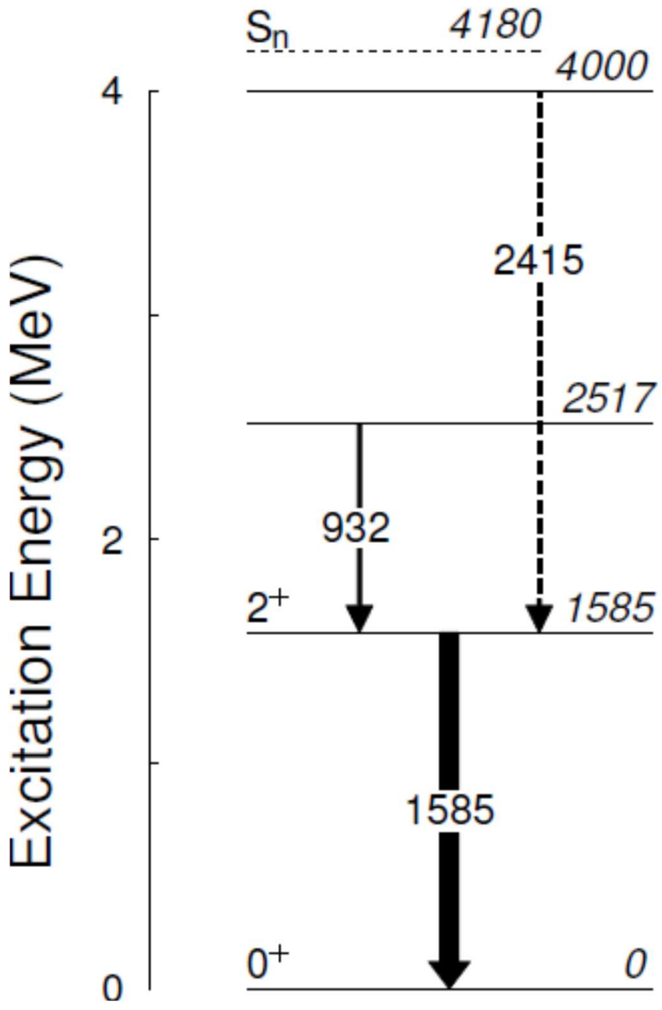
a) Fully shifted
$\tau < t_{stopping}$

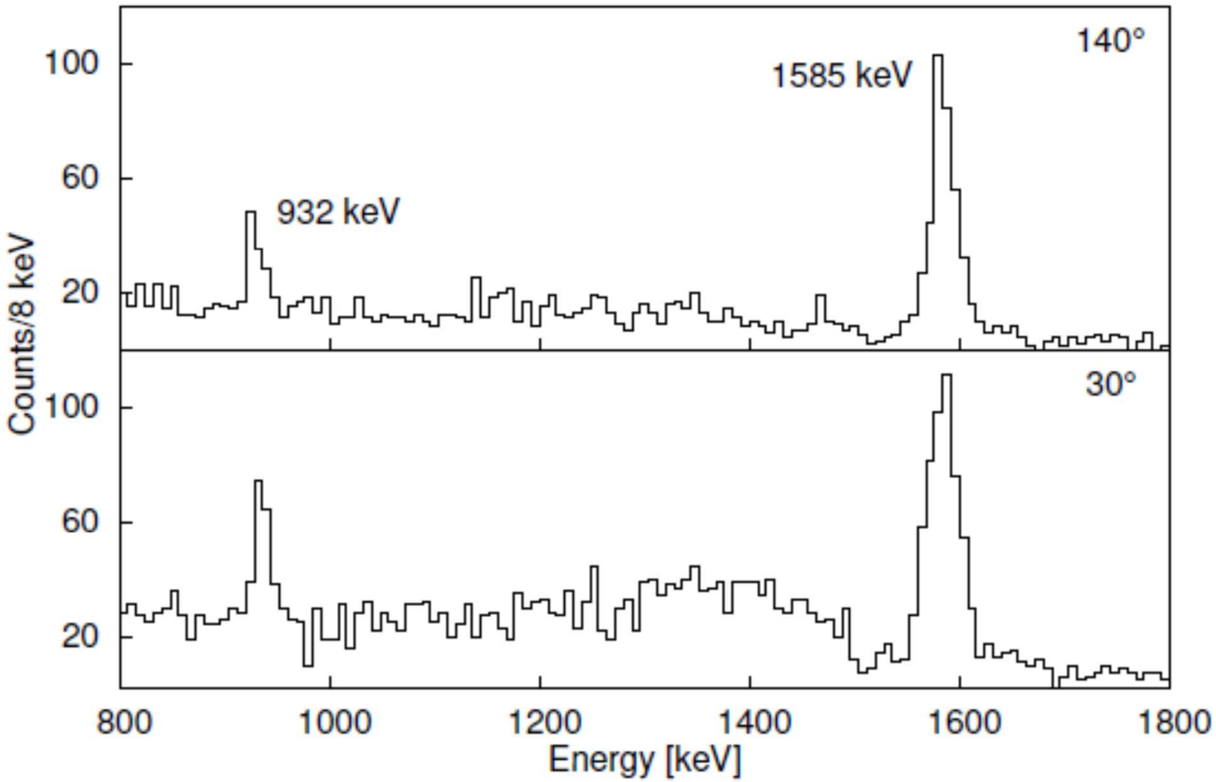
b) Partially shifted
$\tau \approx t_{stopping}$

c) Fully stopped
$\tau > t_{stopping}$

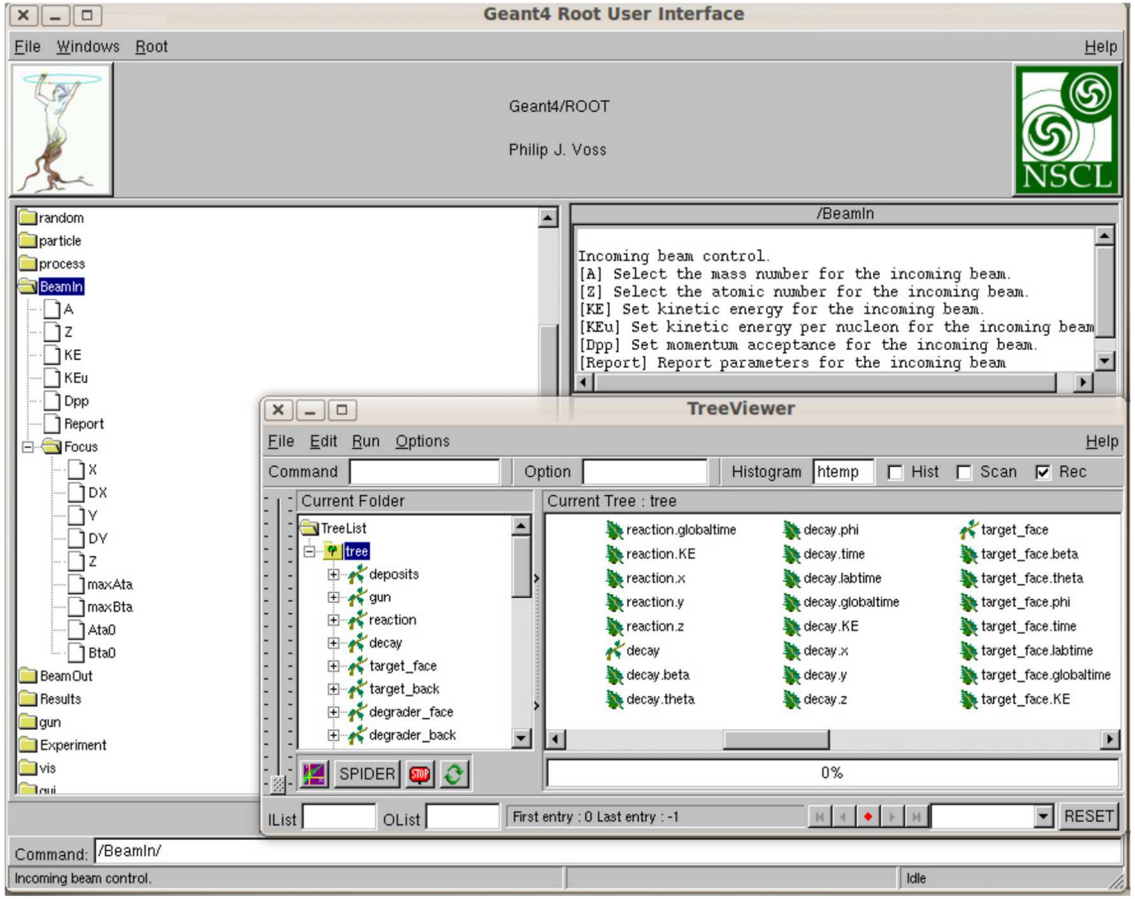
Adapted from Kris Starosta

^{18}C Observed Transitions and Level Scheme





Geant4/ROOT Simulations



```
Incoming beam control.
[A] Select the mass number for the incoming beam.
[Z] Select the atomic number for the incoming beam.
[KE] Set kinetic energy for the incoming beam.
[KEu] Set kinetic energy per nucleon for the incoming beam
[Dpp] Set momentum acceptance for the incoming beam.
[Report] Report parameters for the incoming beam
```

Command: /BeamIn/

Incoming beam control.

Idle

Experimental Geometry

Incident Secondary Beam Properties

Knockout Reaction Kinematics

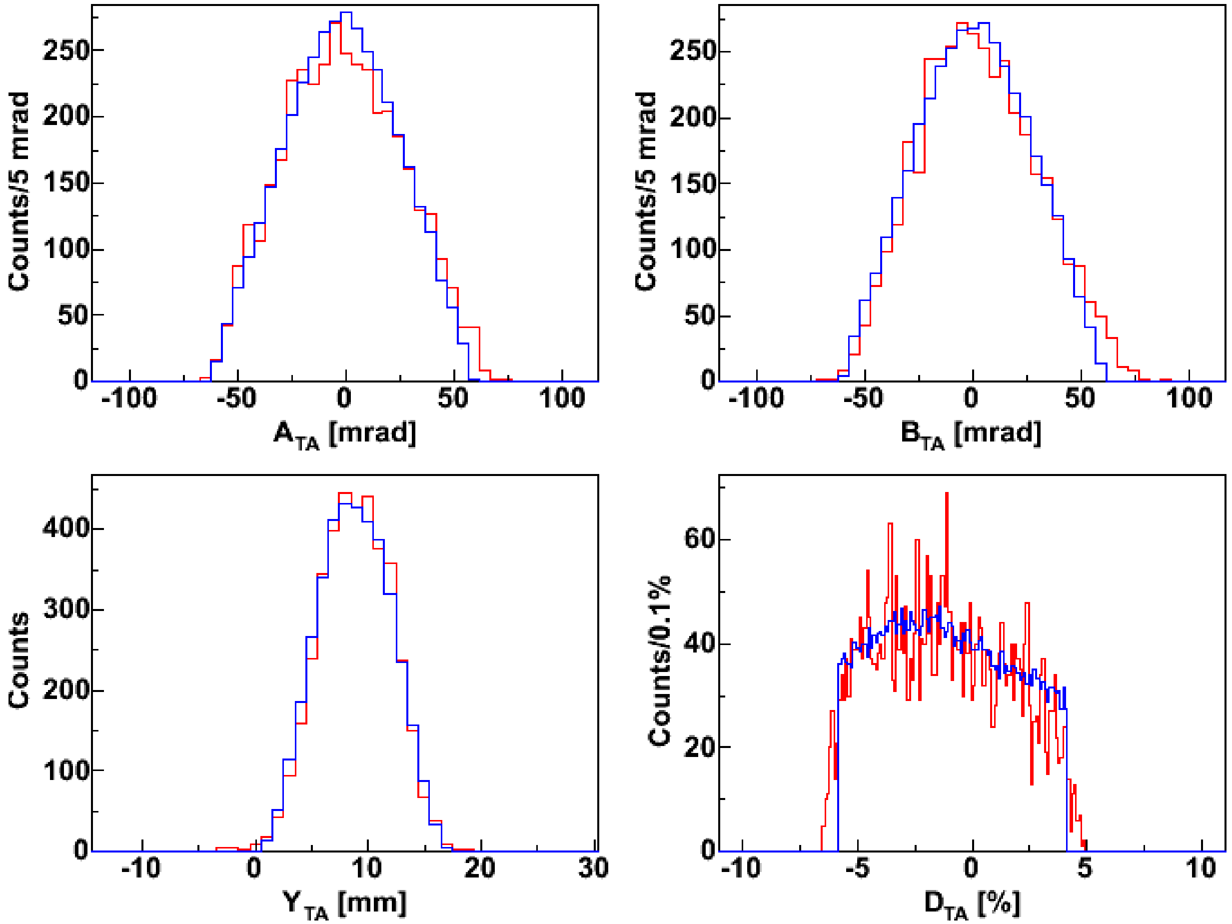
Gamma-Ray Decay Processes

Detector Response

Feeding Corrections

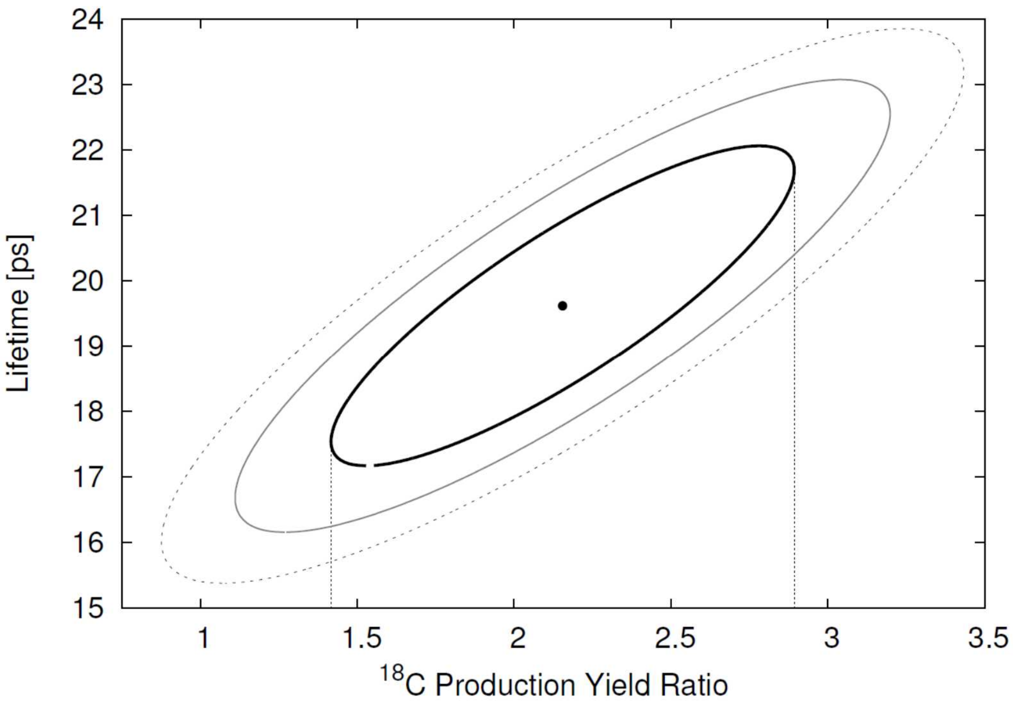
Constraint of Systematic Errors

One-Proton Knockout Reaction Simulations



Comparison of simulated (blue) and experimental (red) ^{18}C reaction residue parameters behind the degrader from the 1p knockout of ^{19}N.

^{18}C: Investigation of Systematic Errors



A two-variable χ^2 hypersurface fit to the data constrained the ^{18}C target-degrader reaction ratio (R_σ). An additional constraint was extracted from the 3.0 mm distance data.

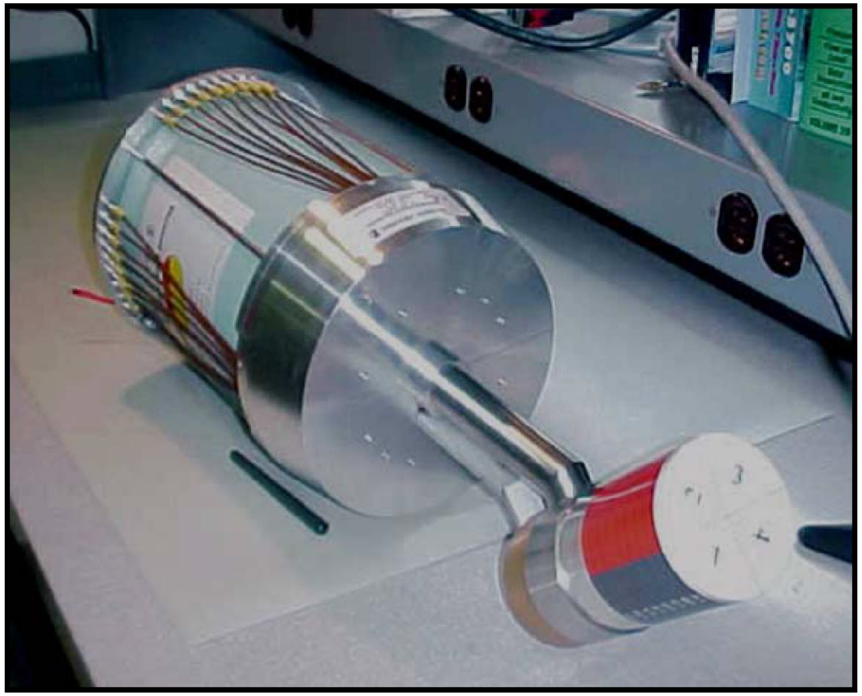
Lifetime scans using the upper and lower limits for R_σ yielded the systematic error.

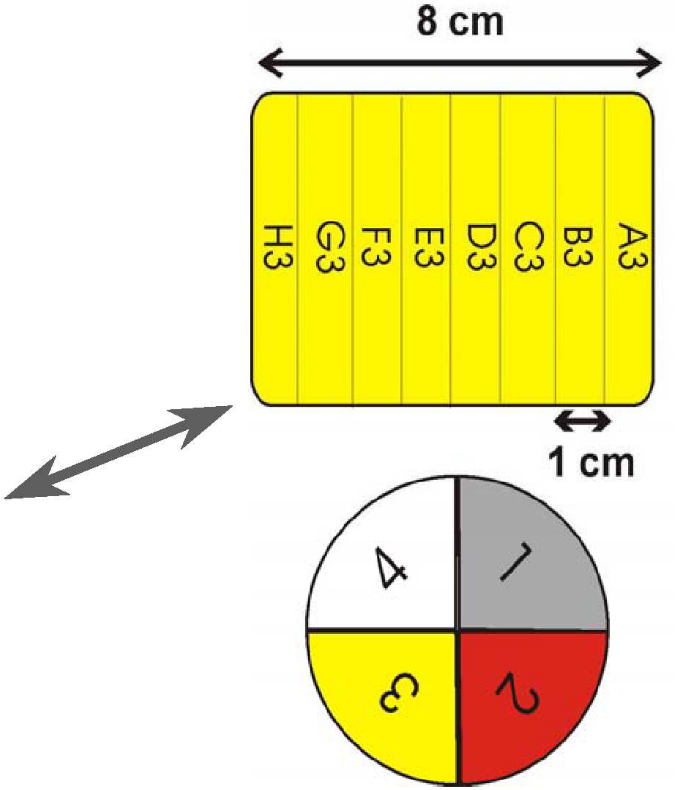
$$R_\sigma = 2.15^{+0.74}_{-0.34} \rightarrow 22.4^{+2.2}_{-1.1}(syst)ps$$

Uncertainties in the ^{18}C momentum distribution also introduced a symmetric systematic error of 1.1 ps. All other sources of error were found to be negligible.

$$\tau = 22.4 \pm 0.9(stat)^{+2.5}_{-1.6}(syst)ps$$

The Segmented Germanium Array





$E_{res} \approx 2.2\%$ after Doppler corrections

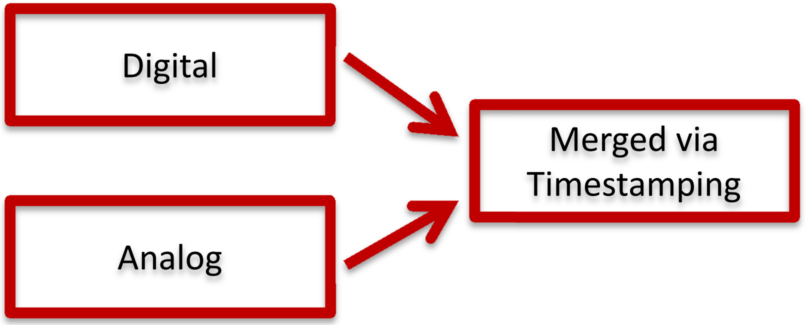
$\varepsilon \approx 2\%$ at 1.33 MeV

Digital Data Acquisition System

All 495 channels of Plunger SeGA were instrumented with DDAS, consisting of 4 Compact PCI/PXI crates and 39 Pixie-16 DGF Modules from XIA.

Individual waveforms of gamma-ray events were captured and stored on a 10 TB storage server, opening the door for pulse shape analysis investigations.

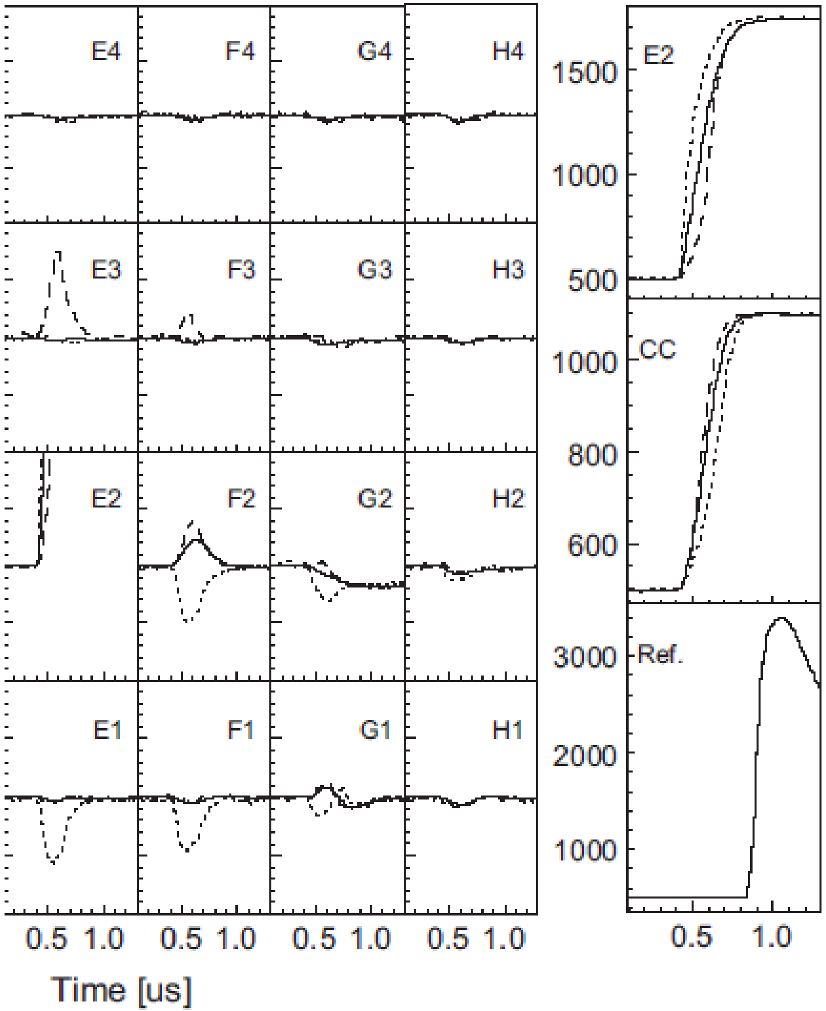
Energy and timing information were extracted and merged with the S800 analog data to fully reconstruct the event , providing near real-time analysis.

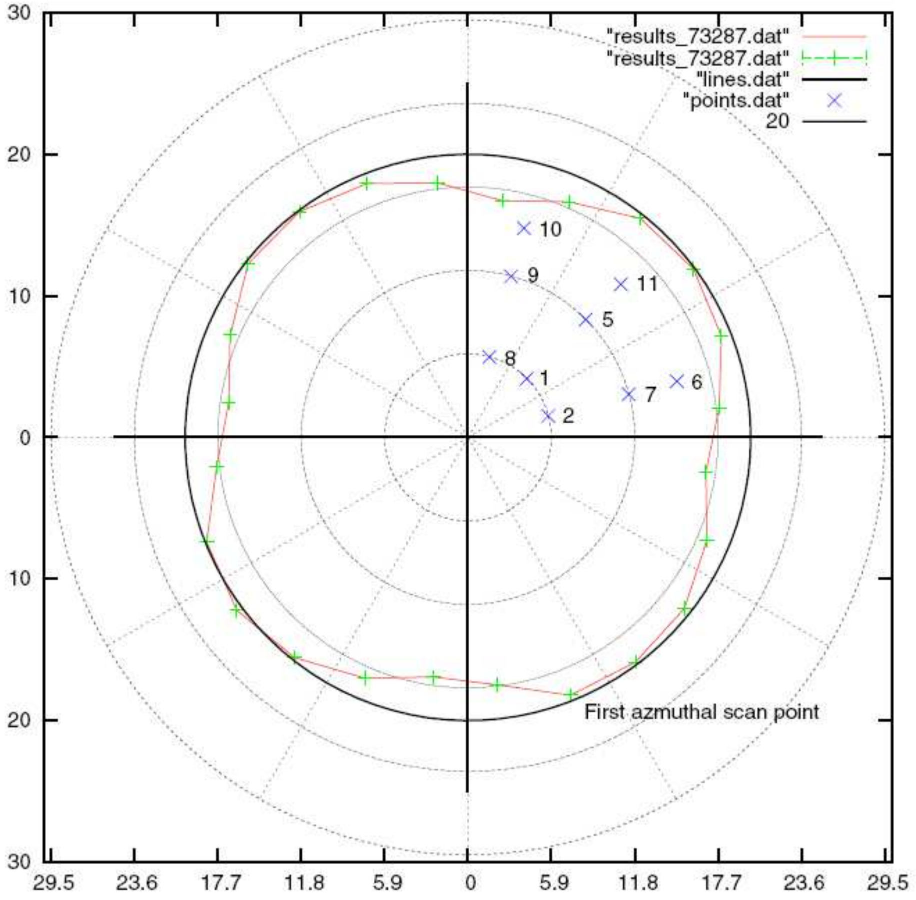

Digital

Analog

Merged via Timestamping

DDAS Pulse Shape Analysis





K. Starosta et al., NIM A **610**, 700 (2009).