Proposal to the ISOLDE and Neutron Time-of-Flight Committee
67th Meeting - 23/06/21

Measurement of the excitation energy of the 5^+ isomeric state in ^{128}Sb for *r*-process nucleosynthesis

Aaron Couture[1] and Lukas Nies[2,3] for the ISOLTRAP Collaboration
[1]Los Alamos National Laboratory, USA
[2]CERN, Switzerland
[3]University of Greifswald, Germany

Los Alamos NATIONAL LABORATORY
UNIVERSITÄT GREIFSWALD Wissen lockt. Seit 1456
ISOL TRAP
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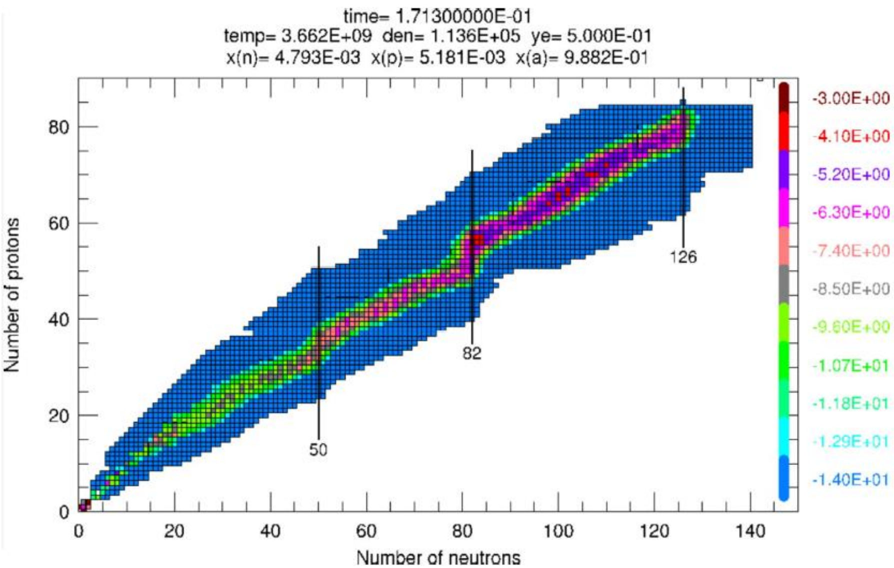
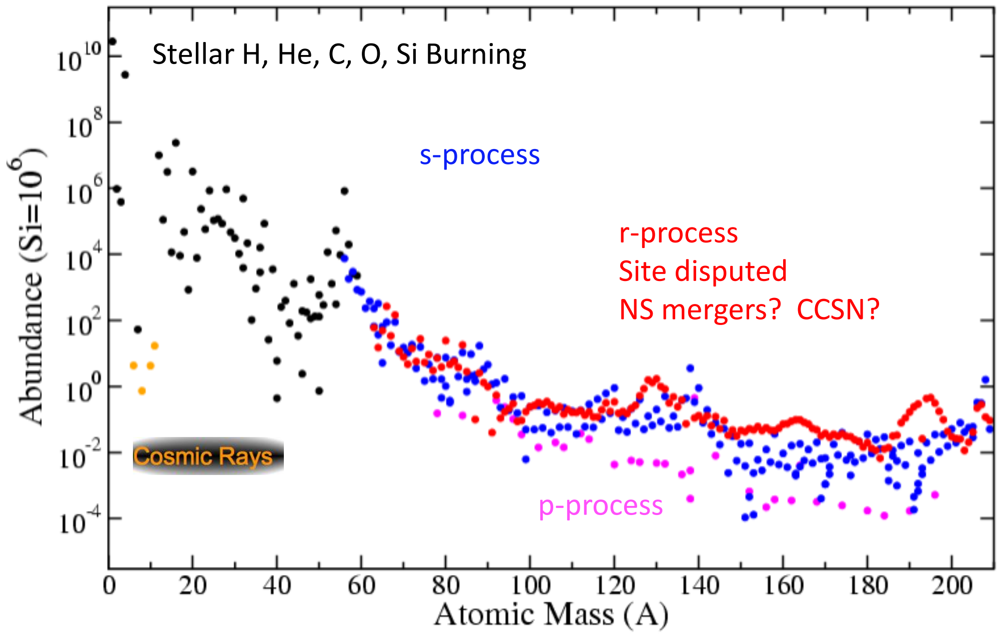
r-process Nucleosynthesis



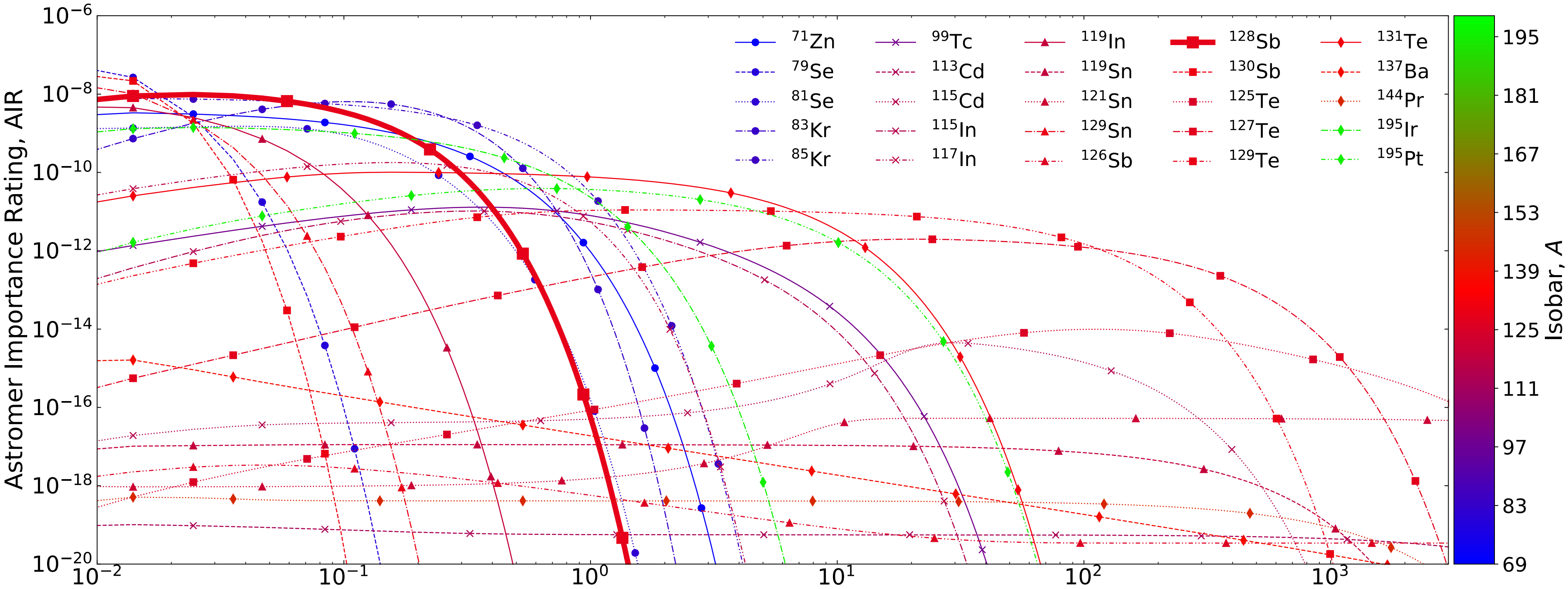
C. L. Fryer, 2009, *private communication*



Abundances and Attribution from Anders & Grevasse, 1989
And Käppeler and Wisshak, 1989

- Elements with Z>26 (Fe) are made through neutron capture processes
- The *r* process takes place *rapidly* (~1 sec) in a cataclysmic event over short timescales, likely far from stability
- After the event, the nuclei decay back to stability in an evolving thermodynamic environment
- A=128 is near one of the r-process peak distributions (the 2nd peak)

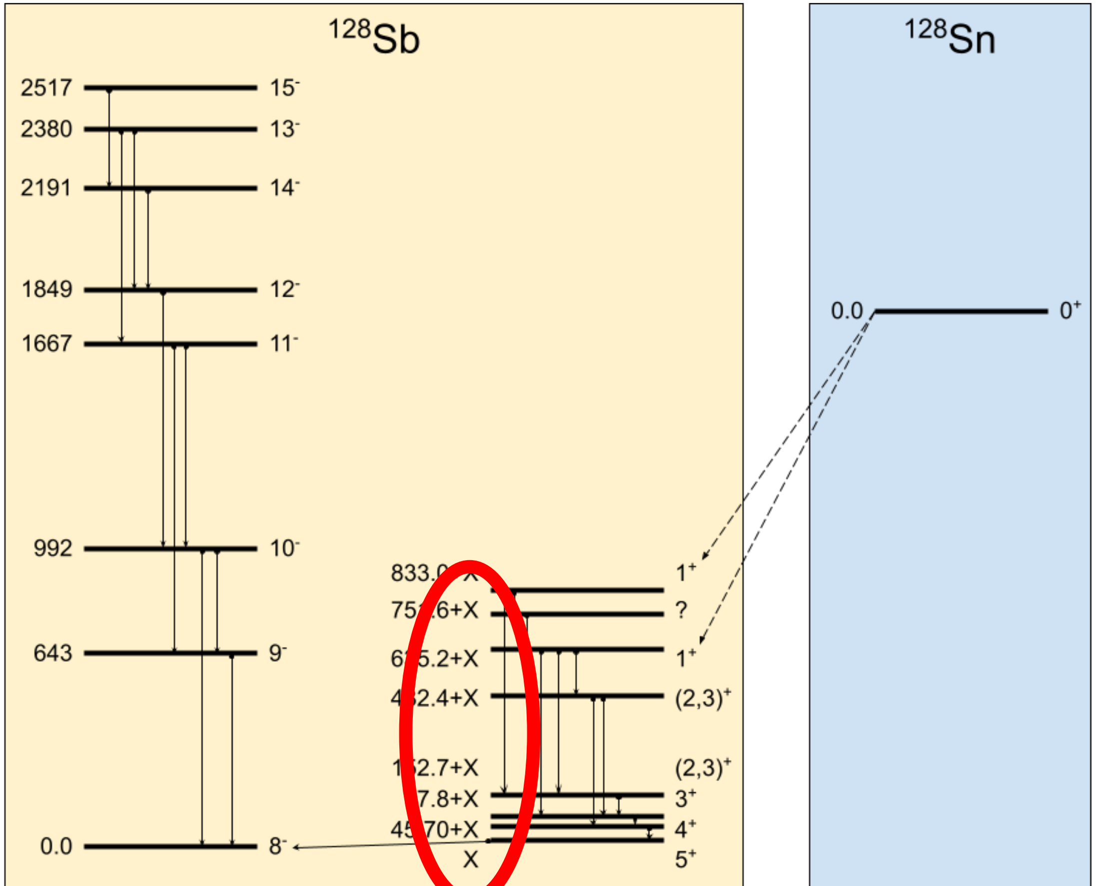
Decay of r-process Isotopes



G. W. Misch. *et al.,* ApJL **913**, L2 (2021)

- Network simulations indicate the impact of an isotopes isomers based on lifetime differences and abundance
- At a timescale of hours, A=128 decay is substantially retarded by ground-state decay
- A hot photon bath *may* accelerate the decay to stability, but depends on the isomer energy

What We Propose to Measure



- We will measure the excitation energy of the 5^+ isomer in ^{128}Sb by measuring the isomer mass
- This will set the energy of all of the states known to be built on the isomer
- These energies are essential for determining transition rates in a thermal photon bath
- This isomer matters because of the large difference in β-decay rates between the ground-state and isomer

- E_X < 20 keV based on half-life systematics
- Half-Lives:
  - gs: 9.05 hours
  - Isomer: 10.41 minutes

Precision Goals:

- ΔE < 1 keV energy determination gives precision comparable to the level structure
- Determination that the state is <5 keV reduces uncertainty in excitation of 1st excited state above the isomer from 50% to 10% and significantly reduces the range of temperatures that will enable thermalization

What We will Learn

Nuclear Structure

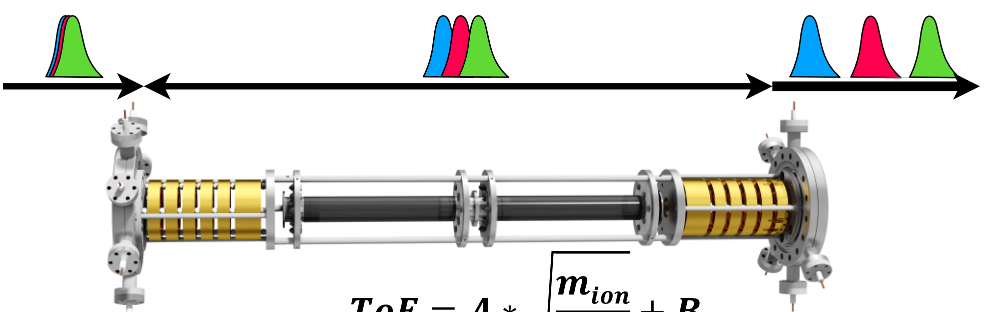
- More complete nuclear structure of odd-odd ^{128}Sb
- Determine transitions and decay lines that identify ^{128}Sb decays in the lab and, potentially, in future gamma-ray missions

Astrophysics

- Determine transition rates for decay on the hours-to-days timescale
- Better understand the *A*=128 mass chain, radioactive decay, and heating of *r*-process ejecta
- This gives a direct tie from nuclear structure properties of an individual isotope into an astrophysical phenomenon

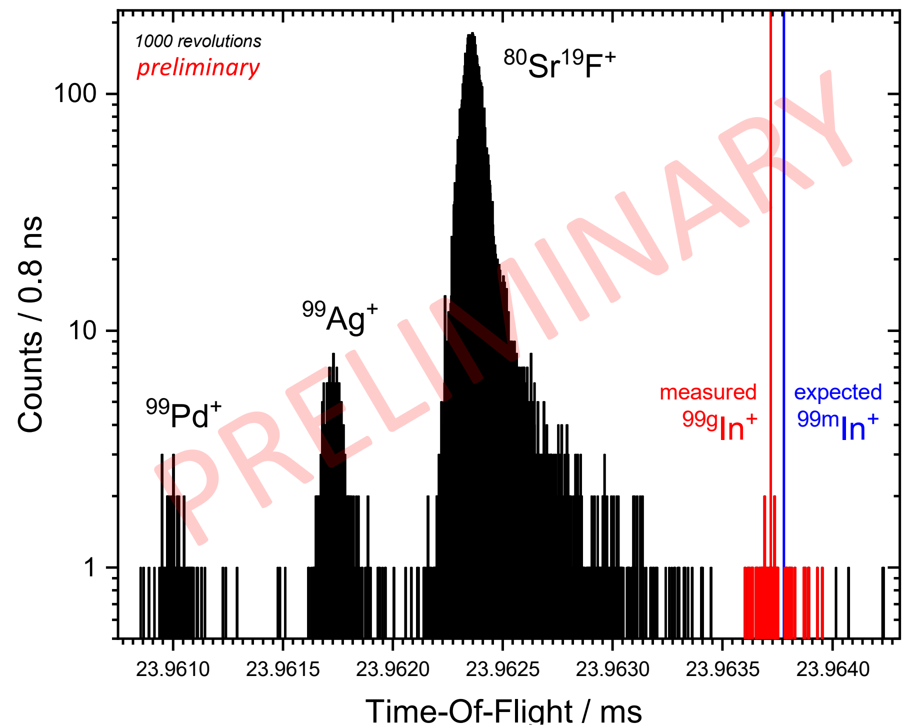
Experimental Techniques

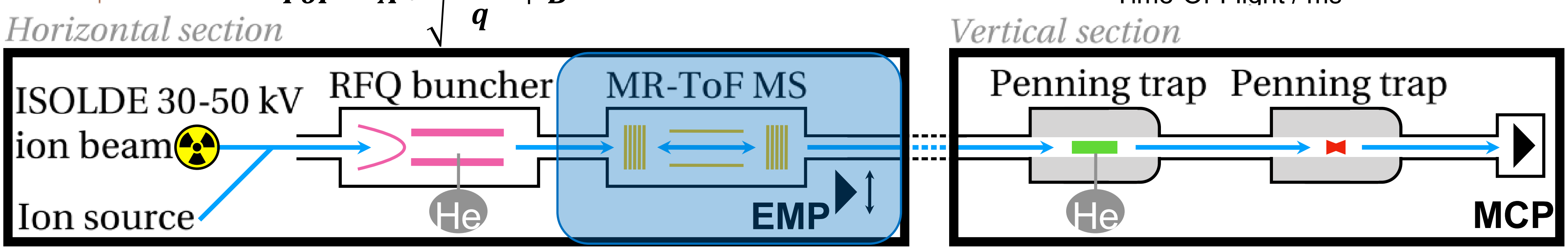
- MR-ToF MS[1,2]: versatile and fast
  - Mass separation mode
  - Mass spectrometry mode
  - Resolving power up to 250k
- Isobaric contaminants can be used as calibrants



$$ToF = A * \sqrt{\frac{m_{ion}}{q}} + B$$

M. Mougeot *et al.*, accepted to Nature Physics (2021)



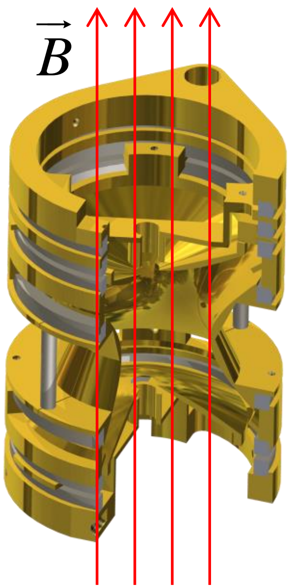


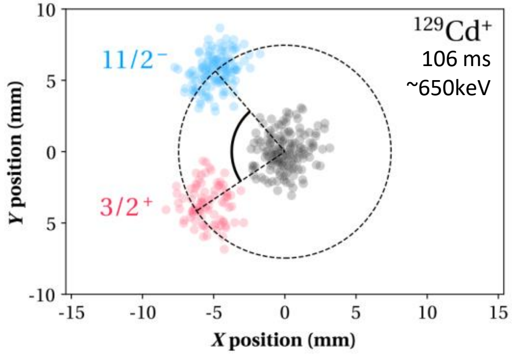
[1]R. N. Wolff *et al.*, Int. J. of Mass Spectr. **349–350** (2013) 123–133
[2]F. Wienholtz *et al.*, NIM B. **463** (2019) 348-356

Experimental Techniques

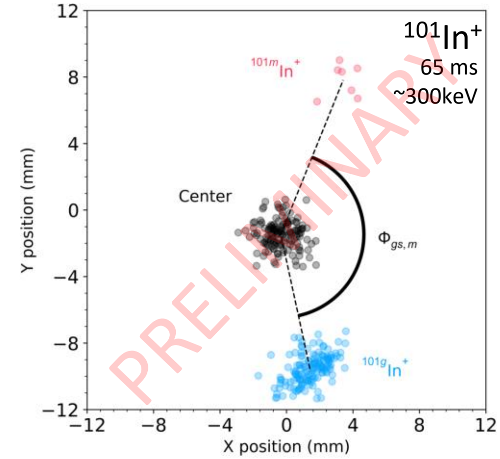
- Newly commissioned **PI-ICR** technique[1]: high precision even with low yields
- Mass resolving power > 10^6 in 100ms at A=129
- Longer storage times improve resolving power
- Isomeric separation capability demonstrated

$$\omega_c = \frac{qB}{m_{ion}}$$





V. Manea and J. Karthein et al., PRL **124**, 092502 (2020)



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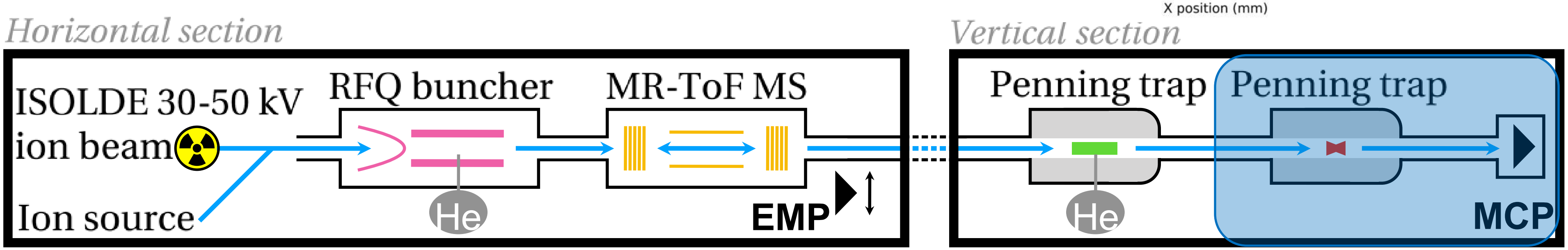
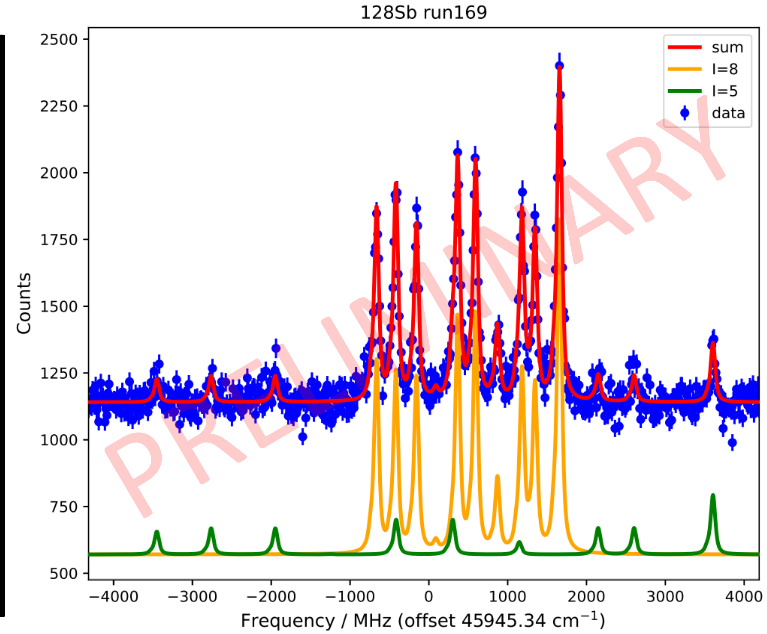


[1]S. Eliseev *et al.*, PRL **110**, 082501 (2013)

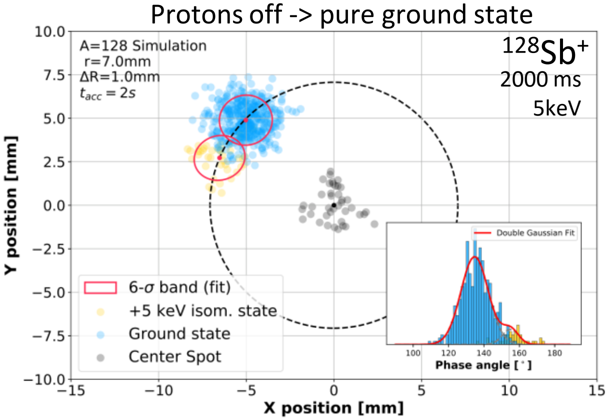
Measurement Method

- **Selective ionization** of ground and isomeric state using RILIS and **protons on/off** tests
- Expected low excitation energy requires **long acc. times**
- Monte-Carlo simulation for estimating experimental sensitivity

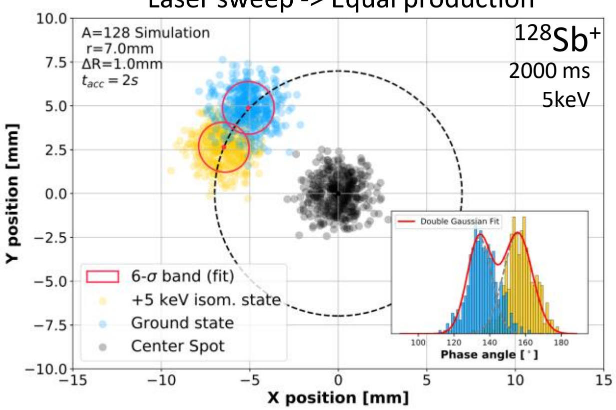


Provided by S. Lechner and the COLLAPS collaboration. Prelim. results of IS635.

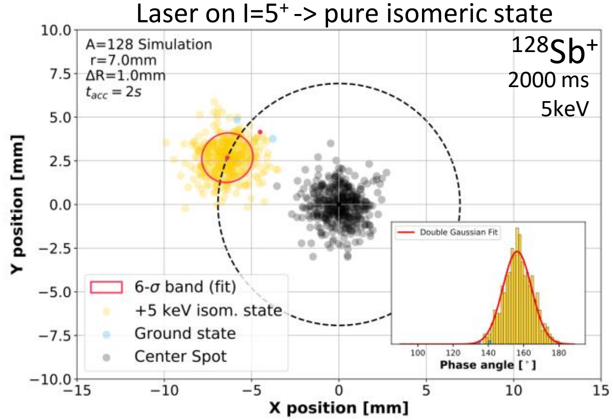
Laser on I=8$^-$ -> 10:1 ground state
Protons off -> pure ground state



Laser sweep -> Equal production



Laser on I=5$^+$ -> pure isomeric state



-> Simultaneous and individual measurement of both states possible

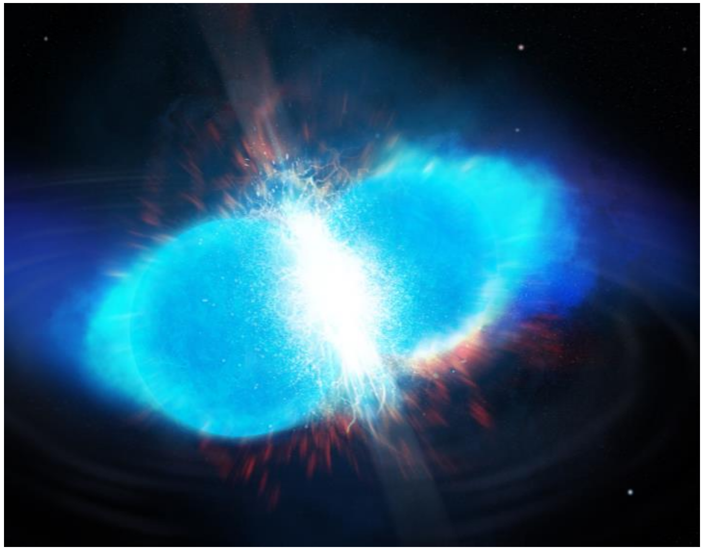
Summary

Determine **excitation energy** of 5^+ isomeric state in ^{128}Sb to

- estimate **equilibrium temperature** of ^{128g,m}Sb in NS mergers
- evaluate **timescale for decays** of A=128 mass chain in *r*-process nucleosynthesis
- calculate **impact on emission curve** from that mass chain

We intend to measure the state

- using **ISOLTRAP** with **PI-ICR** method
- to a **precision** of better than **1 keV**
- employing **state-selective** laser ionization



Artist concept NS Merger, http://matthewmumpower.com

Isotope	J^π	Energy [keV]	Half-life	Yield in CA0 [ions/s]	Method	Target	Ion source	Shifts
^{128g}Sb	8^-	0	~ 9 h	~ 10^8	PI-ICR and MR-TOF MS	UC_x	RILIS	**4**
^{128m}Sb	5^+	<20#	~ 10 min					
Target/ion source optimization, calibration measurements								**4**
Total shifts								**8**

#: estimated

Backup: Resolving Powers

MR-ToF MS:

$$R = \frac{m}{\Delta m} = \frac{t_{obs}}{2\Delta t} \cong \frac{t_{\mathrm{transfer}} + nT}{2\sqrt{\Delta t_{th}^2 + (n\Delta T_A)^2 + \left(\Delta t_E - nT\left(\frac{\partial \delta_T}{\partial \delta_E}\right)\Delta\delta_E\right)^2}}$$

Penning trap PI-ICR:

$$R = \frac{m}{\Delta m} \approx \frac{\nu_+}{\Delta\nu_{+<}} \approx \pi\frac{\nu_+ t_{obs} r_+}{\Delta r_+}$$