# Sub-barrier Coulomb Excitation of $^{112,116,120}$Sn


**Ava Hill**
**Michigan State University**
**Facility for Rare Isotope Beams**


**NSSC3 Kickoff Meeting and Advisory Board Review**
**April 19-20, 2022**

# Introduction

Department of Physics and Astronomy, Department of Computational Mathematics, Science, and Engineering

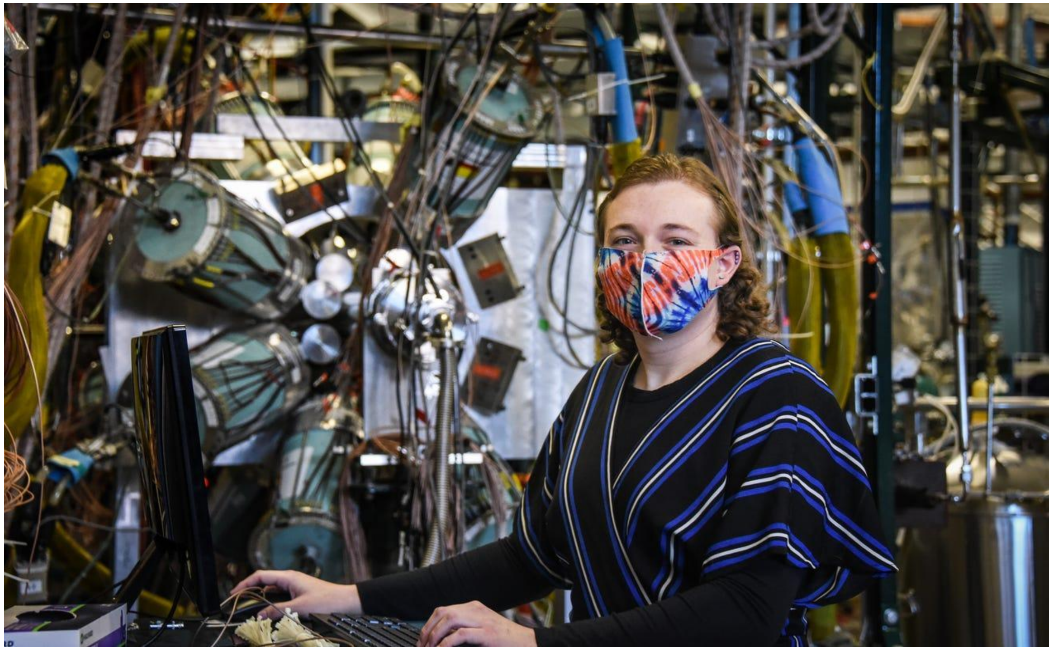
**Academic Advisor:** Dr. Alexandra Gade

**Lab Mentor and Partner Laboratory:** Ching-Yen Wu, Lawrence Livermore National Laboratory

**Mission Relevance of Research:** Measurement of basic nuclear properties to inform and benchmark nuclear models critical to fundamental science and applications and development of novel ML techniques for nuclear spectroscopy

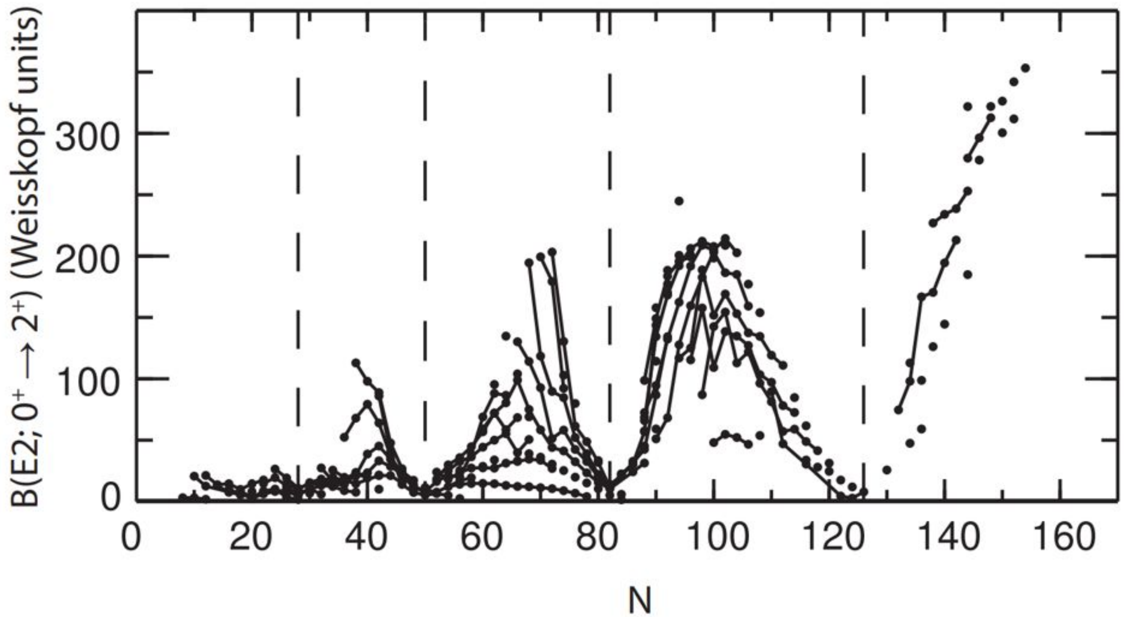
**Focus Areas:** Nuclear Physics

**Estimated Graduation:** May 2024



# Transition Strengths

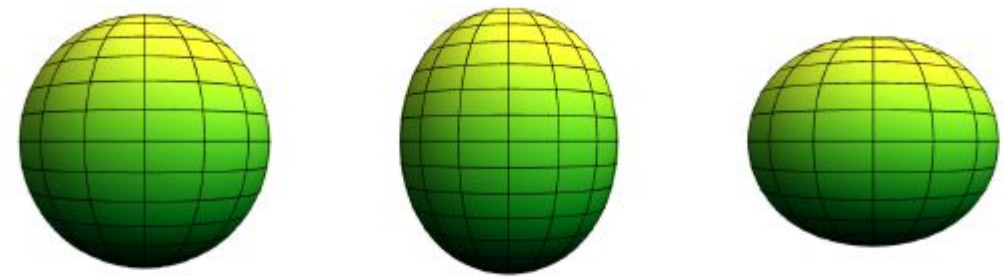
- B(E2) values are a measure of the transition strengths between nuclear energy levels
- Strong signature of collectivity
- Provides a powerful test of nuclear models
- Minimized near magic numbers, maximized between them




B. A. Brown. Lecture Notes in Nuclear Structure Physics. Michigan State University (2020)

# Quadrupole Moments

- Quadrupole moments measure the deformity of the electric charge within the nucleus
- Positive moments indicate a prolate deformation, negative moments indicate an oblate deformation



Spherical | Prolate | Oblate

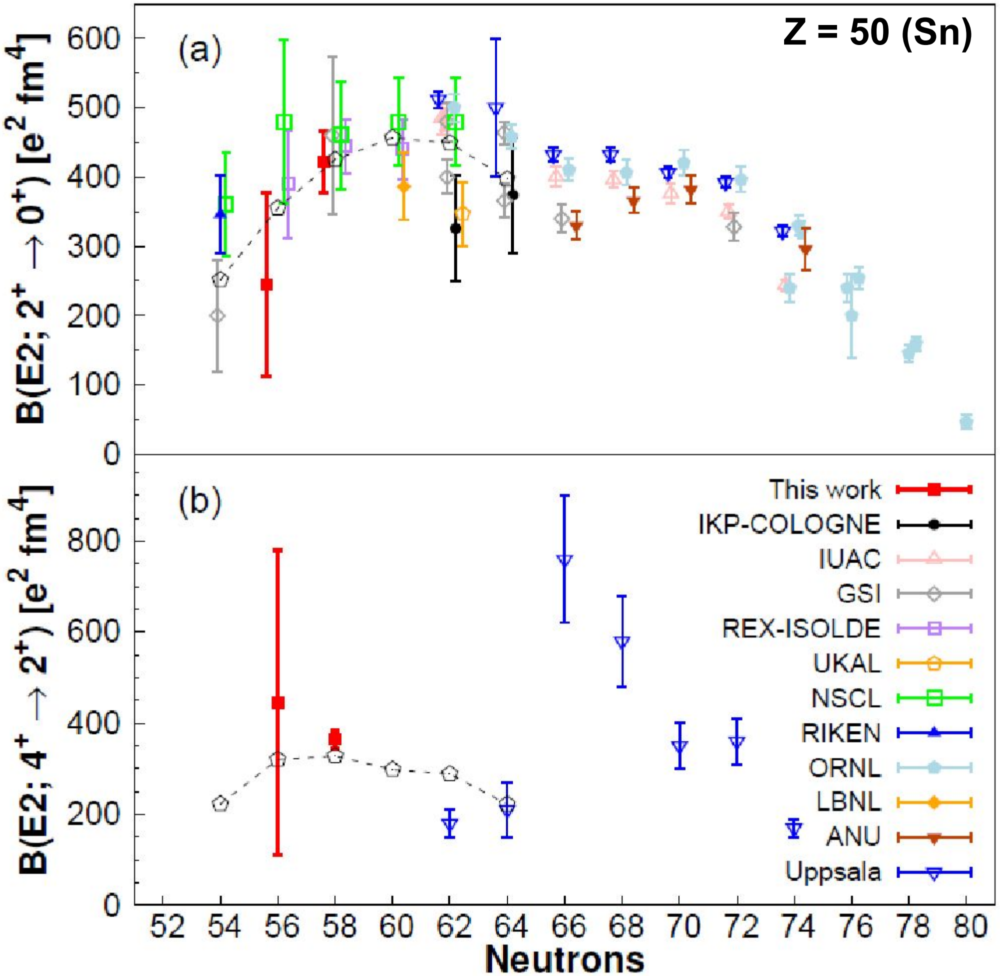
$Q = 0$ | $Q > 0$ | $Q < 0$

Figure taken from:
B. Elman. Probing Proton Cross-Shell Excitations in $^{70}$Ni Using Nucleon Knockout Reactions. Michigan State University (2019)

D.C. Kean. *Measurement of Quadrupole Moments...* Springer (1976)

# Sn Isotopic Chain

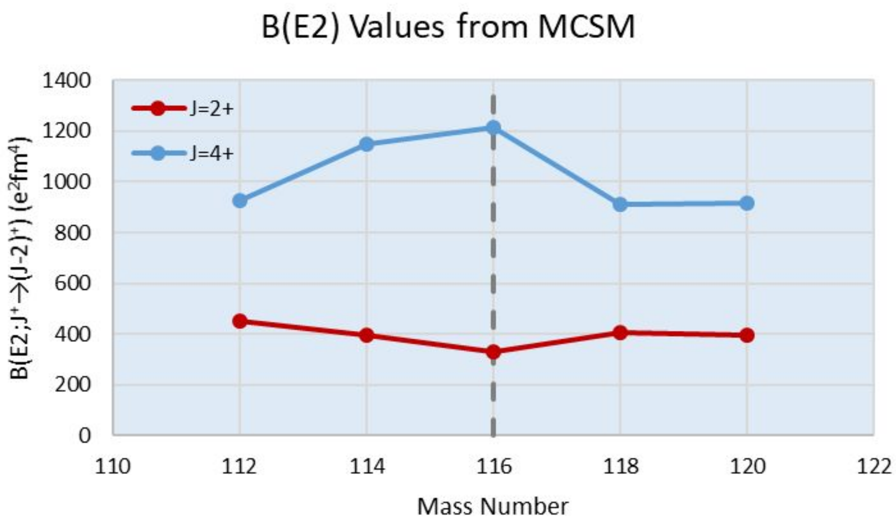
- Sn isotopic chain provides a powerful test of nuclear models
- $B(E2; 2_1^+ \rightarrow 0_1^+)$ reported from $^{104}$Sn to $^{132}$Sn
- Trend is asymmetric about ~N=66
- Recent Monte Carlo Shell Model calculations have been able to describe the trend of B(E2) values across the chain

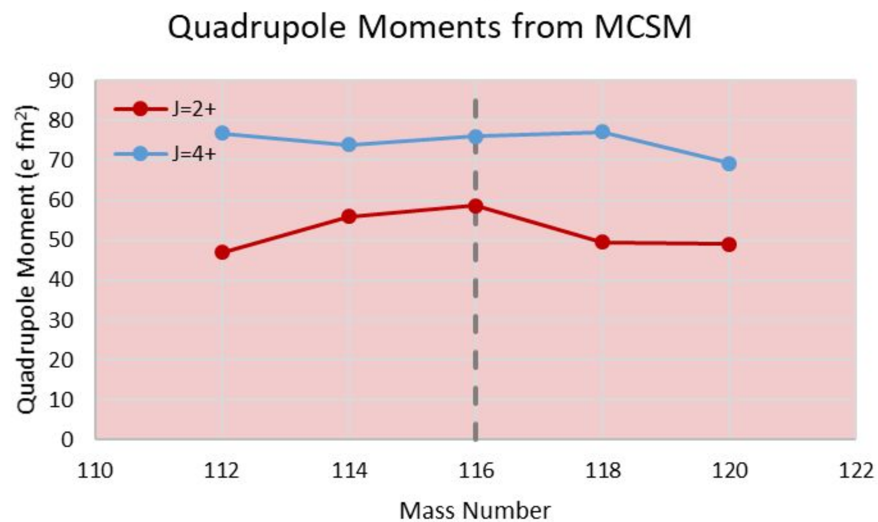



M. Siciliano et al. Phys. Lett. B 806, 135474 (2020)
T. Togashi et al. Phys. Rev. Lett. 121, 062501 (2018)

# Sn Isotopic Chain

- MCSM predicts a phase transition near N=66, from deformed shapes on the neutron-deficient side to spherical shapes on the neutron-rich side
- Associated with this transition are specific trends in B(E2) and Q for $2_1^+$ and $4_1^+$ states
- We attempt to measure these 4 values for $^{112,116,120}$Sn to test these predictions




T. Togashi et al. Phys. Rev. Lett. 121, 062501 (2018)

# Sub-Barrier Coulomb Excitation

- One nucleus excited in Coulomb field of another
- Allows for direct measurement of excitation cross-section
- B(E2) values are directly proportional to excitation cross-sections
- Beam energy restricted to ensure purely electromagnetic interaction

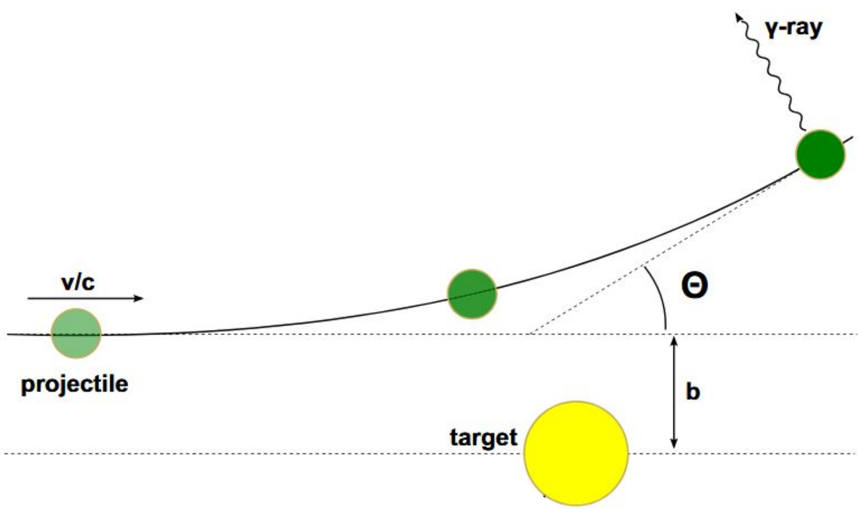
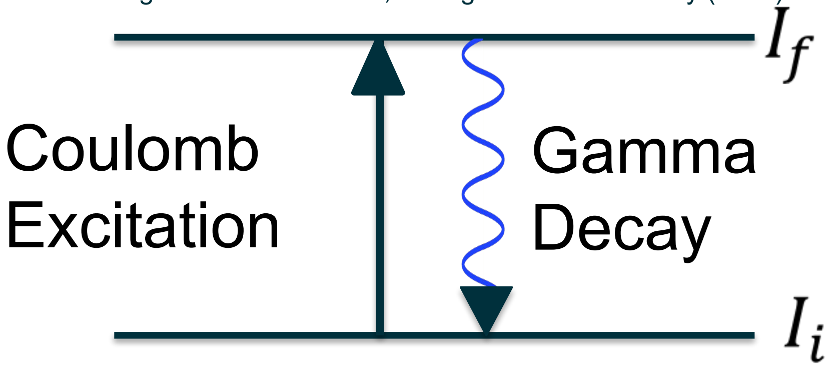


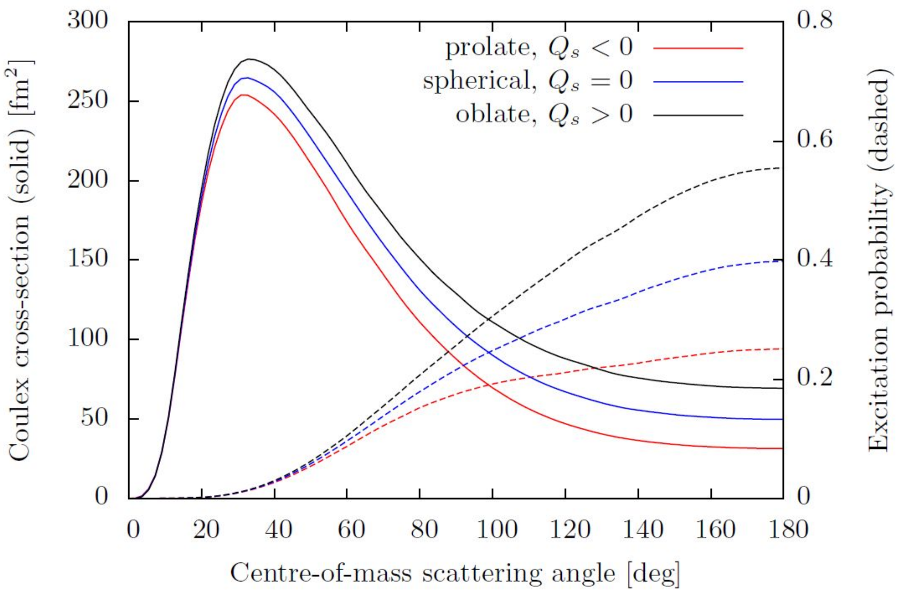

Figure taken from:
E. Lunderberg. Ph.D. Dissertation, Michigan State University (2017)

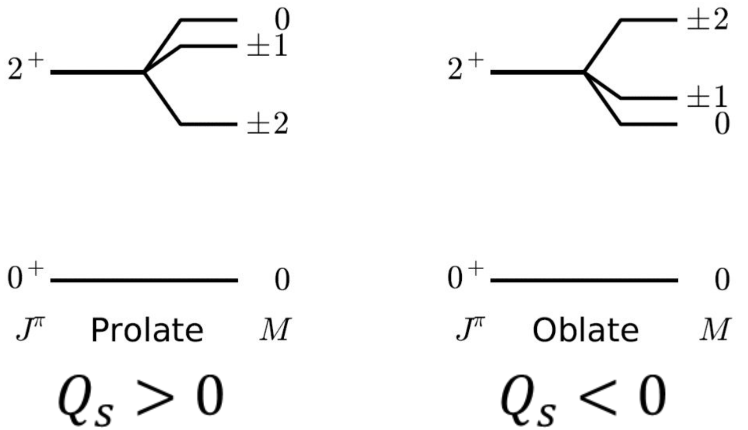



D. Cline. Annual Review of Nuclear and Particle Science, 36(1) (1986)

# Measuring B(E2) and Q

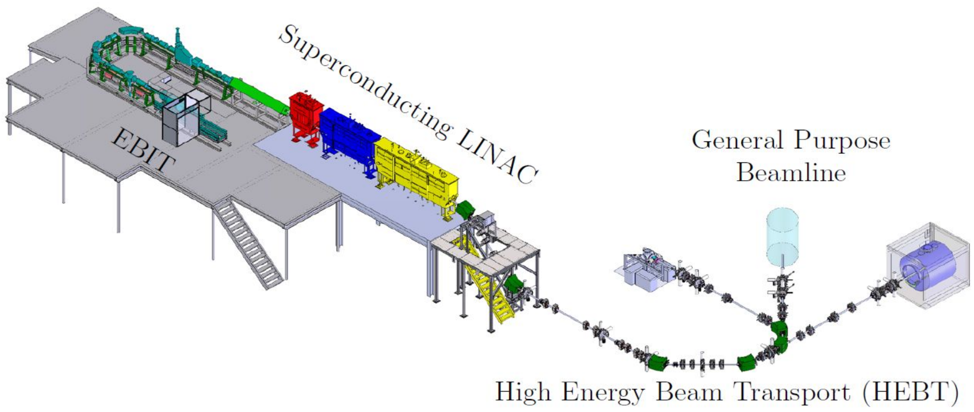
- B(E2) is a measure of transition strengths between energy levels, measured directly through excitation probabilities
- Electromagnetic field of colliding system splits magnetic substates, changing angular dependence of excitation probability
- Q is constrained through measurement of angle-dependent gamma-ray yields




M. Zielińska et al. Eur. J. Phys. A 52, 99 (2016)

# Experimental Details



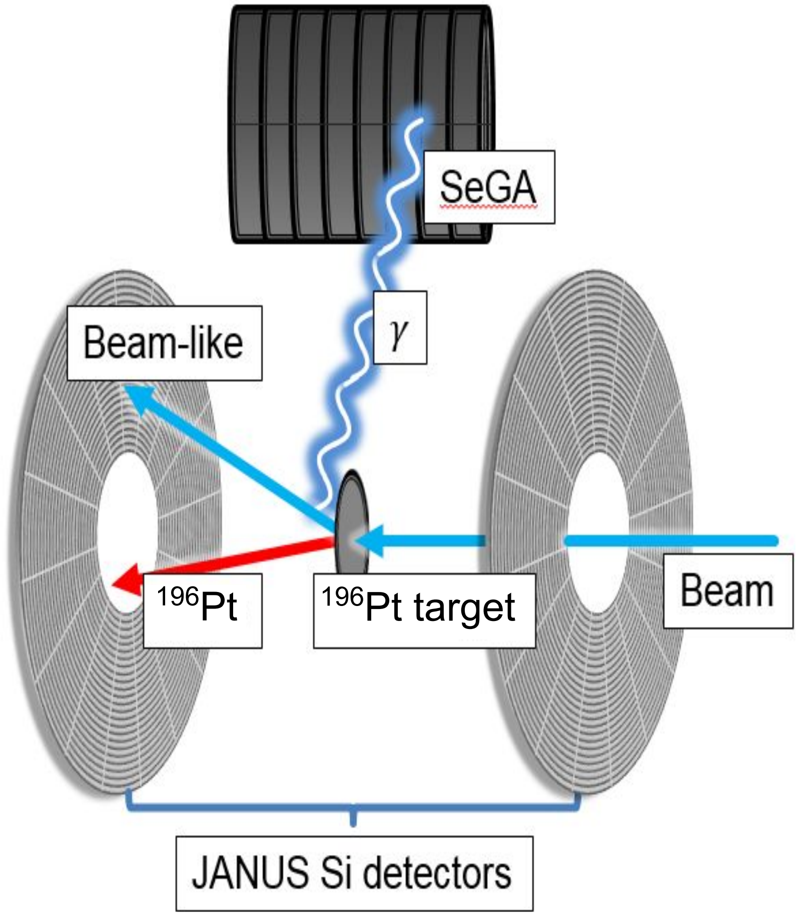

- First experiment ran in October 2020 at NSCL ReA3 facility
  - Problem with EBIT resulted in unusable data
- Second attempt ran in April 2022 at same facility
- Each isotope vaporized and injected into EBIT using an offline source
- Accelerated and delivered to experimental station at 3.85, 3.81, 3.73 MeV/u for $^{112,116,120}$Sn

- $^{196}$Pt target
  - 1.5 mg/cm$^2$ (0.7 μm)
  - High Z increases B(E2) and Q sensitivity
  - Well-known transition strengths allow for normalization

A.C.C. Villari et al. Proceeding of IPAC2016, Busan, Korea. TUPMR024
[A. Lapierre et al. Review of Scientific Instruments 85, 02b701 (2014)

# JANUS Setup

- Joint Array for Nuclear Structure (JANUS)
  - Low energy Coulomb excitation
  - Simultaneously detects particles & gamma rays
- Segmented Germanium Array (SeGA) for gamma-ray detection
  - 16 detectors surround the target
- Two double-sided silicon strip detectors for particle detection
  - One detector on either side of reaction target

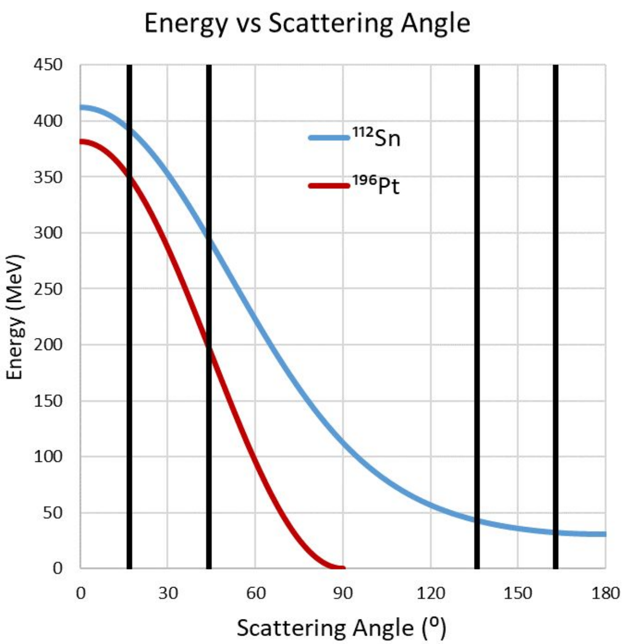


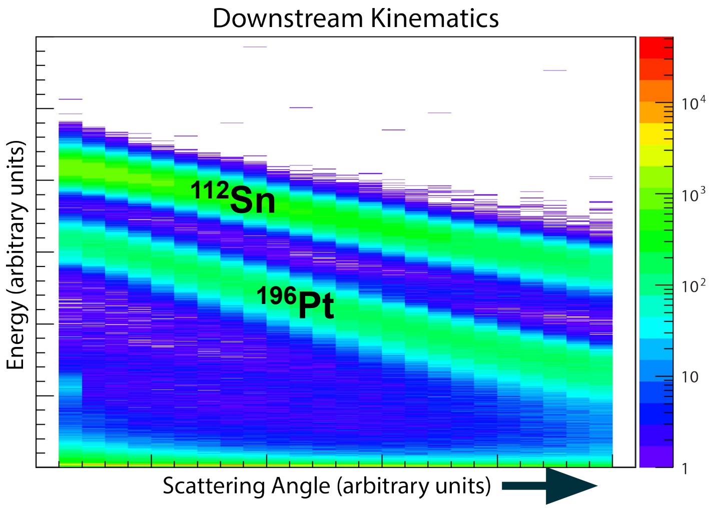

E. Lunderberg et al. Nucl. Instrum. and Meth. in Phys. Res. A 885 (2017)

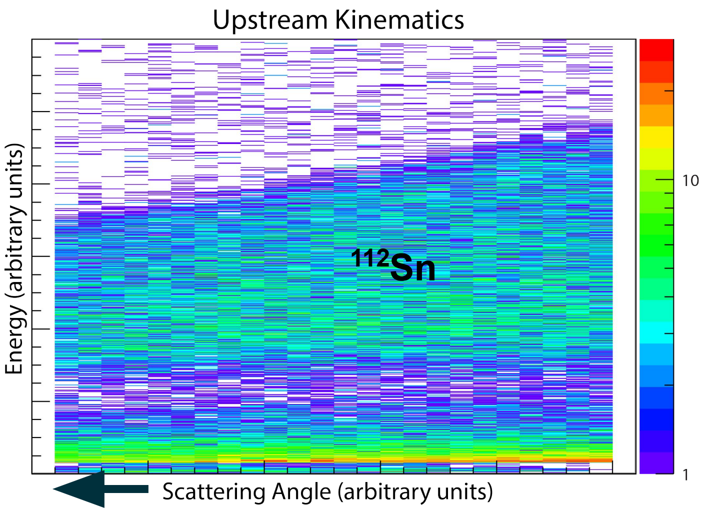
JANUS was original conceived, designed, and built in a collaboration of MSU (Gade), LLNL (Wu), and U. Rochester (Cline) and is now run in collaboration of MSU, LLNL and the University of Surrey (UK)

# Particle Detection

- Two-body scattering dictated by kinematics
- Forward and backward detectors offset 2.8 cm and 3.2 cm from target
- Angular coverage of 21.4°-51.3° and 132.4°-161.0°
- Gates applied to kinematic curves allow for particle discrimination
- Detection of recoiling target nuclei allows us to reconstruct undetected projectiles, gain additional effective coverage

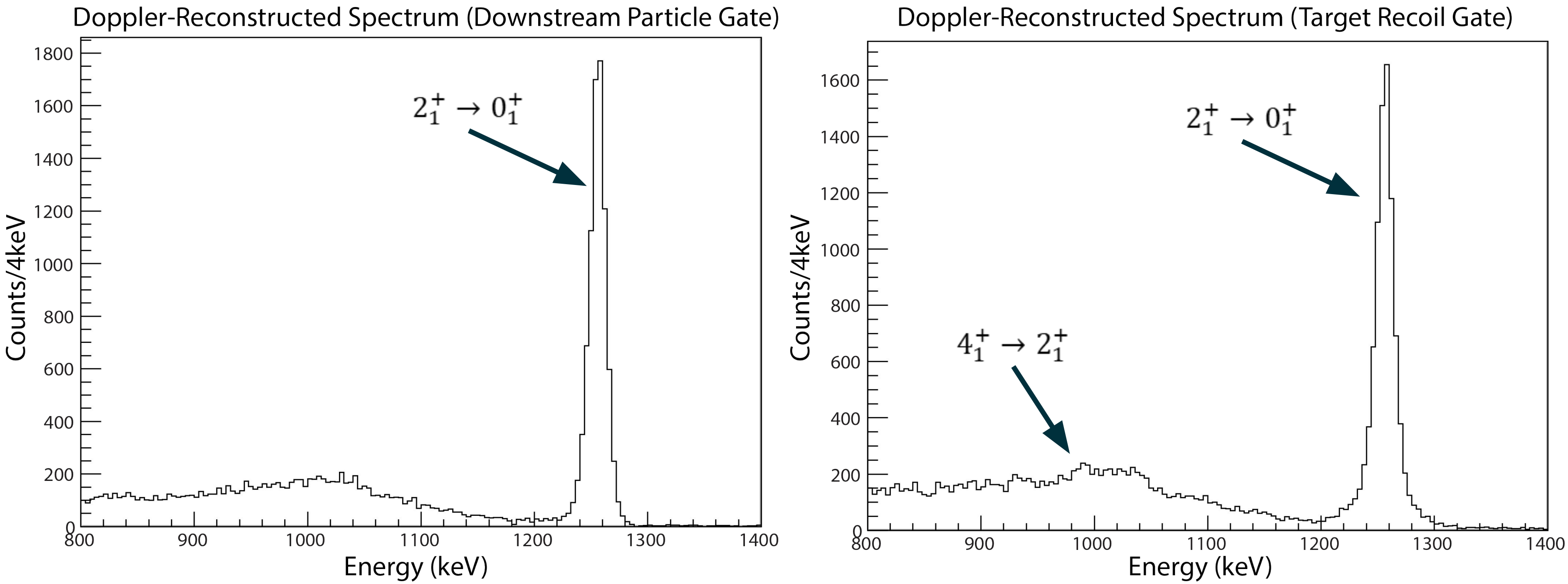


# Example Spectra: $^{112}$Sn

- For $^{112}$Sn, we measure ~16,000 counts of the $2_1^+ \rightarrow 0_1^+$ transition (1257 keV) and ~150 counts of the $4_1^+ \rightarrow 2_1^+$ transition (991 keV)



# GOSIA Coupled-Channels Analysis

- Runs a **minimization procedure** fitting the well-known Coulomb excitation equations to angle-dependent gamma ray intensities
- Incorporates lifetimes, transitional matrix elements, nuclear moments, branching ratios, and multiple mixing rations for each observed state
- Normalizes transition strengths relative to yields of $^{196}Pt$ gamma rays produced from target excitations
- **Large number of fit parameters**, some of which are strongly correlated with one another
- We will develop an **unsupervised machine learning** framework to find these **correlations**

T. Czosnyka et al. Bull. Am. Phys. Soc. 28, 745 (1983) (GOSIA)

# Proposed Analysis

- Use a Monte-Carlo simulation in conjunction with GOSIA to generate a large set of fit parameters and their associated $\chi^2$ values
- Accept or reject data points using random draws on the $\chi^2$ probability density function
- Properties of n-dimensional $\chi^2$ surface is not known
- We will try several different forms of components analysis to find which technique works best for this problem
  - Principal components analysis (PCA)
  - Kernel PCA
  - Independent components analysis
- New analysis technique will be developed and tested using already analyzed data from previous Coulomb excitation experiment on $^{106}$Cd

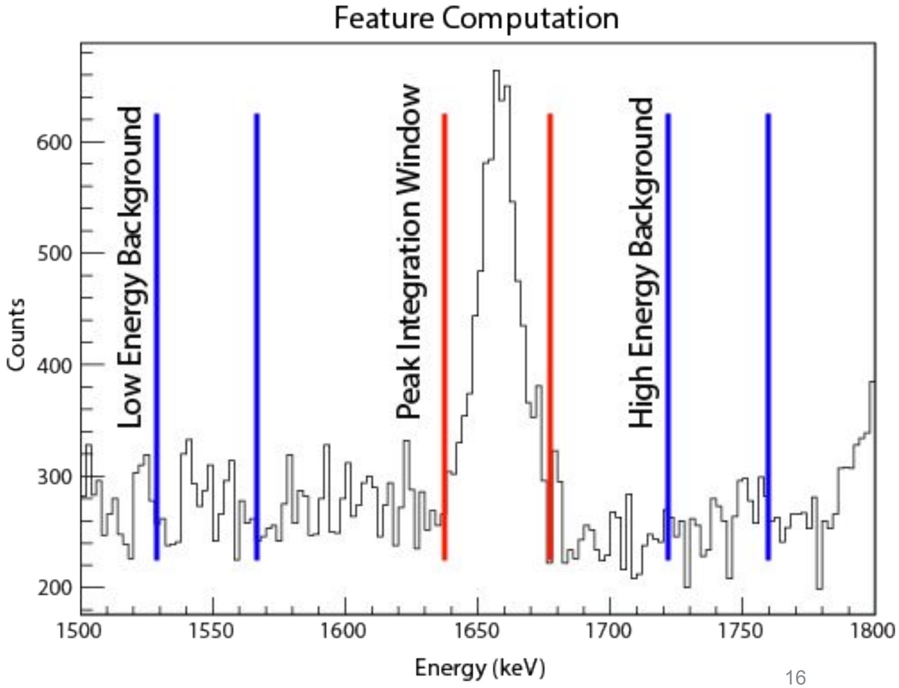
D. Rhodes et al. Phys. Rev. C 103, L051301

# Summary

- The large range of accessible nuclei makes the Sn isotopic chain a valuable place for testing nuclear models
- New MCSM calculations successfully predict $B(E2;2_1^+ \rightarrow 0_1^+)$ values across isotopic chain
  - Predicts structural change around $^{116}Sn$, observable in the trends of B(E2) and Q values for $2_1^+$ and $4_1^+$ states
- Experiment ran successfully in April 2022, analysis is ongoing
- New Coulomb excitation analysis framework will be developed using components analysis in conjunction with GOSIA

# The NSSC Experience

- Attended the Data Science Summer Institute at LLNL
- Mix of courses/workshops and a research project
- Project was to improve a model used for identifying nuclear fuel types based on gamma-ray spectra
- Features for model computed from ~2,500 known spectral lines associated with decays of interest
- Two main efforts:
  - Develop an algorithm to optimize the integration regions for computing features
  - Use feature analysis to select ideal parameters for the model
- Reduced classification error by ~10%, and created a framework to facilitate further optimization with better data



NSSC
NUCLEAR SCIENCE and SECURITY CONSORTIUM

# Acknowledgements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  - Joseph Chung [a b]
  - Peter Farris [a b]
  - Daniel Rhodes [a b]
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# Questions?

# Backup Slides

# Sub-Barrier Coulomb Excitation

- No nuclear contribution outside 'safe' distance:

$$R_{min} = \left[1.25 * \left(A_P^{1/3} + A_T^{1/3}\right) + 5\right] fm$$

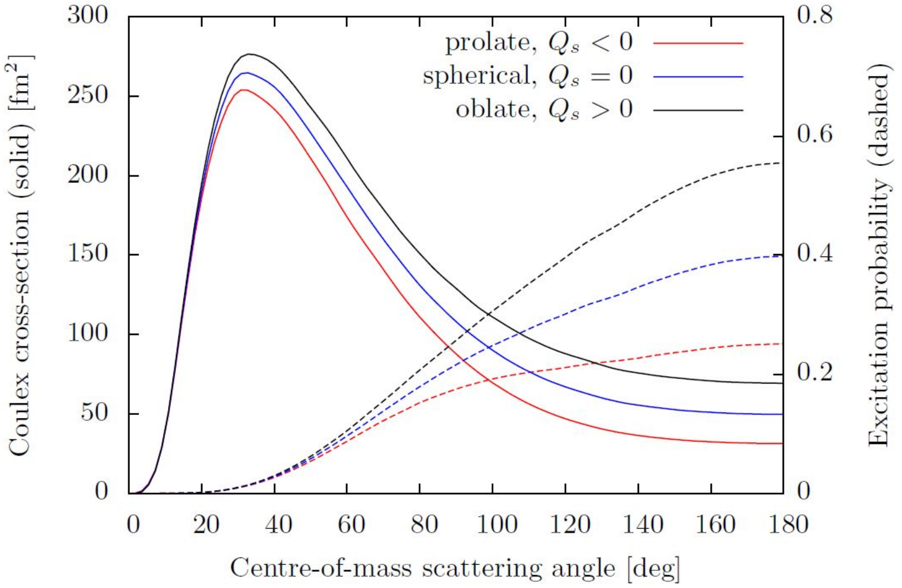
- Safe beam energy:

$$E = \frac{e^2}{4\pi\varepsilon_0} \frac{A_P + A_T}{A_T} \frac{Z_P Z_T}{R_{min}}$$

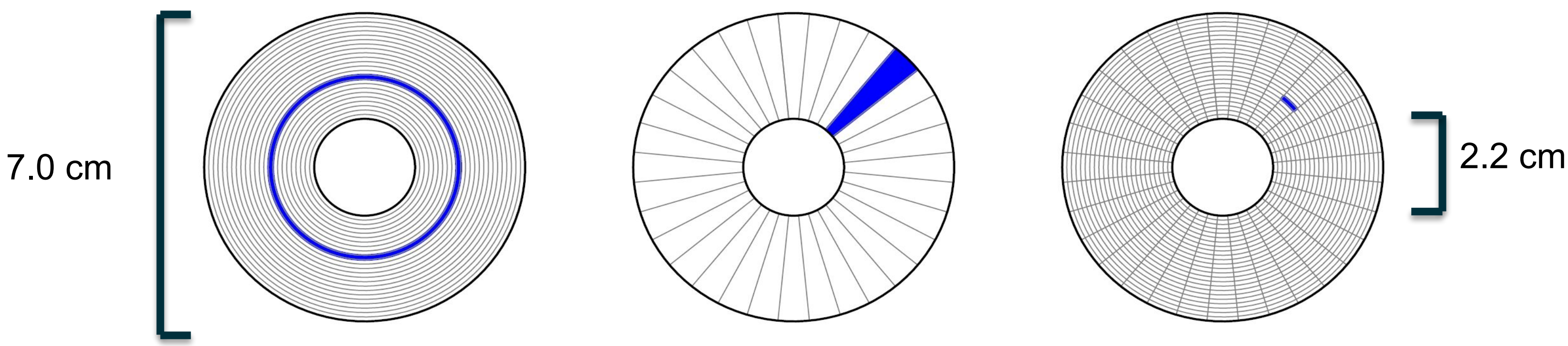
| Isotope | Safe Beam Energy | This Experiment |
|---|---|---|
| $^{112}Sn$ | 482.6 MeV | 431.2 MeV |
| $^{116}Sn$ | 487.0 MeV | 442.0 MeV |
| $^{120}Sn$ | 491.4 MeV | 447.6 MeV |

# Excitation Probability vs Coulex Cross-section

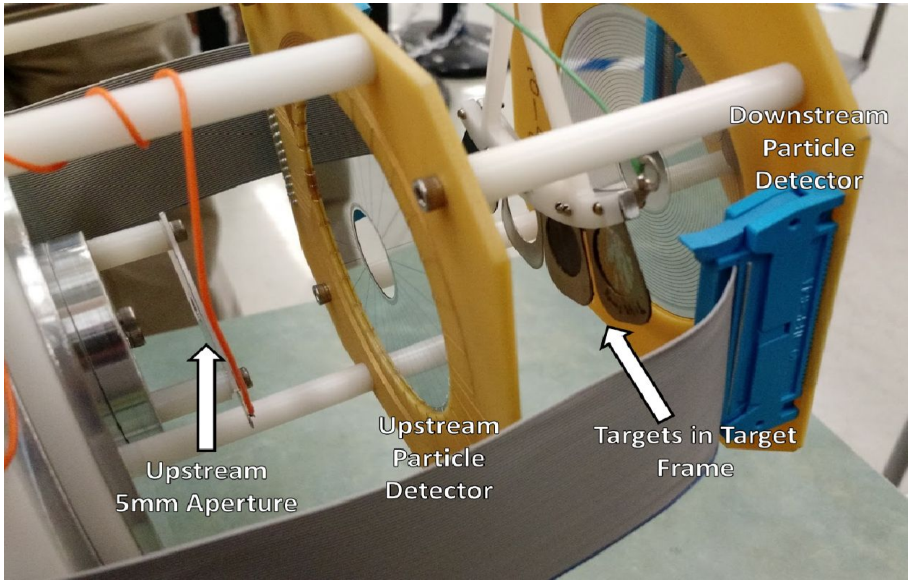
- Excitation Probability – probability of excitation when the projectile is scattered at this angle
- Coulex cross-section – excitation probability multiplied by Rutherford cross-section



# Silicon Detectors



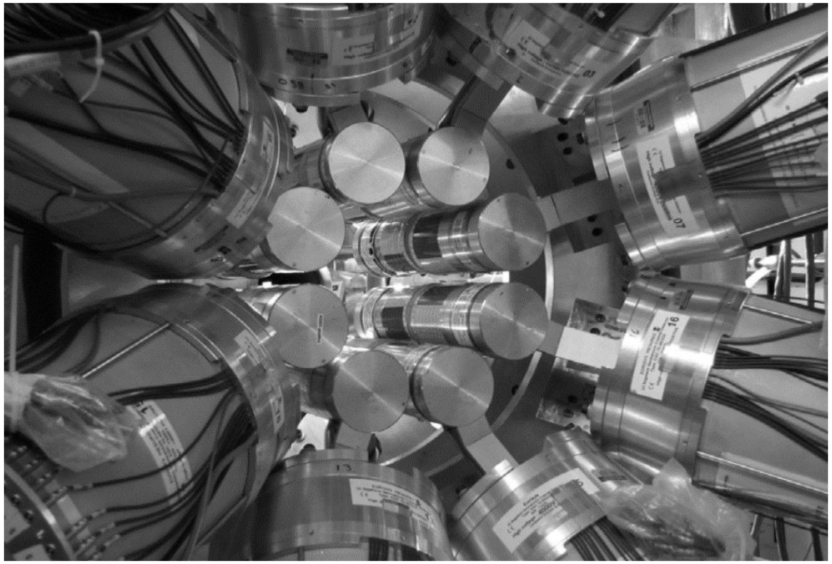

- Two annular Si detectors
  - 300 μm thick
  - Double sided
  - 1.1 cm and 3.5 cm radii
  - 24 radial segments
  - 32 azimuthal segments
  - 768 1 mm x 5mm pixels

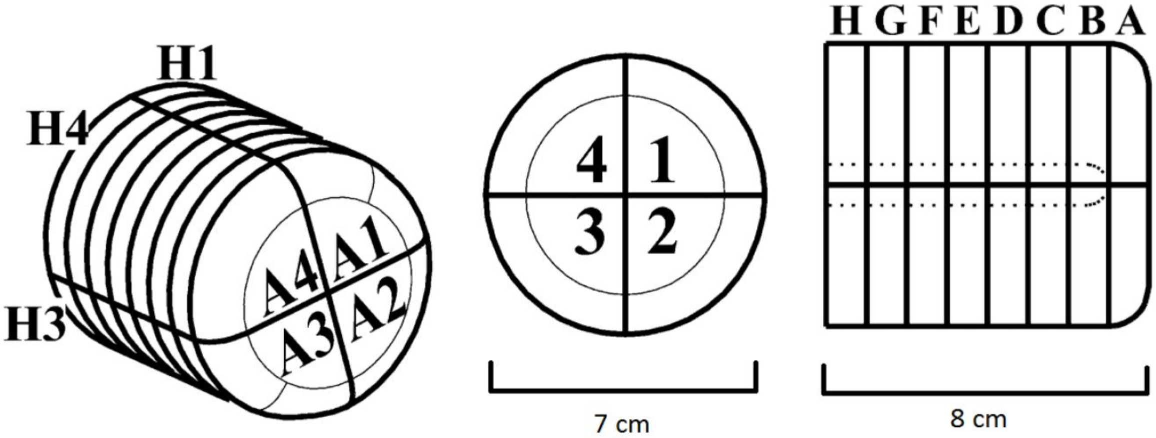



[9] E. Lunderberg et al. Nucl. Instrum. and Meth. in Phys. Res. A 885 (2017)

# Segmented Germanium Array

- 16 cylindrical HPGe detectors
  - 8 "slices"
  - 4 quadrants per slice
  - 1 central contact
- Concentrically surround target position

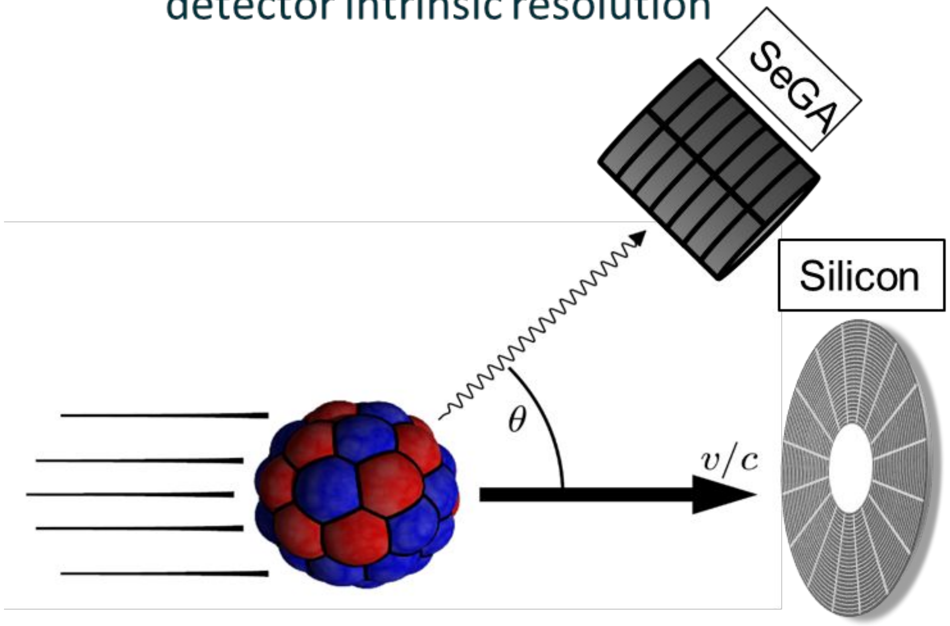


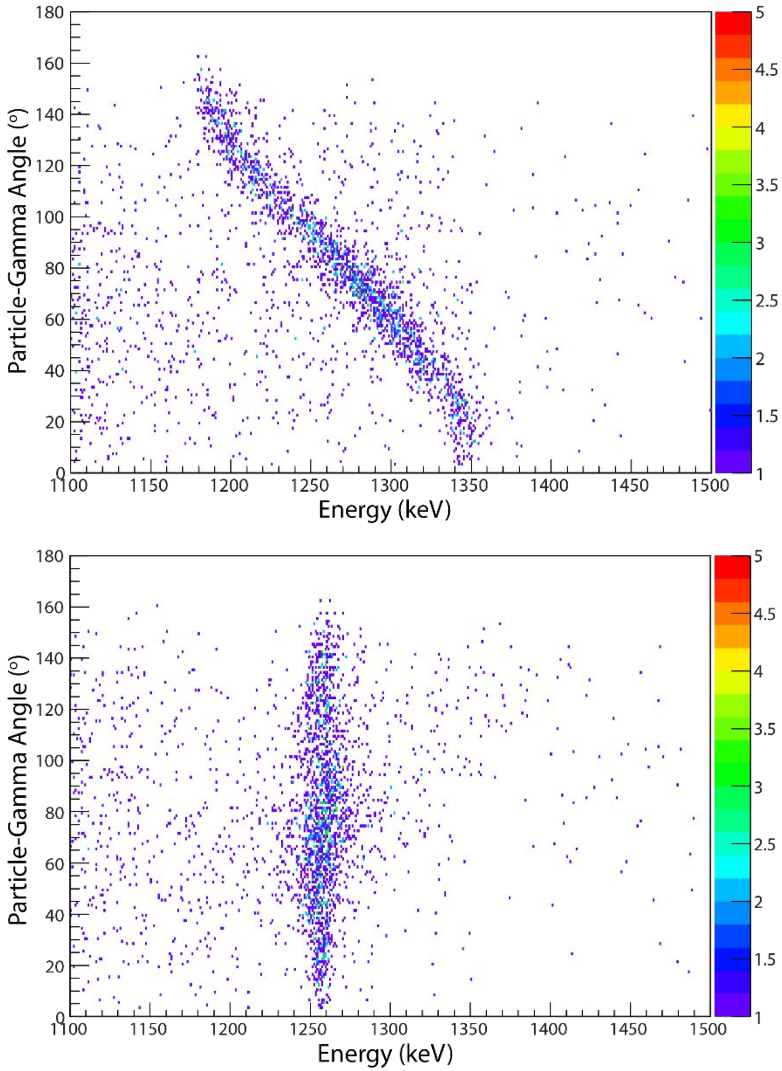



[14] W. F. Mueller et al. Nucl. Instrum. And Meth. In Phys. Res. A 466 (2001)

# Gamma-Ray Doppler Reconstruction

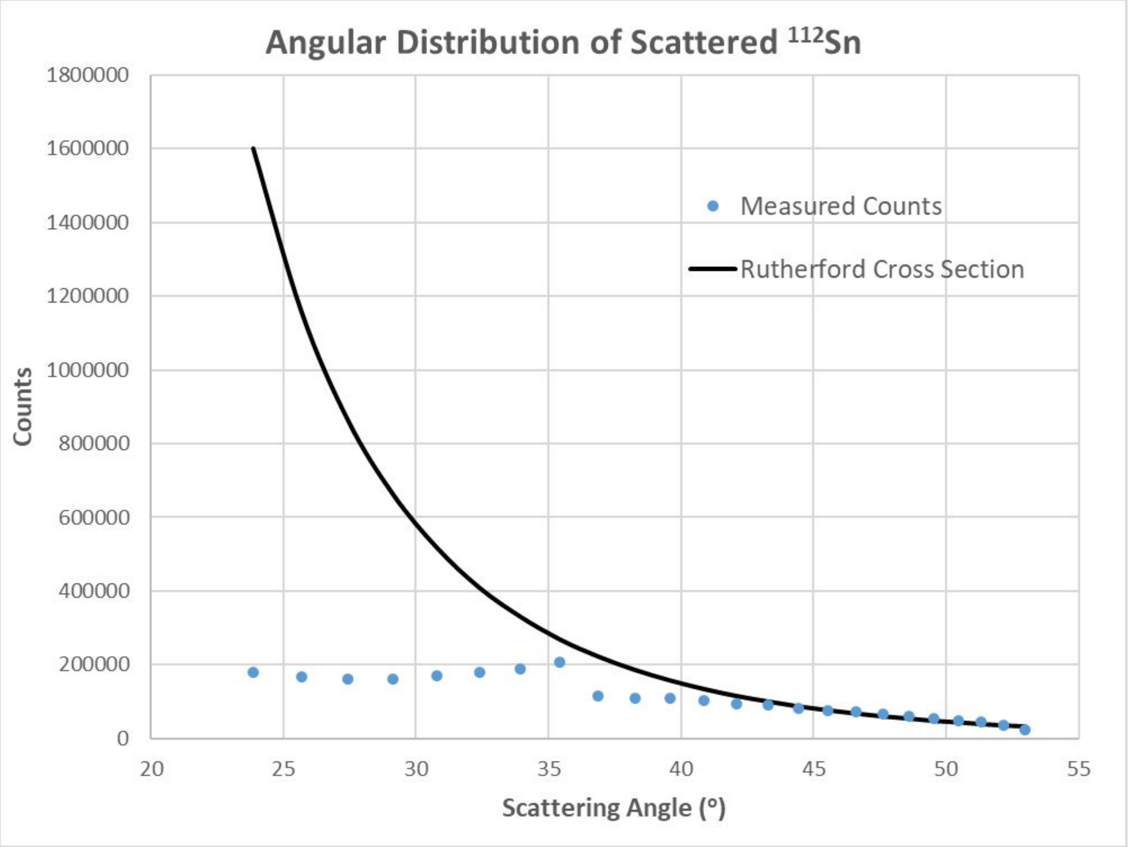
- 
- $E_{LAB} = \frac{E_{REST}}{\gamma_l(1-\beta\cos\theta)}$
  - $\gamma_l = \frac{1}{\sqrt{1-(\beta/c)^2}}$
- $\beta = \frac{v}{c}$ is a function of the scattering angle
  - B ranges from 0.024 to 0.089
  - Up to a 9% effect, much larger than detector intrinsic resolution



# Preliminary Results

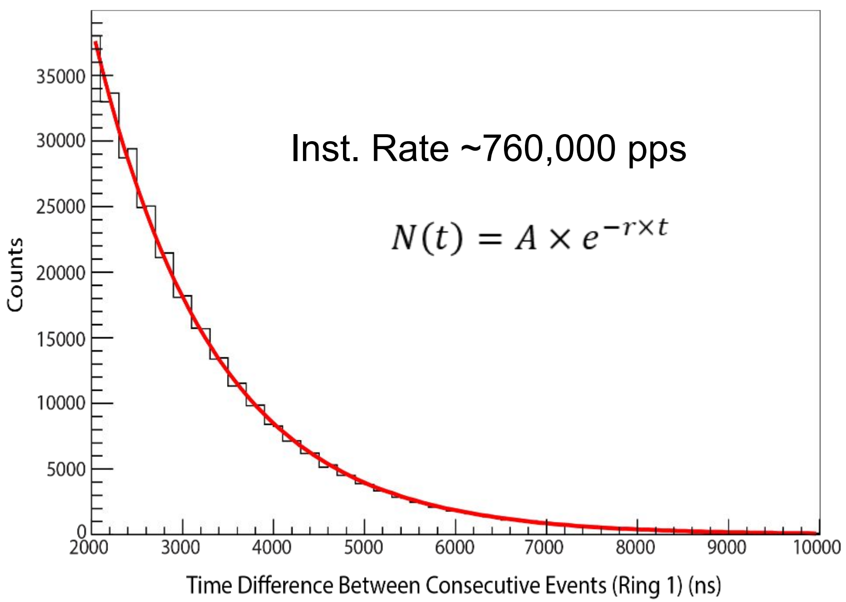
- Scattering reaction is a pure Coulomb interaction
- Angular distribution of scattered particles should follow a Rutherford cross-section
  - $\frac{d\sigma}{d\Omega} = \left(\frac{Z_1 Z_2 \alpha \hbar c}{4E_k}\right)^2 \frac{1}{\sin(\theta/_2)^4}$
- Problem was with Electron-Beam Ion Trap, which led to high instantaneous rate that created pileup in the particle detectors



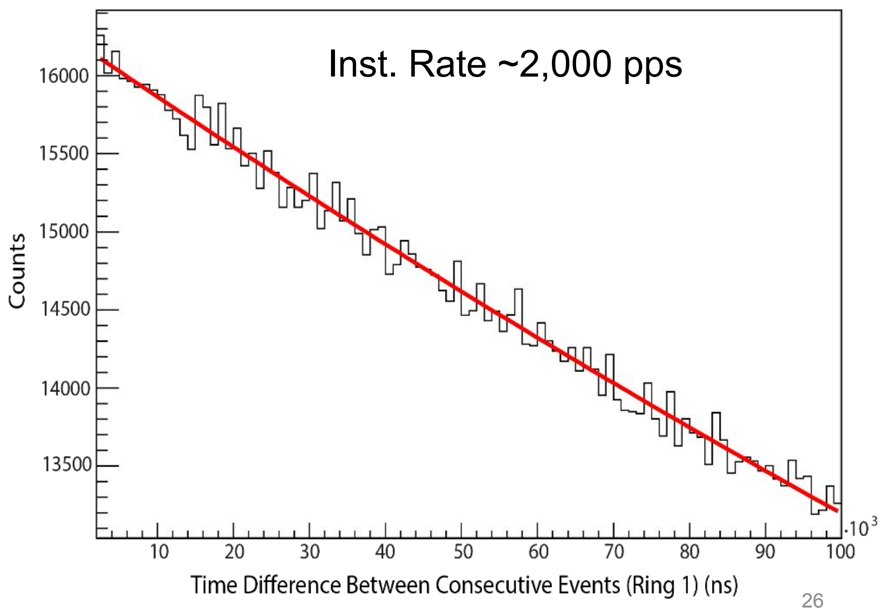
# Instantaneous Rate

- Assuming a constant rate during beam pulses, timing difference between consecutive events should follow an exponential distribution
- High instantaneous rate (orders of magnitude greater than previous experiments) resulted in loss of data
- Due to low scattering cross section in upstream detector, rate is comparable to downstream rate in previous experiments

e20011

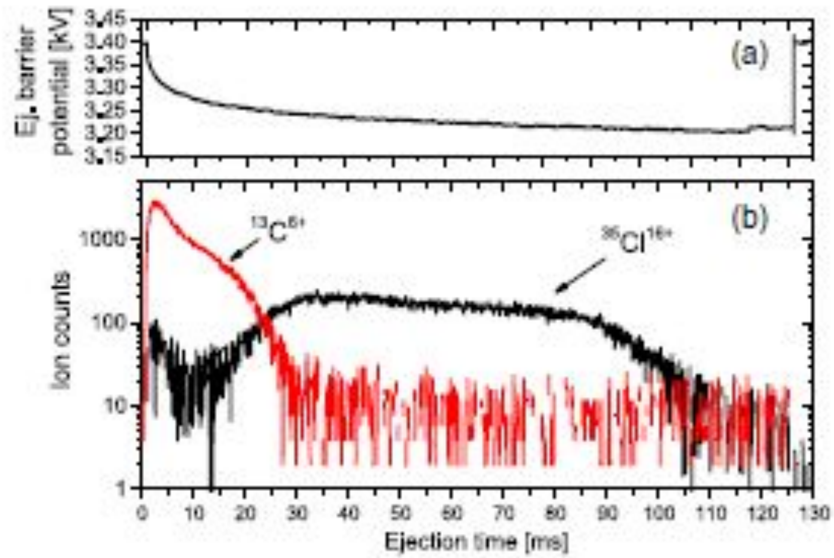



e20504



# The problem was due to EBIT

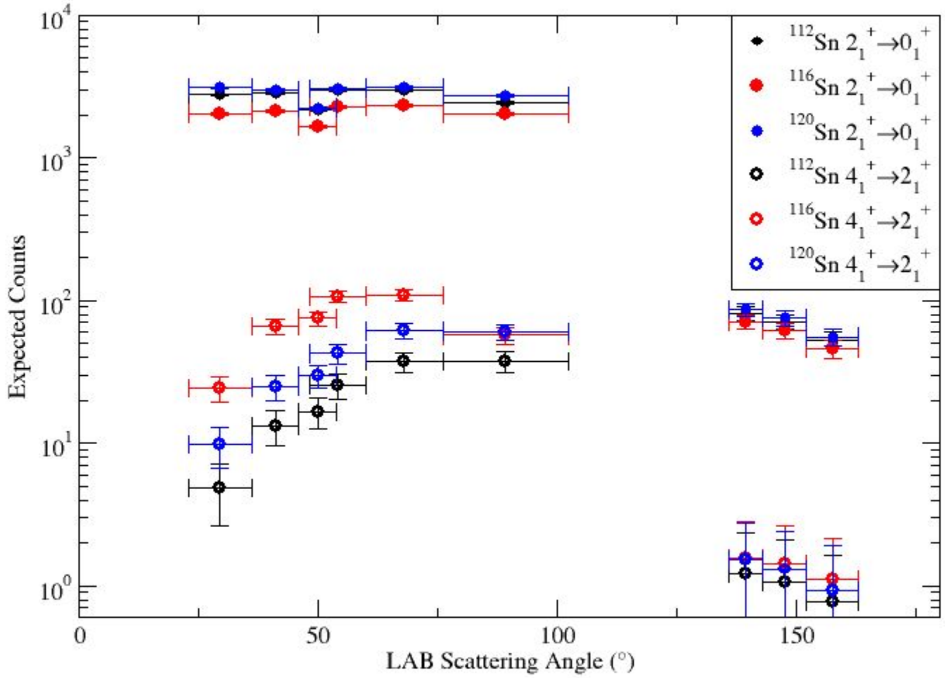
- Electron-Beam Ion Trap charge breeder
- Beams are injected into EBIT, trapped in a potential well
- Trapped ions are bred to desired charge state with electron beam
- Pulses are stretched by slowly lowering the ejection barrier
- Stretches pulse width from tens of µs to ms, reducing the instantaneous rate
- Pulse stretching failed in this experiment, but the operators did not have the diagnostics to see this issue, so it was not caught until after the experiment was complete



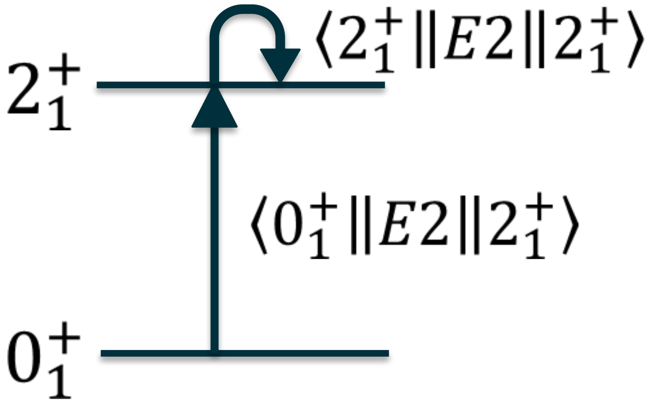

[10] A. Lapierre et al. Phys. Rev. Accelerators and Beams 21, 053401 (2018)

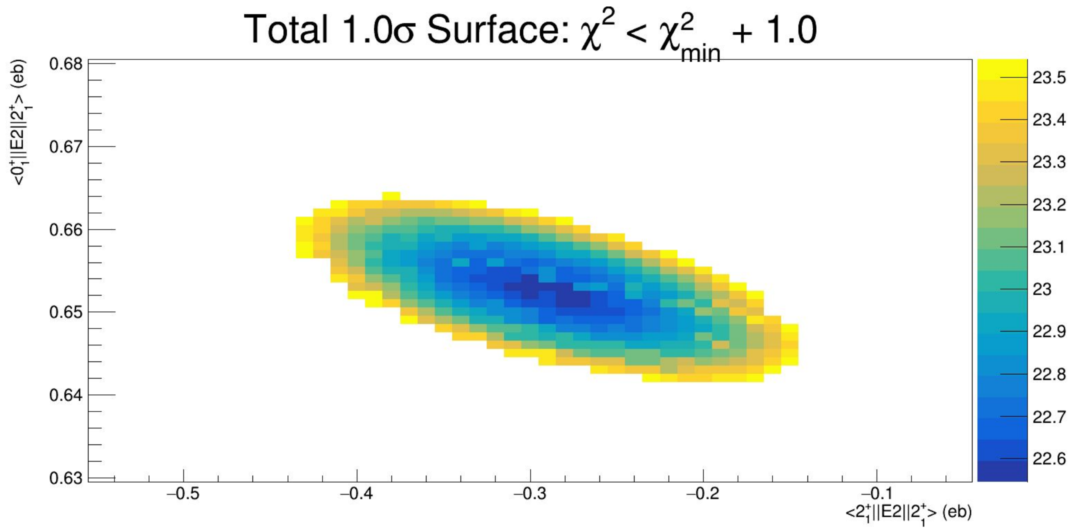
# Expectations from Theory

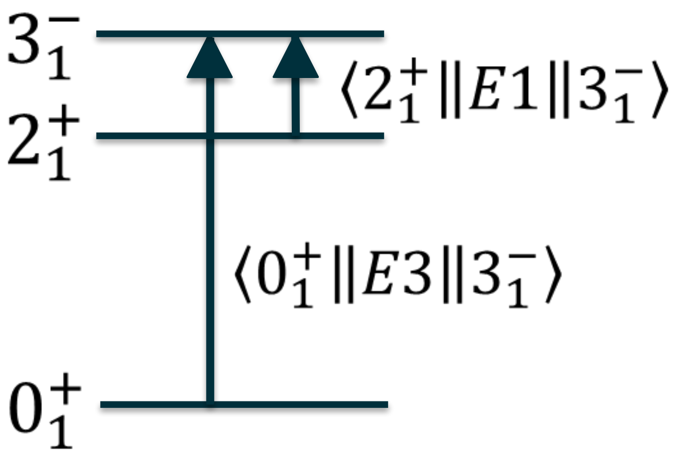
- Expected several thousand counts of $2_1^+ \rightarrow 0_1^+$ for all three isotopes
- Expected several hundred counts of $4_1^+ \rightarrow 2_1^+$ for all three isotopes

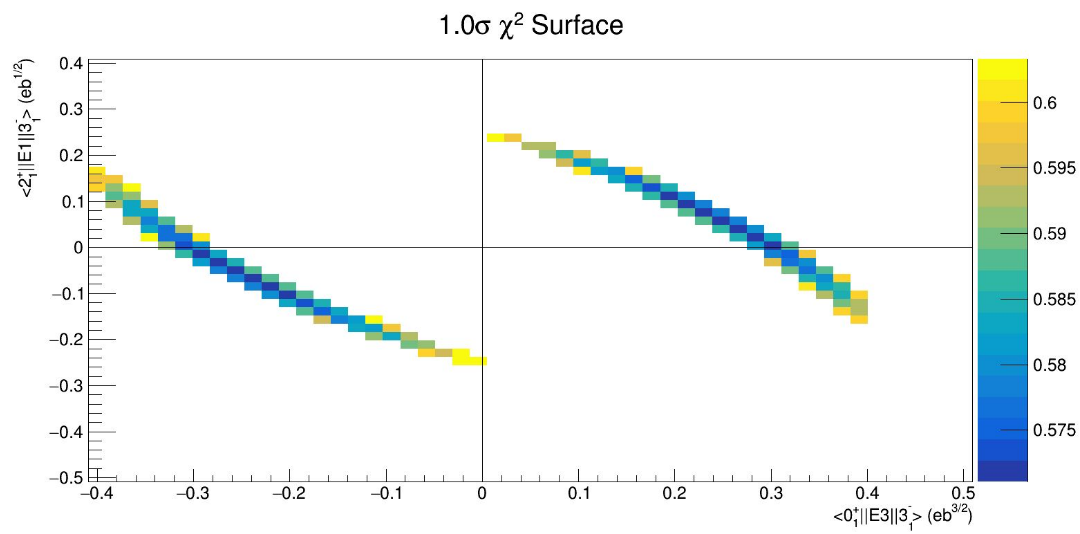


# Correlated Fit Parameters for $^{106}$Cd



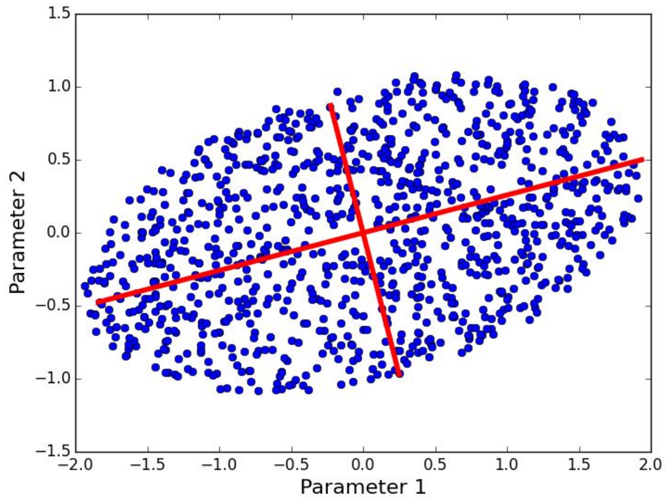



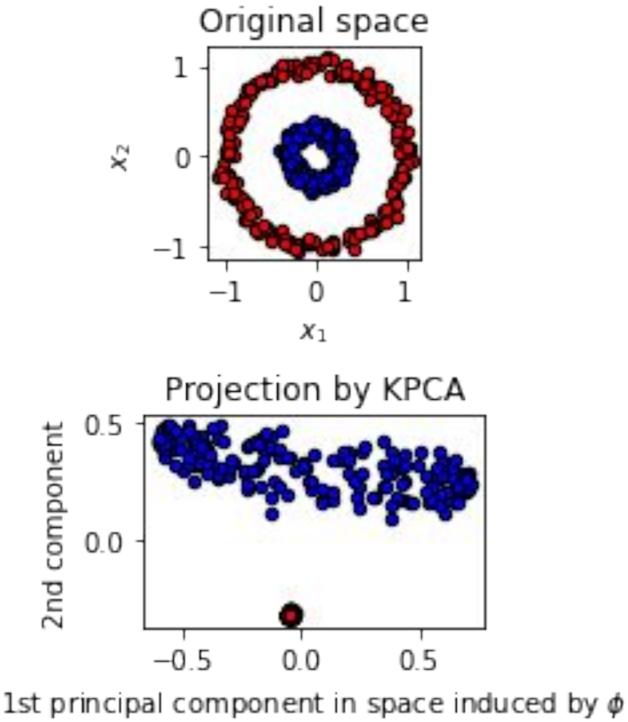
# Principal Components Analysis

- PCA finds linear combinations of parameters which maximize the variance of the data
- Mathematically a singular value decomposition
- $u_{(1)} = \max_u \frac{u^T X^T X u}{u^T u}$
- $u_{(i)} = \max_u \frac{u^T X^T X u}{u^T u}$ such that $u_{(i)} \neq u_{(j)}, j < i$
- Component eigenvalues are proportional to the fraction of the total variance they represent



# Kernel PCA

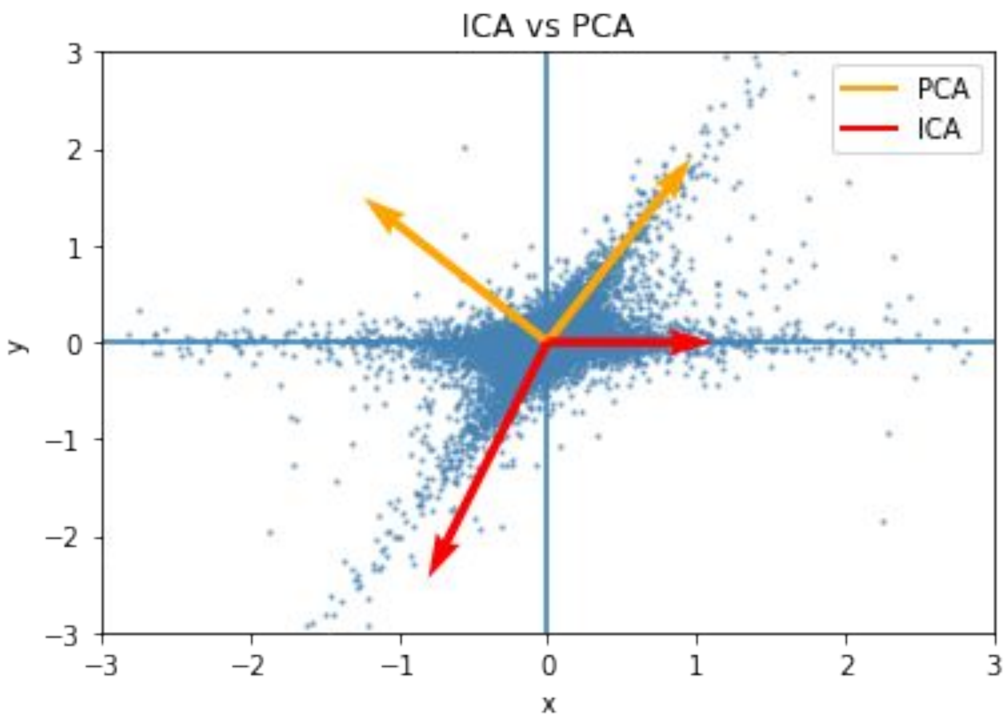
- Kernel PCA technique can find nonlinear correlations in the data
- $\phi(x_i)$ maps the data into a reproducing kernel Hilbert space (RKHS)
- Gram matrix K is defined by the inner produce of each pair of points in the RKHS
  - $K_{ij} = k(x_i, x_j) = \langle \phi(x_i), \phi(x_j) \rangle$
- Apply standard PCA to the Gram Matrix
  - $u_{(1)} = \max_u \frac{u^T K u}{u^T u}$
  - $u_{(i)} = \max\limits_u \frac{u^T K u}{u^T u}$ such that $u_{(i)} \neq u_{(j)}, j < i$




[15] Scikit-learn: Machine Learning in Python, Pedregosa et al., JMLR 12, pp. 2825-2830, 2011.

# Independent Components Analysis

- ICA learns components which are linear combinations of the original parameters, but are not necessarily orthogonal to each other
- Uses a cost function to minimize mutual information and maximize component variance
- Many different possible cost functions and implementations




[15] Scikit-learn: Machine Learning in Python, Pedregosa et al., JMLR 12, pp. 2825-2830, 2011.