Lawrence Livermore National Laboratory

Physical Sciences

Narrowing of the *sd-pf* shell gap in radioactive ^{29}Na

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Overview

Motivation:

- Why measure ^{29}Na [$T_{1/2}$ = 44.9 ms]?

Experimental highlights:

- TRIUMF/ISAC-II + TIGRESS/BAMBINO
- Coulomb excitation of ^{29}Na @ 70 MeV on ^{110}Pd

Results and interpretation:

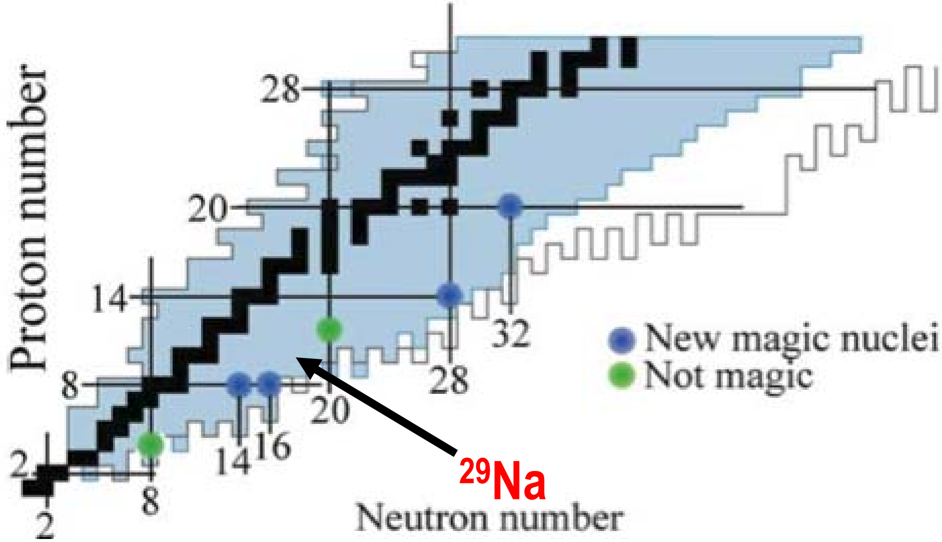
- coincident γ-ray spectroscopy of ^{29}Na
- $\mathcal{M}(E2; 3/2^+ \rightarrow 5/2^+)$ value for ^{29}Na
- structural implications for ^{29}Na

Summary and outlook

Physical problem: ^{29}Na

Motivation:

- Test predictive capability of *modern* nuclear theory
- ^{29}Na is at the transitional region for breakdown of *traditional* shell model
- Magic number *N = 20* vanishes for exotic nuclei (extreme *N/Z* ratio)



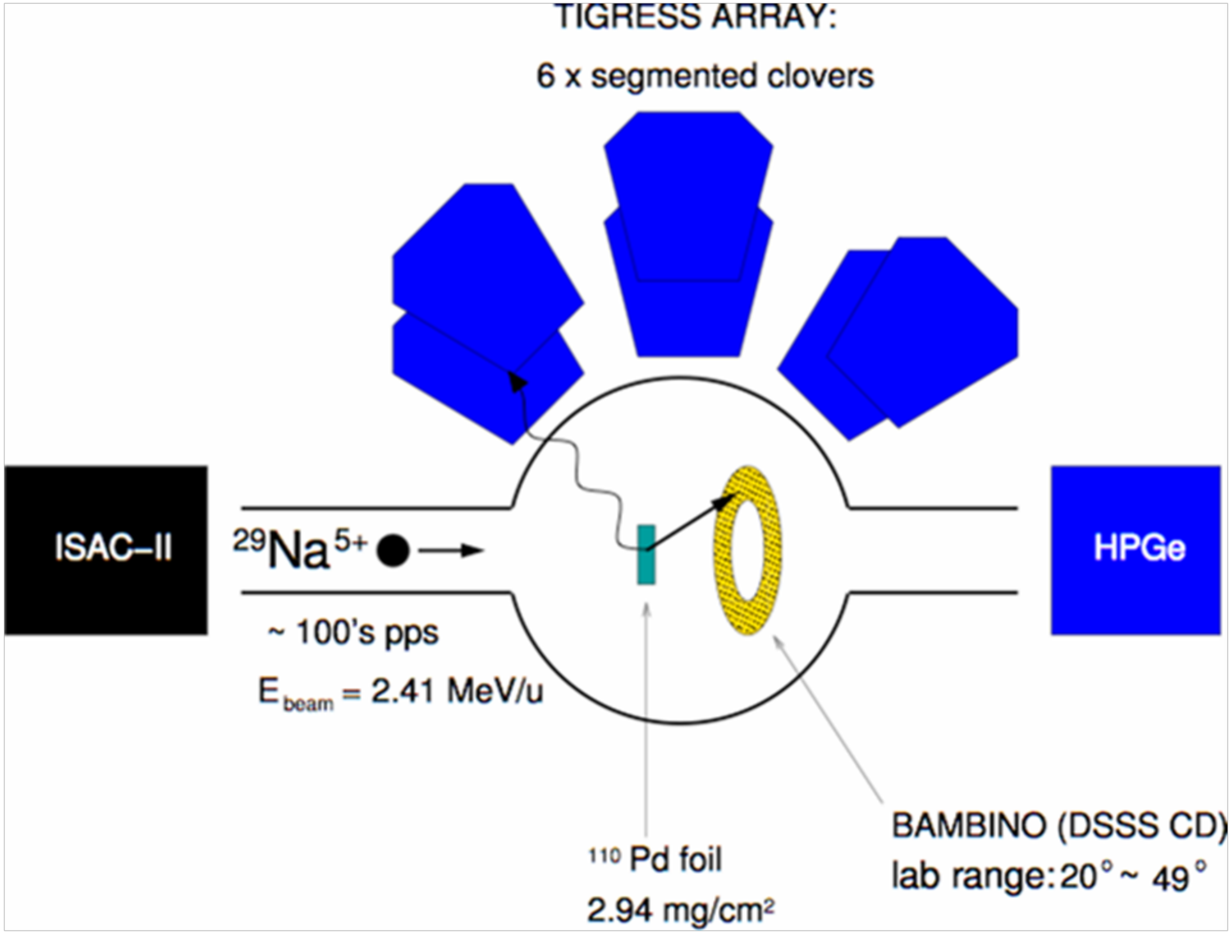
Goal:

- Quantify the configuration mixing between the *sd* and *pf* major shells in ^{29}Na
- Measure transition *M(E2)* to first excited state in ^{29}Na; sensitive to strength of shell gap

Methodology:

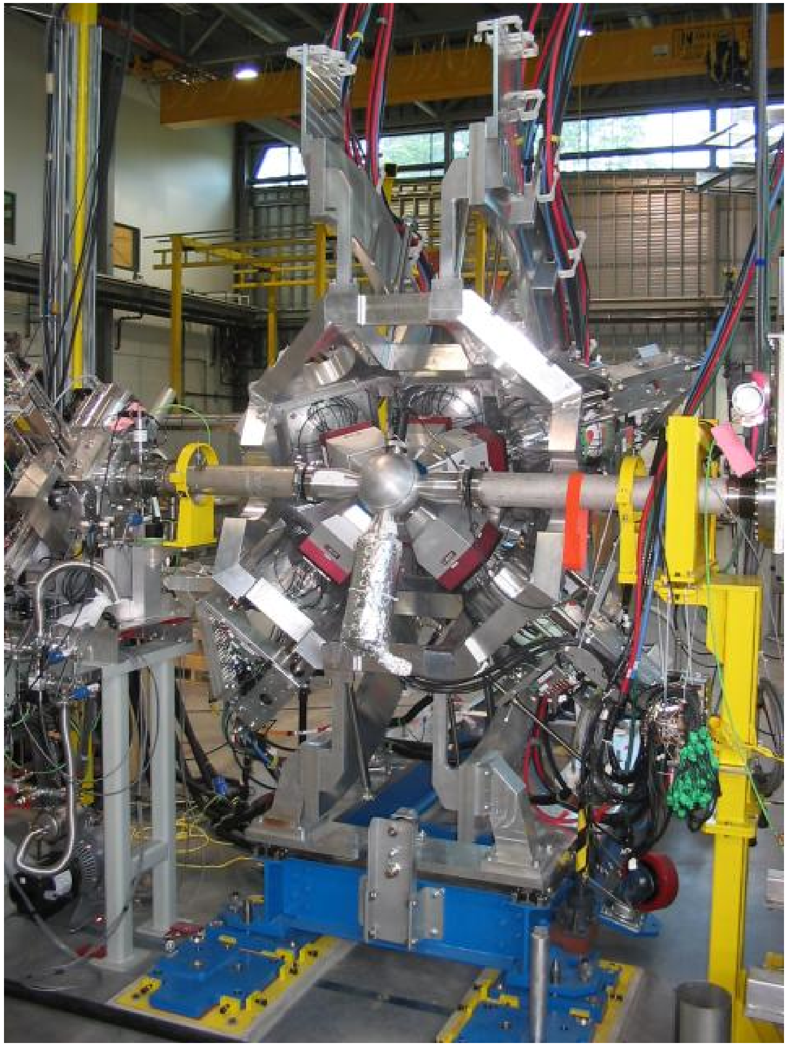
- Sub-barrier Coulomb excitation (Coulex)
- Post accelerated radioactive beam of neutron-rich ^{29}Na @ TRIUMF/ISAC-II

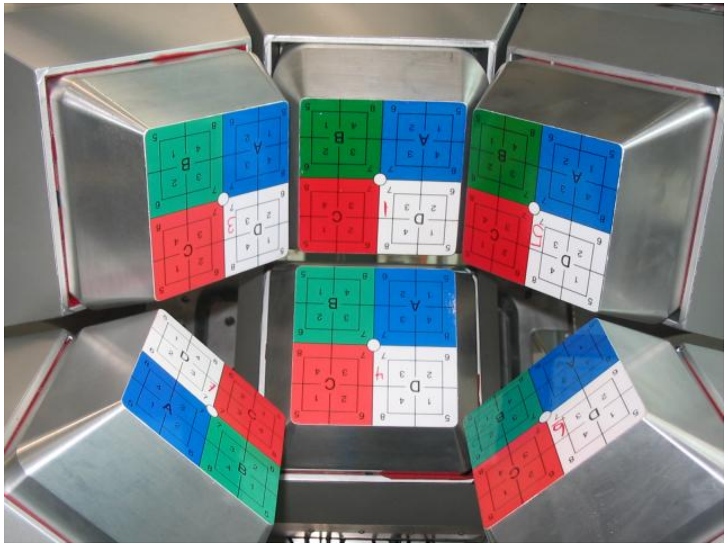
Experimental setup: ^{110}Pd(^{29}Na,^{29}Na*) @ 70 MeV



Measure particle-γ coincidences

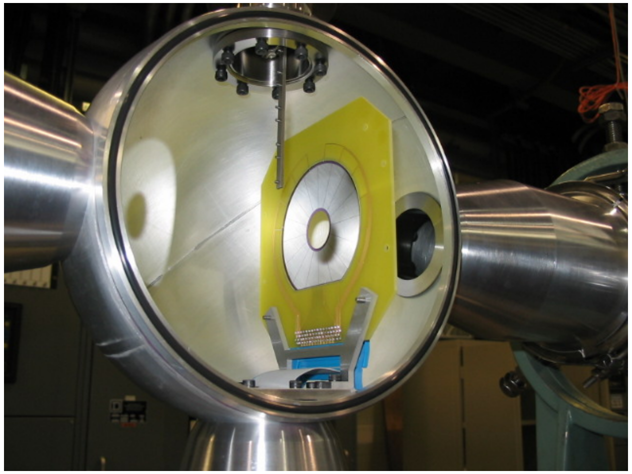
TIGRESS γ-ray spectrometer





- 6 x 32-fold clover detectors
- Each clover mounted with segmented suppression scintillators (BGO and CsI)
- Close geometry around target chamber
- ~36 % of 4π

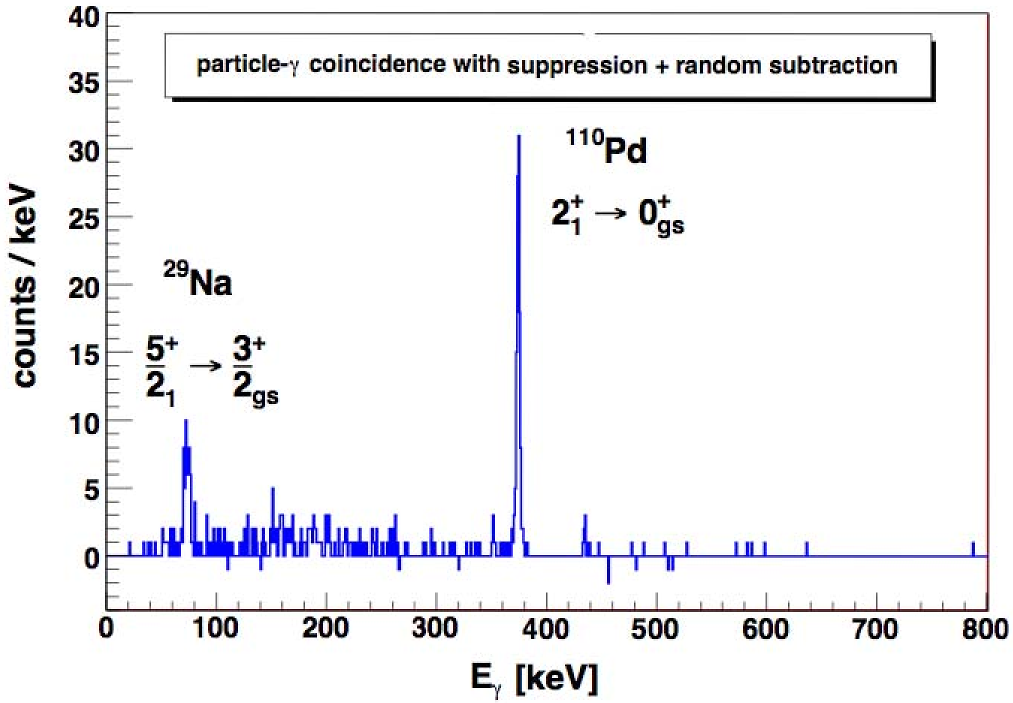
BAMBINO auxiliary particle detector

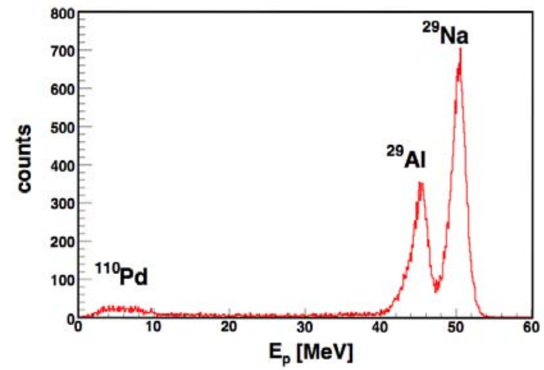


- Provided by LLNL
- Segmented DSSSD for heavy-ion detection: scattered beam and recoiling target particles
- Front face: 32 x sector strips
- Back face: 24 x annular rings

Coulomb excitation of ^{29}Na + ^{110}Pd @ 70 MeV

Any particle-γ coincidence: projectile + recoil





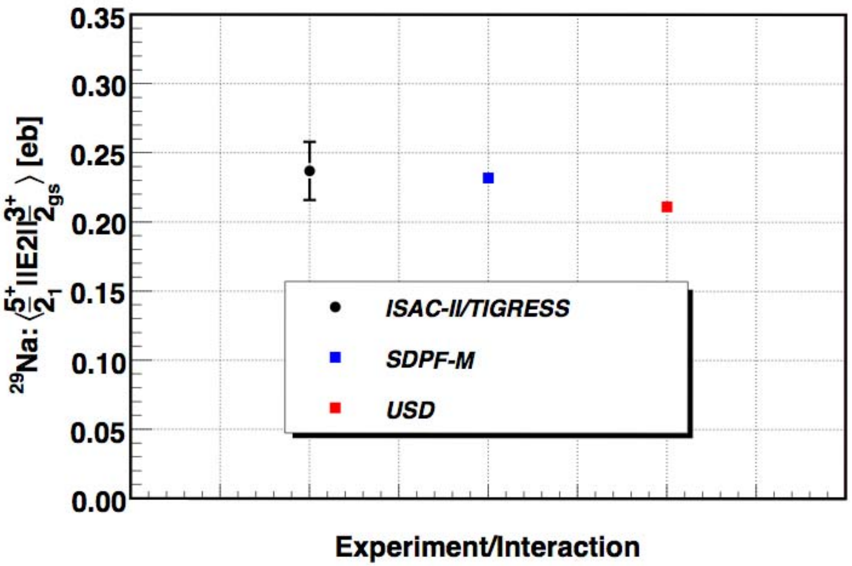
BAMBINO: enables ^{29}Na/^{29}Al isobar separation

Beam on target ~ 70 h

Intensity ~ 600 pps

$$\sigma_{CE}(^{29}\mathrm{Na}) = \frac{N_\gamma(^{29}\mathrm{Na})}{N_\gamma(^{110}\mathrm{Pd})} \cdot \frac{\varepsilon_\gamma(^{110}\mathrm{Pd})}{\varepsilon_\gamma(^{29}\mathrm{Na})} \cdot \frac{W_\gamma(^{110}\mathrm{Pd})}{W_\gamma(^{29}\mathrm{Na})} \cdot \sigma_{CE}(^{110}\mathrm{Pd})$$

Results: extracted $\langle 5/2^+_1 || E2 || 3/2^+_{gs} \rangle$ for ^{29}Na



EXPT [eb]	SDPF-M [eb]	USD [eb]
0.237(21)	0.232	0.211

SDPF-M: *sd*, $p_{3/2}f_{7/2}$ **shell-model spaces + cross-shell mixing**

USD: constrained ***sd*** **shell-model space (universal** ***sd*****)**

Calculations: Y. Utsuno *et al*., PRC **70**, 044307 (2004)

Coulomb-excitation measurement:

- Consistent with SDPF-M calculation
- Aligned with previous work, e.g. $I_{gs} = 3/2^+_{gs}$, spectroscopic *Q*, consistent with SDPF-M prediction
- Neutron excitations across *sd-pf* shell gap: 30 ~ 40% 2p-2h admixture in $\psi(5/2^+_1)$
- Consistent with narrow *sd-pf* neutron shell gap of ~ 3 MeV (c.f. ~ 6 MeV along line of β-stability)

Strong evidence for *sd-pf* shell mixing in $3/2^+_{gs}$ and $5/2^+_1$ in ^{29}Na

Phenomenological analysis:

- *B(E2)* ≈ 18 W.u., large overlap of ground and first excited states: enhanced transition probability
- Rotational model: intrinsic quadrupole moment derived according to:
  - (1) transition matrix element: Q_t = 0.524(46) eb
    c.f. SDPF-M calculation: Q_t = 0.513 eb
  - (2) static quadrupole moment: Q_0 = 0.430(15) eb
    c.f. SDPF-M calculation: Q_0 = 0.455 eb

Summary and outlook

• We have performed a successful Coulomb excitation measurement with a very low-flux radioactive-ion beam with only a few hundred pps - beyond the expectations of the community.

• Opens the door to the ever-more exotic nuclei with a few tens of pps when the next generation of γ-ray detector arrays (AGATA and GRETA) come online.

• First-ever measurement of transition probability between ground and first-excited state in ^{29}Na.

• Most neutron-rich Na isotope where this measurement has been made using the ISOL technique.

• ^{29}Na is the most striking example where such large degrees of mixing between normal (*sd*) and intruder (*pf*) configurations have been observed at the boundary to the island of inversion.

• TRIUMF/ISAC-II experiments are in the production phase providing new and exciting data that challenge current shell-model theories.

• ^{29}Na results have been submitted for publication.

Meaningful test of theoretical predications requires measurements in a region, not just a solitary nucleus

• Extend our measurements to ^{30}Na and ^{31}Mg after 2010 - working with TIGRESS collaboration at TRIUMF with accompanying theoretical support from LLNL.

TIGRESS Collaboration

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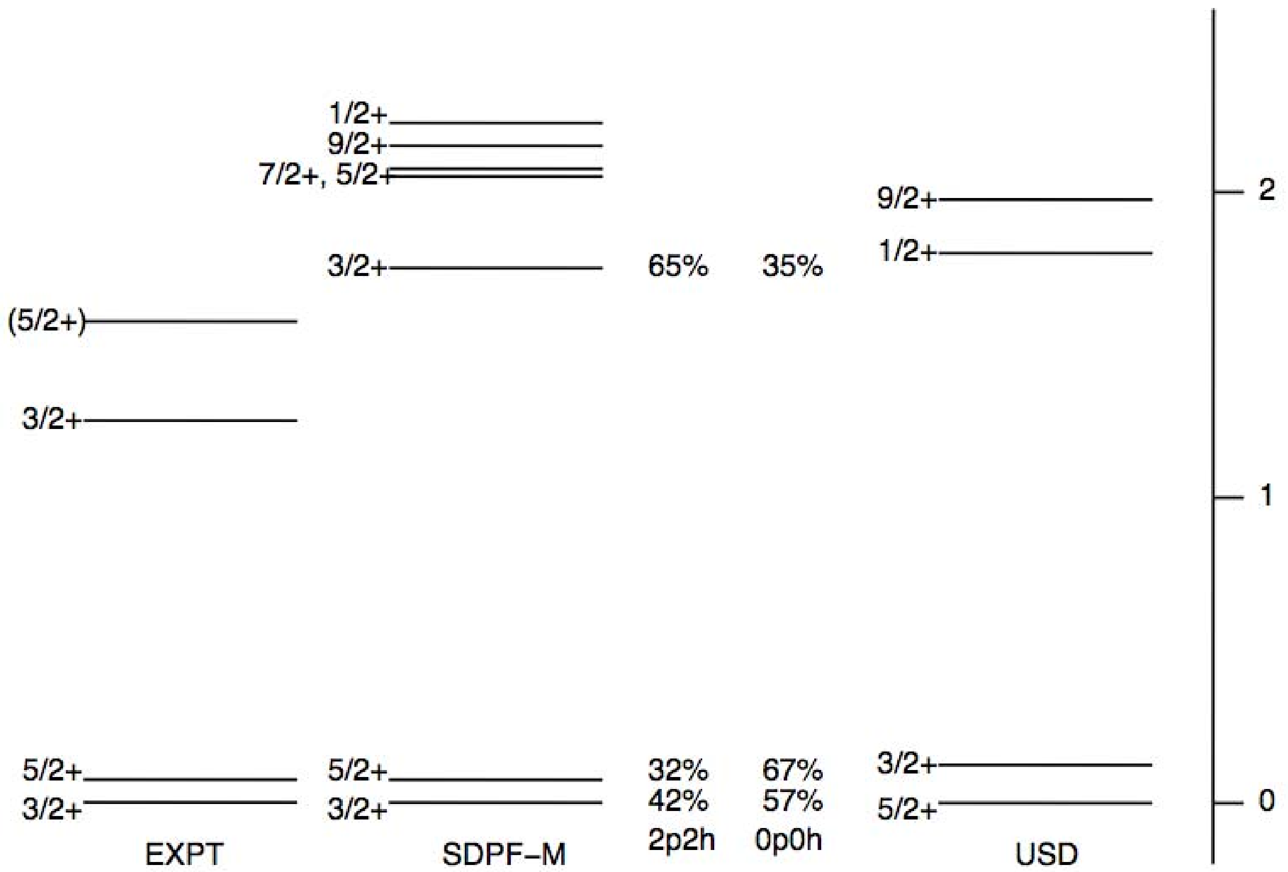
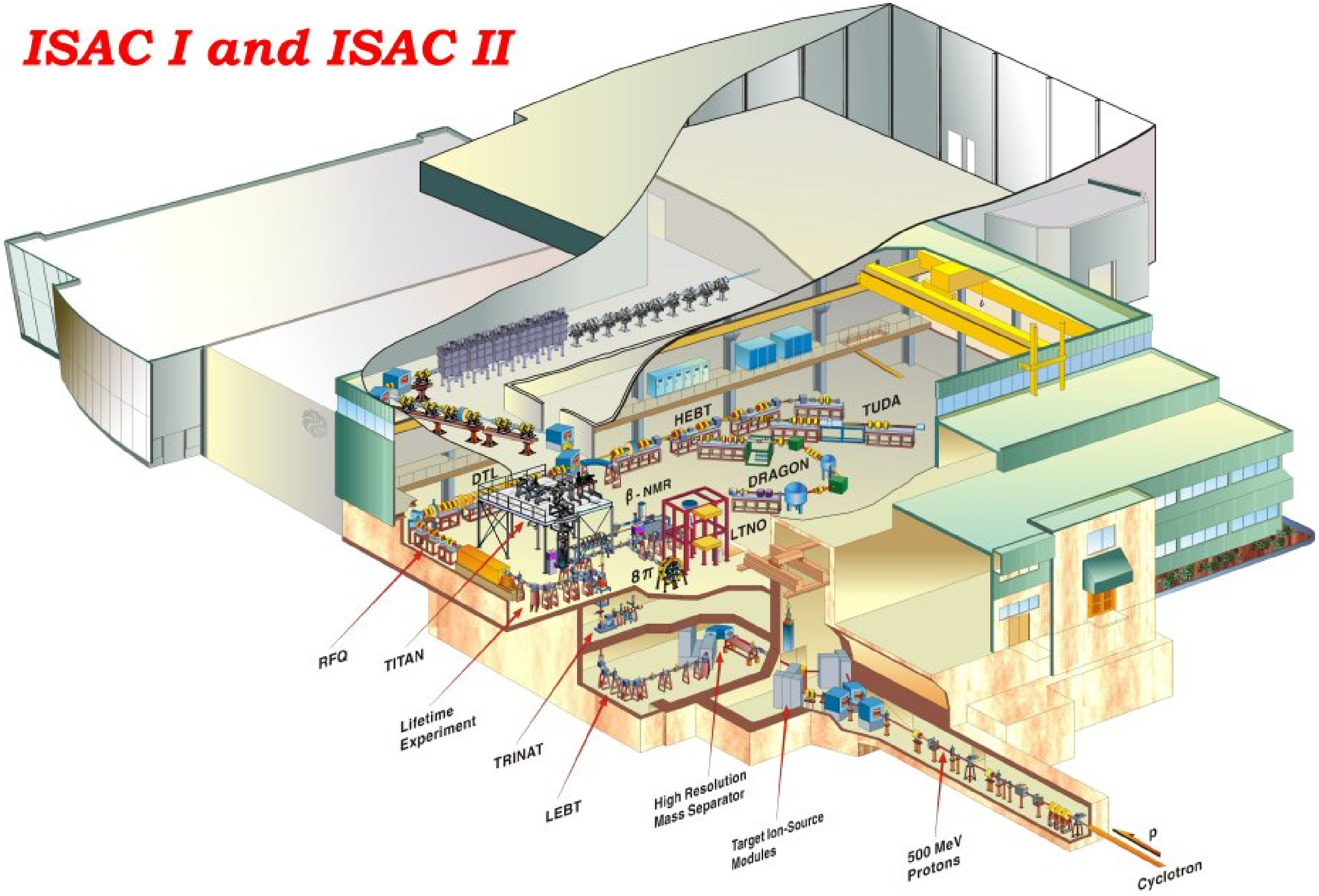
^{29}Na shell-model calculations



V. Tripathi *et al*., PRC **76**, 021301(R) (2007)

ISOL @ TRIUMF



- 500 MeV, 70 μA proton beam + ^{nat}Ta production target
- Produce ^{29}Na atoms
- ^{nat}Re surface-ion source
- Produce $^{29}Na^{+}$ ions
- Stripper foil
- Produce $^{29}Na^{5+}$ ions
- ISAC-II: *A/q* = 5.8

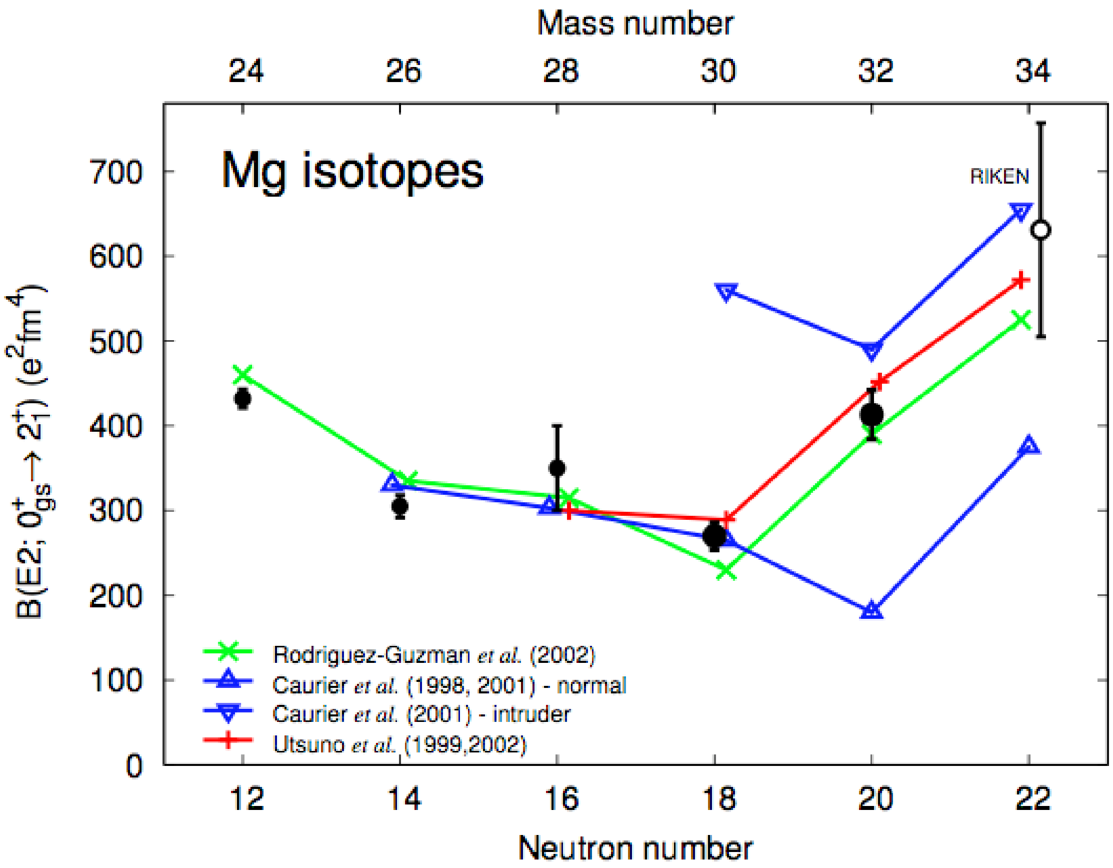
What we know about Na isotopes with $N \approx 20$

- ☐First observation of $^{27\text{-}31}$Na isotopes
  R. Klapisch *et al.*, PRL **23**, 652 (1969)
- Anomalously large binding energies revealed in ^{31,32}Na
  C. Thibault *et al.*, PRC **12**, 644 (1975)
- Ground-state magnetic moments and spins of $^{26\text{-}30}$Na isotopes
  G. Huber *et al.*, PRC **18**, 2342 (1978)
- Ground-state quadrupole moments of $^{26\text{-}29}$Na
  M. Kieim *et al.*, EPJA **8**, 31 (2000)
- Shell model calculations: *B(E2)* predictions for ^{29}Na
  Y. Utsuno *et al.*, PRC **70**, 044307 (2004)

SDPF-M	USD
135 e^2fm^4	111 e^2fm^4

- β-decay spectroscopy of ^{29}Na: detailed level scheme + interpretation of states
  V. Tripathi *et al.*, PRL **94**, 162501 (2005)

What is the signature of shell model breakdown?



- *B(E2)* values are a good indication e.g. systematics for even-even Mg [*Z* = 12] isotopes
- Experimental *B(E2)* values reverses trend predicted by traditional shell model (increase rather than decrease)
- Traditional shell model breakdown at *N* = 20 and *A* ≈ 30
- Inversion of *sd* - *pf* shell-filling sequence due to change in the effective NN interaction for nuclei with extreme isospin

Develop systematics for Na [*Z* = 11] isotopes

Experimental method

We want to extract a value for $\sigma_{CE}(^{29}Na)$ from the experimental data

Experimental observable: $N_\gamma \propto L \cdot \sigma_{CE}$ beam luminosity: $L = I_b \left(\frac{N_A}{A} \right)_t$

Absolute measurement of Coulex cross section:

$$N_\gamma = \varepsilon_\gamma \cdot W_\gamma \cdot \sigma_{\mathrm{CE}} \cdot L \cdot \varepsilon_{\mathrm{sys}}$$

DIFFICULT!

- Radioactive beam flux varies throughout experiment. Difficult to get an accurate handle on beam intensity
- Many Systematic uncertainties e.g. dead time of data acquisition, beam energy, target thickness, particle detection efficiency…..
- Need to account for all systematic uncertainties
- Cross section with very large error bar!

Coulomb-excitation cross section $\sigma_{CE}(^{29}\mathrm{Na})$

Remove as many sources of error as possible

PROJECTILE EXCITATION:

$$N_\gamma(^{29}\mathrm{Na}) = \varepsilon_\gamma(^{29}\mathrm{Na}) \cdot W_\gamma(^{29}\mathrm{Na}) \cdot \sigma_{\mathrm{CE}}(^{29}\mathrm{Na}) \cdot L \cdot \varepsilon_{\mathrm{sys}}$$

TARGET EXCITATION:

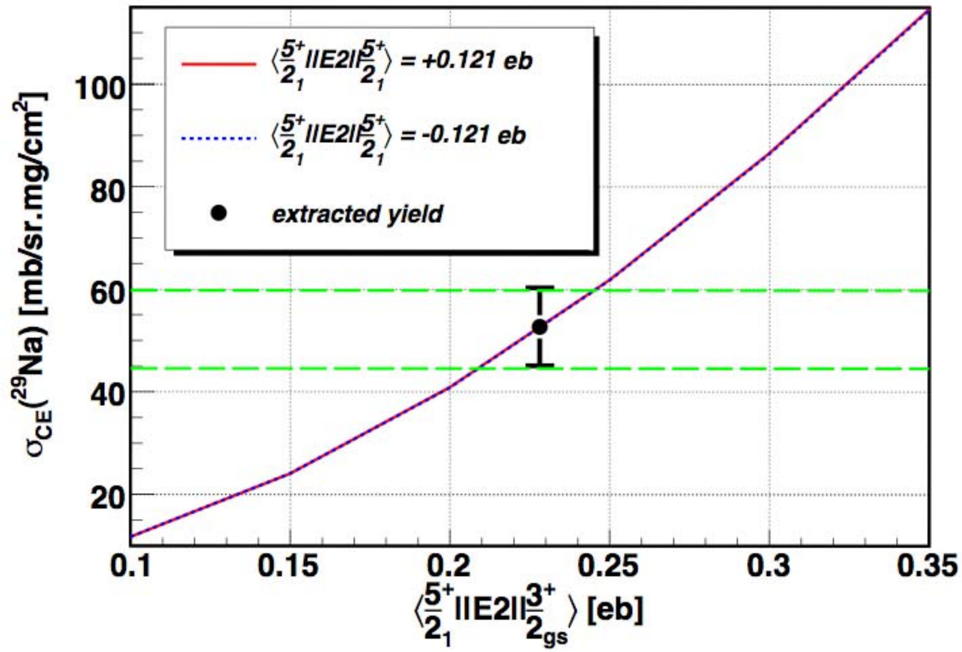
$$N_\gamma(^{110}\mathrm{Pd}) = \varepsilon_\gamma(^{110}\mathrm{Pd}) \cdot W_\gamma(^{110}\mathrm{Pd}) \cdot \sigma_{\mathrm{CE}}(^{110}\mathrm{Pd}) \cdot L \cdot \varepsilon_{\mathrm{sys}}$$

Take ratios of γ-yields $\Rightarrow$ relative determination of Coulex cross section:

$$\sigma_{\mathrm{CE}}(^{29}\mathrm{Na}) = \frac{N_\gamma(^{29}\mathrm{Na})}{N_\gamma(^{110}\mathrm{Pd})} \cdot \frac{\varepsilon_\gamma(^{110}\mathrm{Pd})}{\varepsilon_\gamma(^{29}\mathrm{Na})} \cdot \frac{W_\gamma(^{110}\mathrm{Pd})}{W_\gamma(^{29}\mathrm{Na})} \cdot \sigma_{\mathrm{CE}}(^{110}\mathrm{Pd})$$

Simplified expression independent of *L* and ε_{sys}

Derivation of *M(E2)* from Coulomb-excitation yield

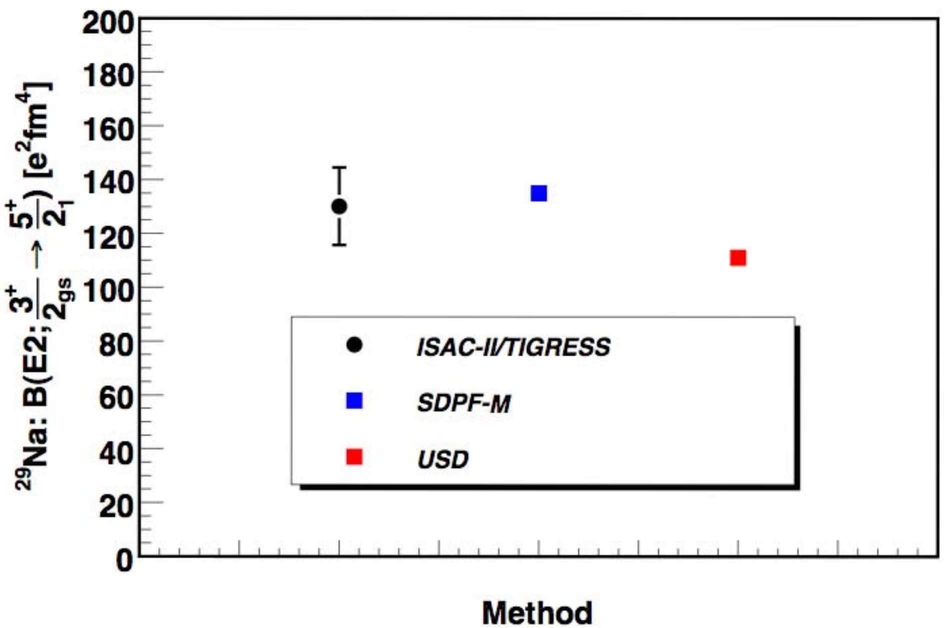


$\sigma_{CE}(^{29}Na)$ [mb]	*M(E2)* [eb]
52.3(78)	0.237(21)

M(E2) **deduced from graphical solution of measured and calculated (GOSIA) Coulomb excitation cross sections**

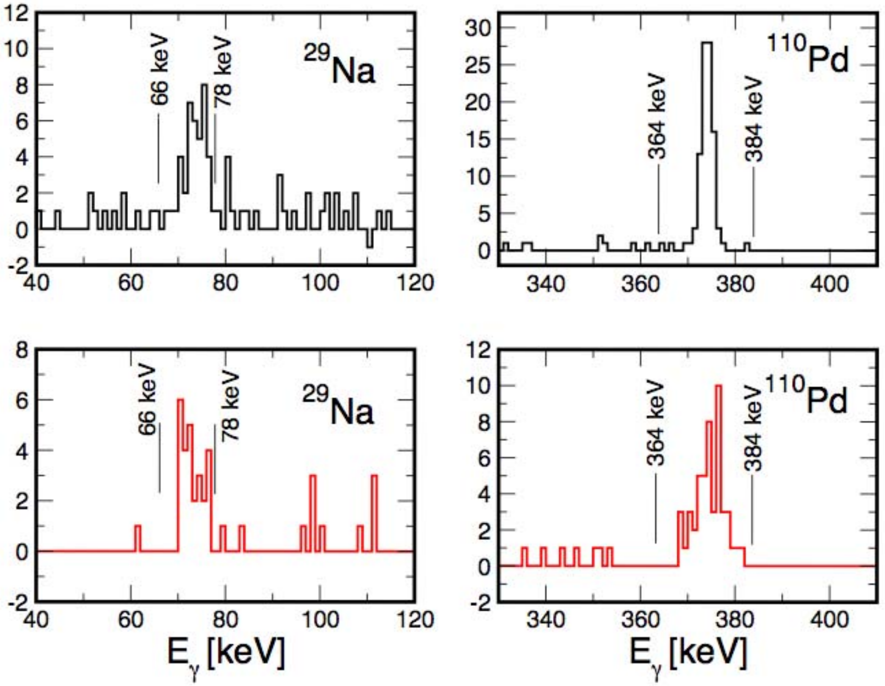
Results: $B(E2; 3/2^+ \rightarrow 5/2^+)$ for ^{29}Na

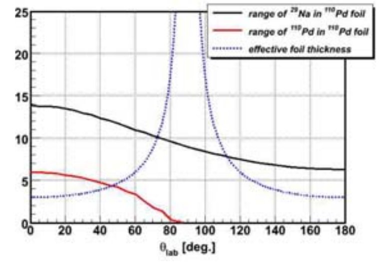
Expt [e^2fm^4]	SDPF-M [e^2fm^4]	USD [e^2fm^4]
140(25)	135	111

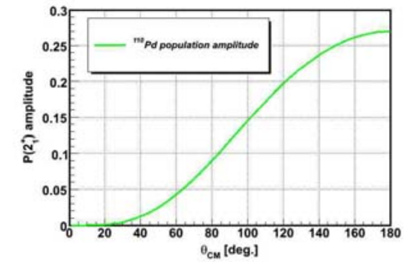


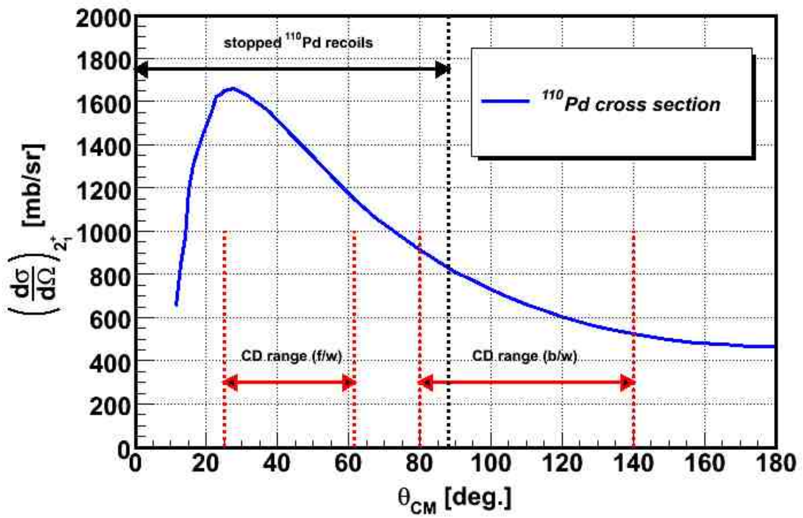
- **Experimental result favours SDPF-M calculation (consistency at 1-σ level)**
- **Result is indicative of a strongly mixed configuration; with an intruder *pf* states comprising ~32 % of the wave function**
- **Result supports narrowing of *sd-pf* shell gap from ~6 MeV in stable nuclei to ~3.25 MeV in ^{29}Na**
  [Y. Utsuno *et al.*, PRC **70**, 044307 (2004)]
- **Auxiliary-Field MCSM calculations by LLNL theory group in progress**

Back-up: γ-ray spectroscopy of ^{29}Na + ^{110}Pd









$$E_{\rm DS} = \frac{E_0\sqrt{(1-\beta^2)}}{1-\beta(\cos(\theta_{\rm p,\gamma}))}$$

Back-up: ^{110}Pd yield correction

$^{110}Pd(^{29}Na,^{29}Na^{*}) + {}^{110}Pd(^{29}Al,^{29}Al^{*}) \Rightarrow {}^{110}Pd^{*}$ excitation

Need correction factor to $N_{\gamma}(^{110}Pd)_{tot}$

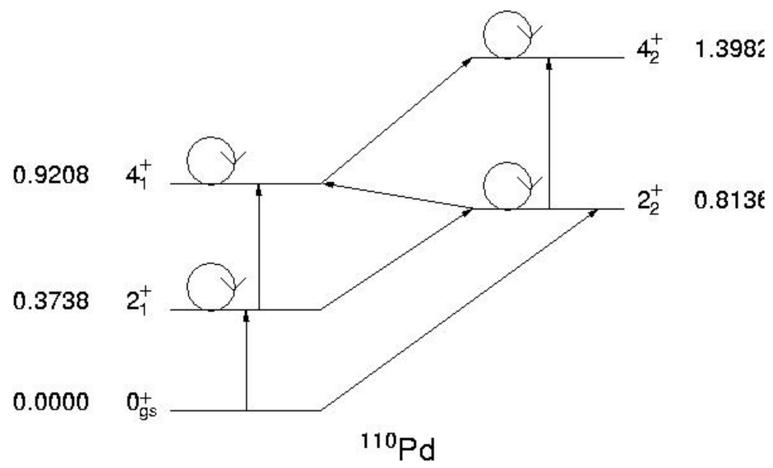
$$N_{\gamma}(^{110}\mathrm{Pd})_{\mathrm{tot}} = N_{\gamma}(^{110}\mathrm{Pd})_{\mathrm{Na}} + N_{\gamma}(^{110}\mathrm{Pd})_{\mathrm{Al}}$$

Get expression for $N_{\gamma}(^{110}Pd)_{Al}$ in terms of $N_{\gamma}(^{110}Pd)_{Na}$

$$\frac{N_{\gamma}(^{110}\mathrm{Pd})_{\mathrm{Al}}}{N_{\gamma}(^{110}\mathrm{Pd})_{\mathrm{Na}}} = \frac{f(^{29}\mathrm{Al}) \cdot \sigma_{\mathrm{CE}}(^{110}\mathrm{Pd})_{\mathrm{Al}}}{f(^{29}\mathrm{Na}) \cdot \sigma_{\mathrm{CE}}(^{110}\mathrm{Pd})_{\mathrm{Na}}}$$

Back-up: GOSIA calculations

GOSIA: semi-classical code used to calculate integrated γ-ray yields i.e. Coulomb excitation cross sections

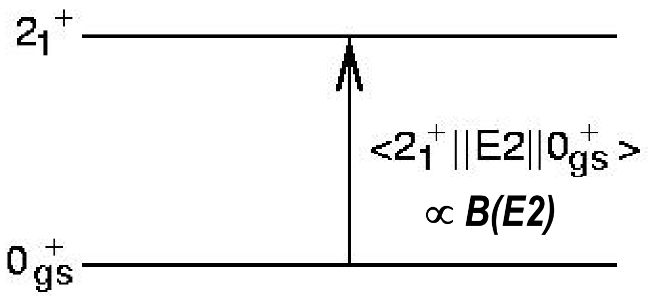


$$M(^{110}\mathrm{Pd};E2)=\begin{pmatrix} 0 & 0.919(24) & -0.096(3) & 0 & 0 \\ 0.919(24) & -0.87(16) & -0.863(14) & 1.579(21) & -0.066(14) \\ -0.096(3) & -0.863(14) & 0.70(20) & 0.51(22) & 0.97(4) \\ 0 & 1.579(21) & 0.51(22) & -1.6(3) & -0.94(5) \\ 0 & -0.066(14) & 0.97(4) & -0.94(5) & -0.01(19) \end{pmatrix}$$

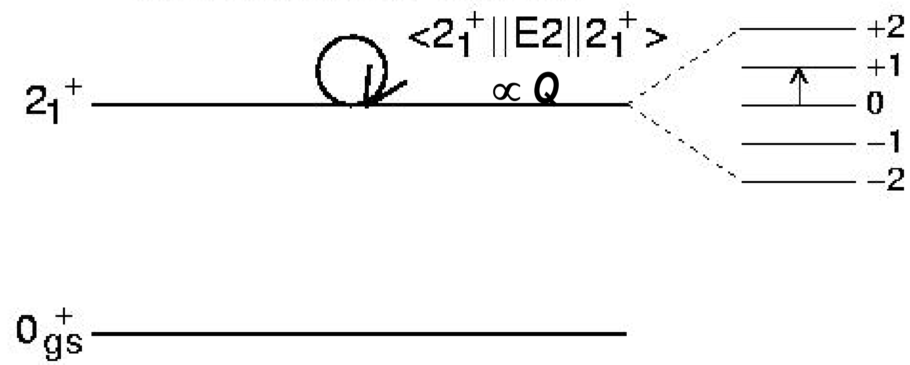
- ^{110}Pd level scheme
- Significant couplings considered in calculation of $\sigma_{CE}(^{110}\mathrm{Pd})$
- Spherical electric quadrupole tensor corresponding to defined level scheme for ^{110}Pd
- Irreducible representation of transitional and diagonal matrix elements
- ^{110}Pd data: University of Rochester, NSRL-338 (1989) [unpublished]
- Calculate $\sigma_{CE}(^{110}\mathrm{Pd})$ directly

Back-up: Reduced matrix elements

Transitional matrix element



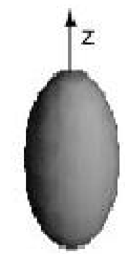
Diagonal matrix element



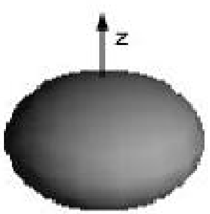
For even-even nuclei

=> if Coulex yield is consistent with:

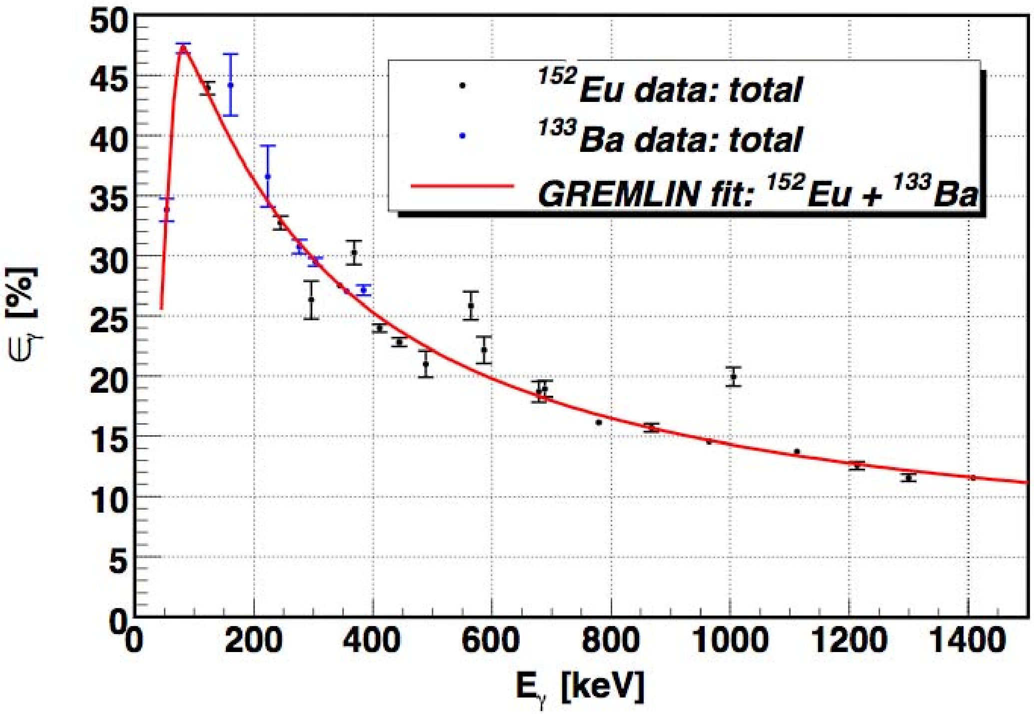
(1) negative $<2_1^+||E2||2_1^+>$ => prolate shape



(2) positive $<2_1^+||E2||2_1^+>$ => oblate shape



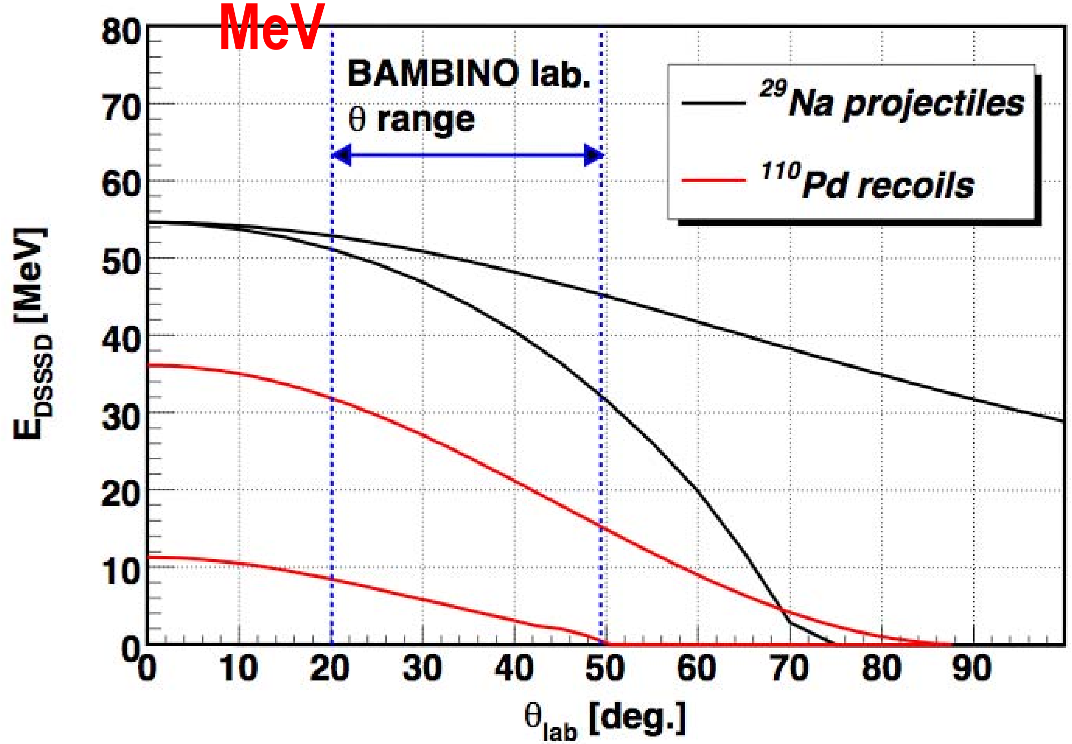
Back-up: Efficiency curve



Determine ε_γ(^{29}Na) and ε_γ(^{110}Pd) from efficiency curve; correction factors for yields N_γ (^{29}Na) and N_γ(^{110}Pd) determined from spectra

Calculated particle kinematics

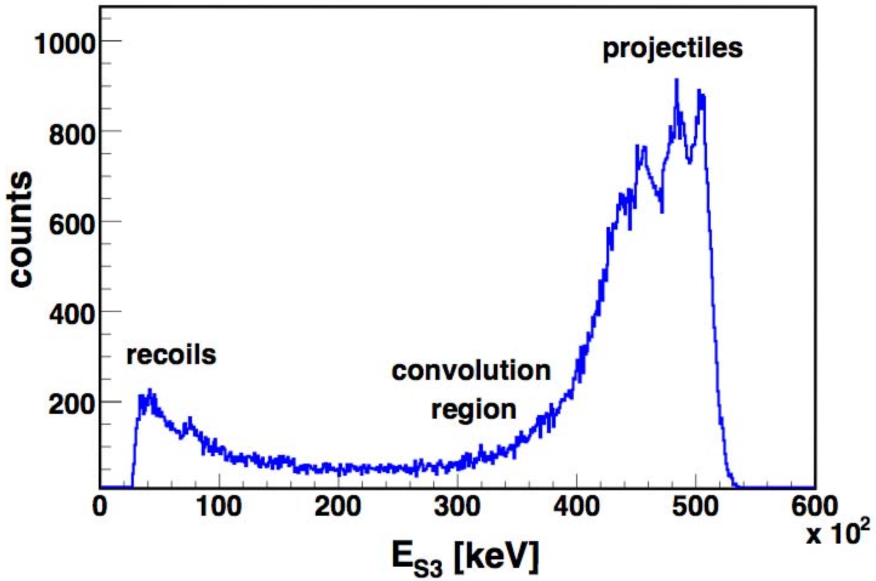
^{110}Pd(^{29}N□a,^{29}Na*) @ 70 MeV



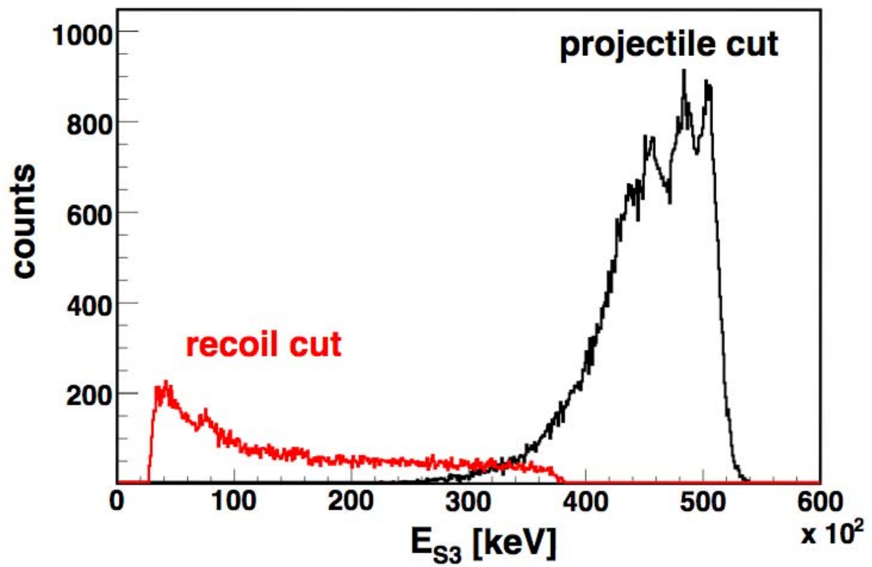
Projectile/recoil *energy* and *angle* enable particle ID [$E_p(\theta_{lab})$]

Particle identification in BAMBINO

All particles

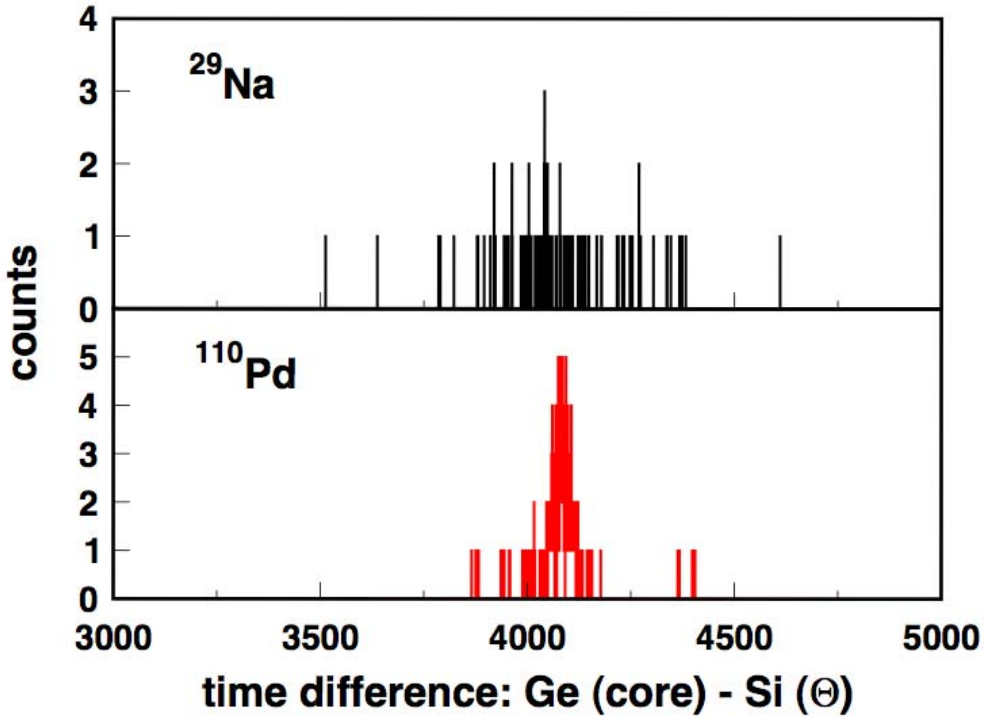


Particle-energy gated



2D energy and angle gating in BAMBINO enables PID

P-γ coincidence measurements: low energy issues?



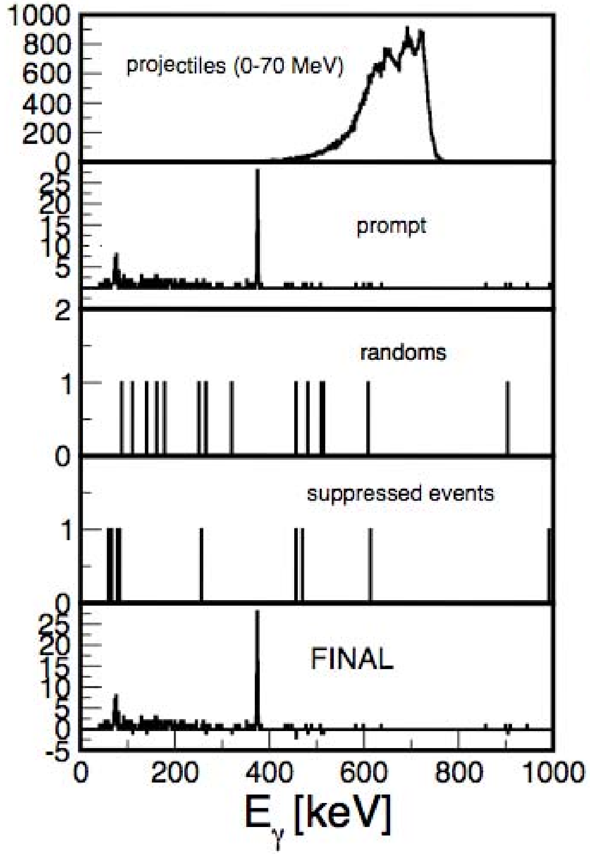
- Particle-γ coincidence time window
- Coincidence ε_γ for low-energy γ rays is an expt. issue
- Poorer timing at low energy: ^{29}Na (E_γ = 72 keV) c.f. ^{110}Pd (E_γ = 374 keV) $\Rightarrow$ broader spectrum!
- Collect ^{29}Na events with max ε_γ
- Determine width of prompt (and random!) windows

- E_γ(^{29}Na) ~ 72 keV [cut: 66 - 78 keV]
- E_γ(^{110}Pd) ~ 374 keV [cut: 364 - 384 keV]

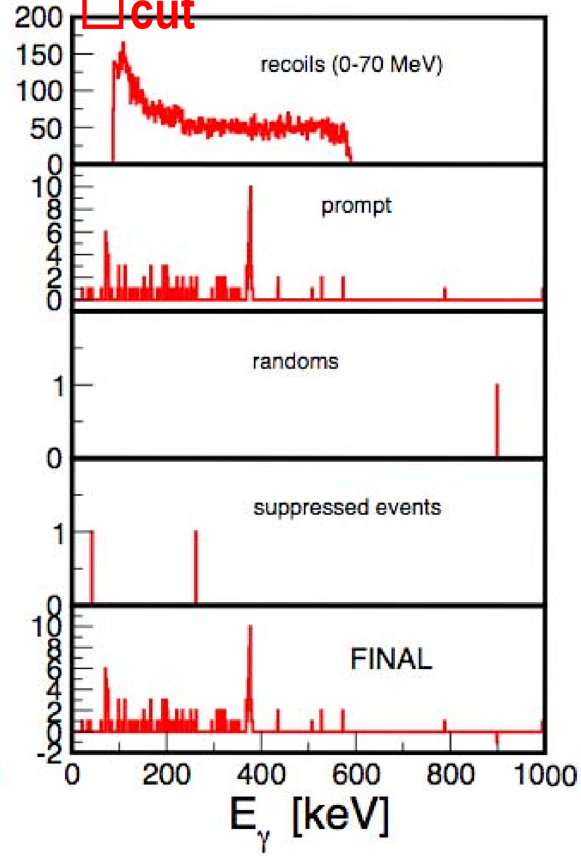
We can operate at E_γ = 72 keV !!!

γ-ray spectroscopy of ^{29}Na + ^{110}Pd

^{29}Na projectile cut

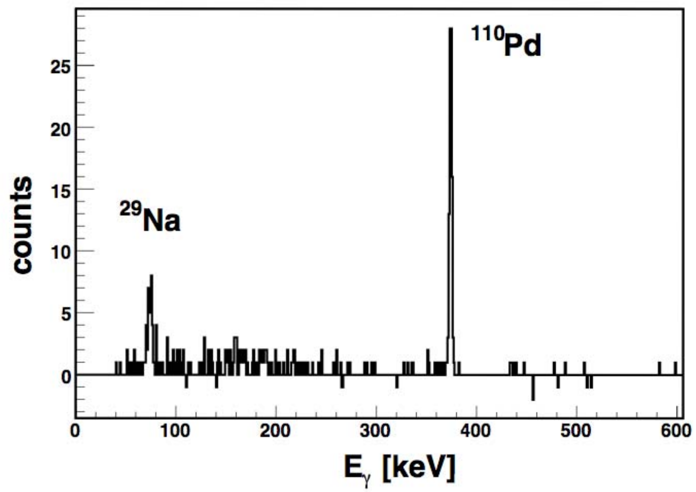


^{110}Pd target recoil □cut

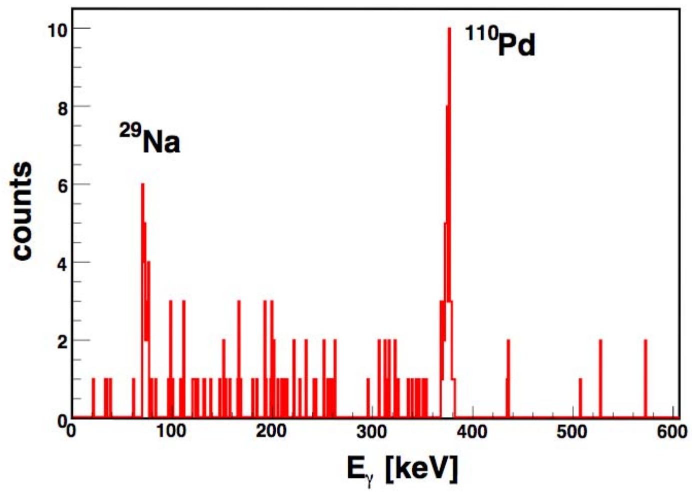


Back-up: Kinematically-constrained events

^{29}Na projectile cut



^{110}Pd target-recoil cut



Calculations assume *M(E2)* = 0.237 eb

Extracted yield [mb]	Calculated yield [mb]
155(30)	144

Extracted yield [mb]	Calculated yield [mb]
61(22)	65

Results are consistent!