Understanding Cross-shell Interaction in Exotic Nuclei: Case of ^{36}Al and ^{36}Si

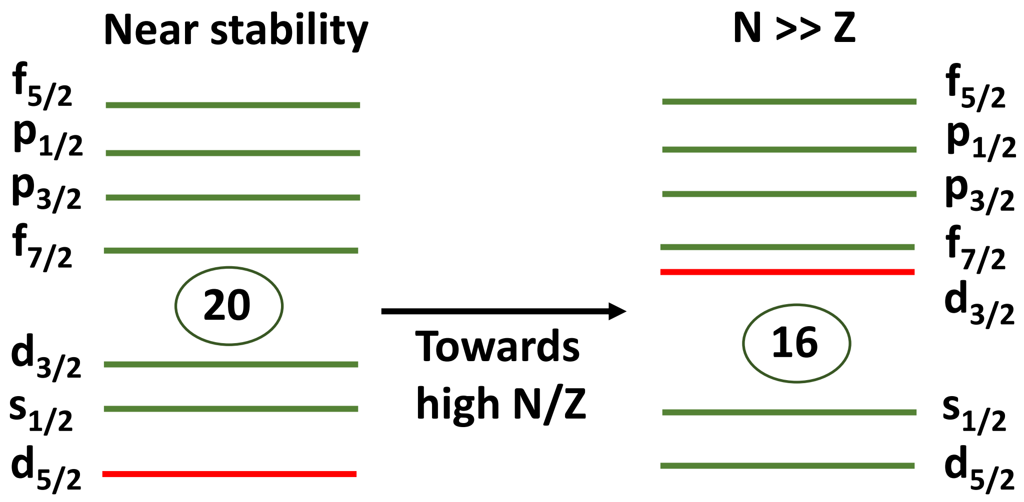
Rebeka Sultana Lubna

Facility for Rare Isotope Beams(FRIB)

This material is based upon work supported by the U.S. Department of Energy Office of Science under Cooperative Agreement DE-SC0000661, the State of Michigan and Michigan State University. Michigan State University designs and establishes FRIB as a DOE Office of Science National User Facility in support of the mission of the Office of Nuclear Physics.

Evolution of Nuclear Shell Structure

- **Nuclear shell gaps and hence the structure chnges for varying N/Z.**
- **Isotopes with N >> Z are rich testing ground for the models.**



- **Onset of deformation.**
- **Disappearance of canonical magic numbers.**
- **Emergence of new magic numbers.**

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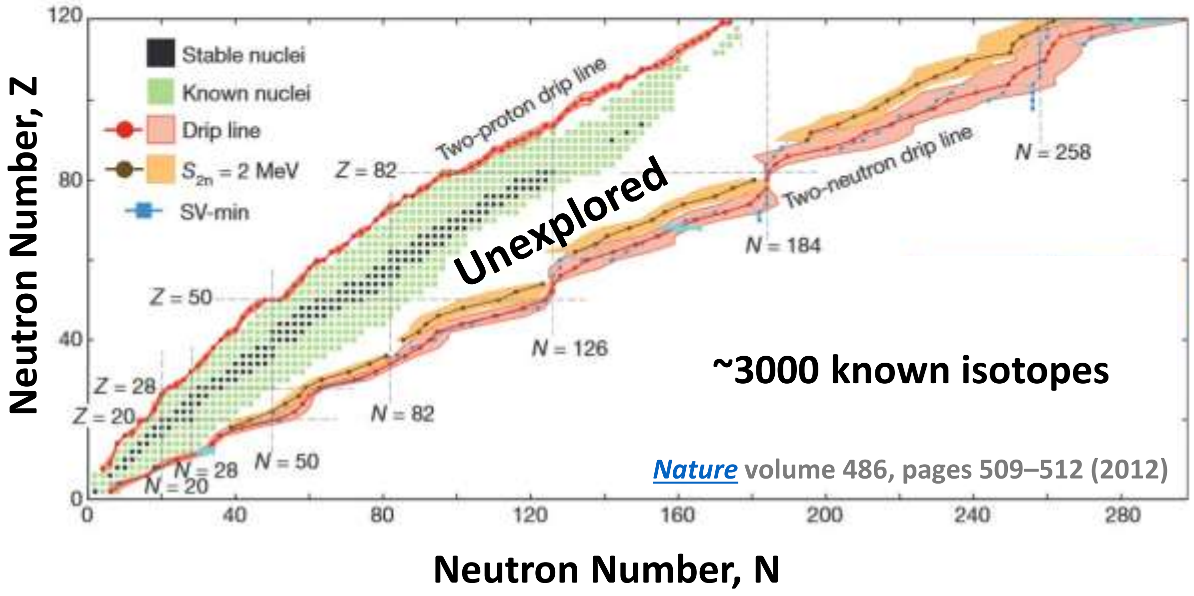
Evolution of Nuclear Shell Structure



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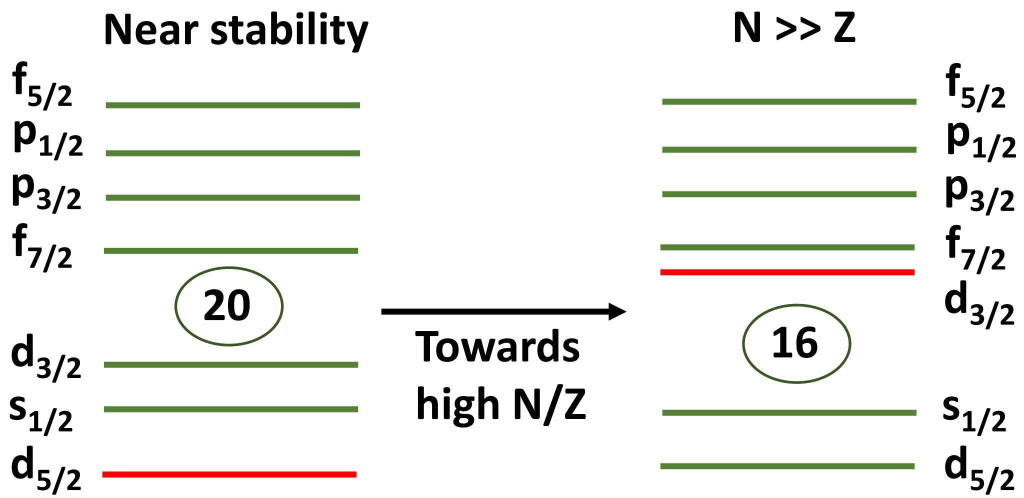

- Systematic study to understand the evolution of nuclear shell structure.
- Pinpoint different components of nuclear force.

- Onset of deformation.
- Disappearance of canonical magic numbers.
- Emergence of new magic numbers.

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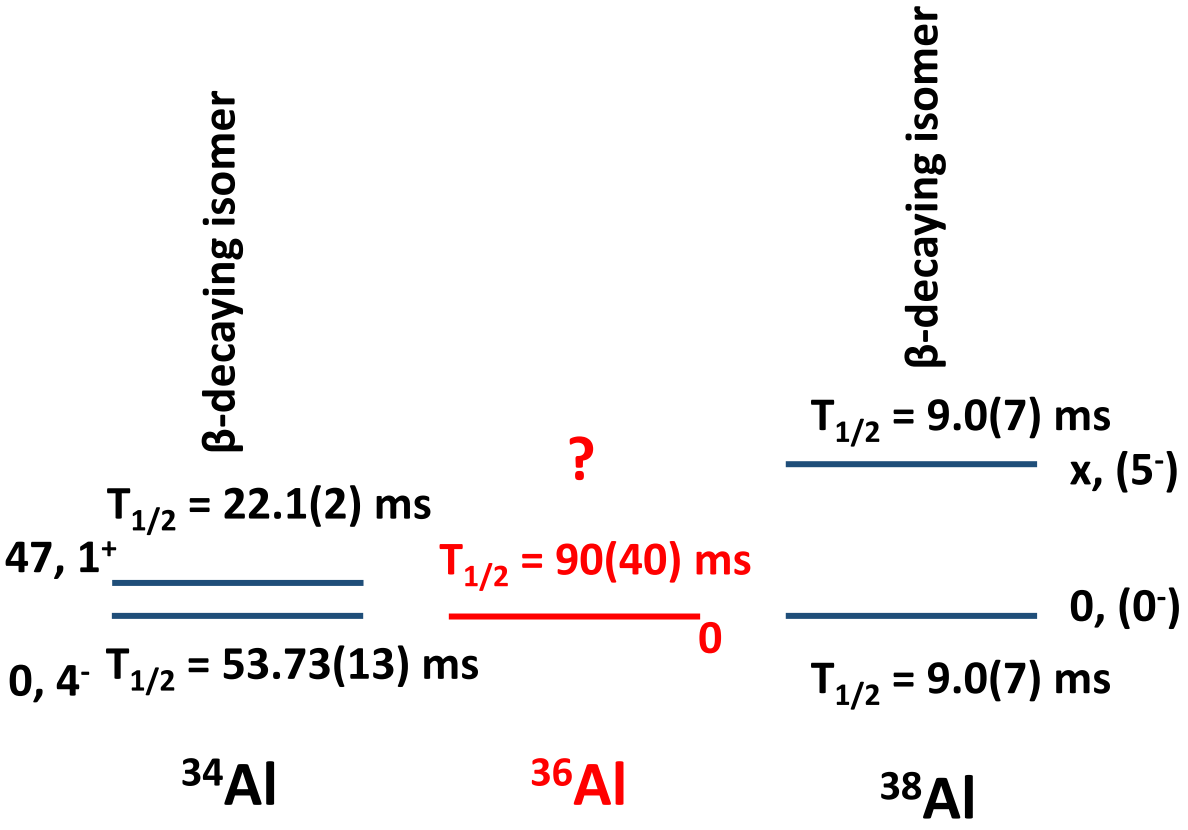
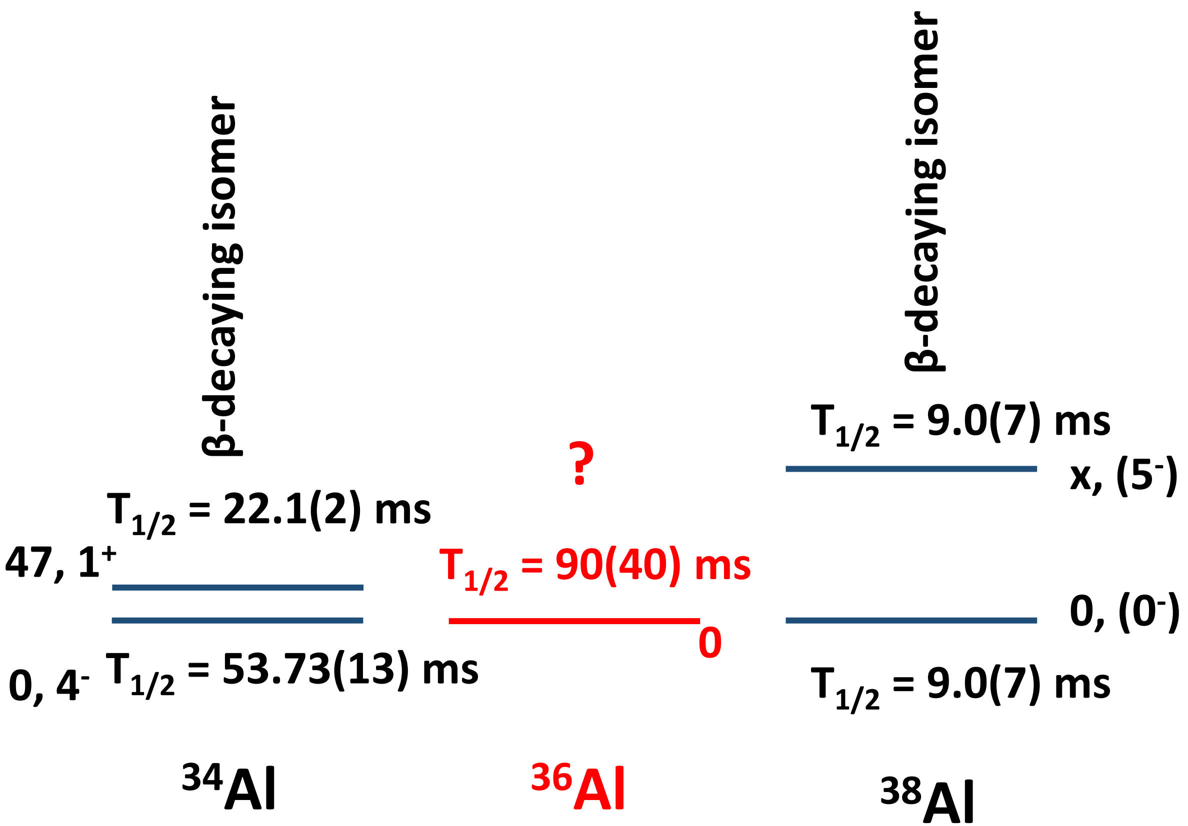
Structure of ^{36}Al and ^{36}Si



- Even-mass Al isotopes exhibit β-decaying isomer.
- Structure of ^{36}Al is not well known.

Structure of ^{36}Al and ^{36}Si



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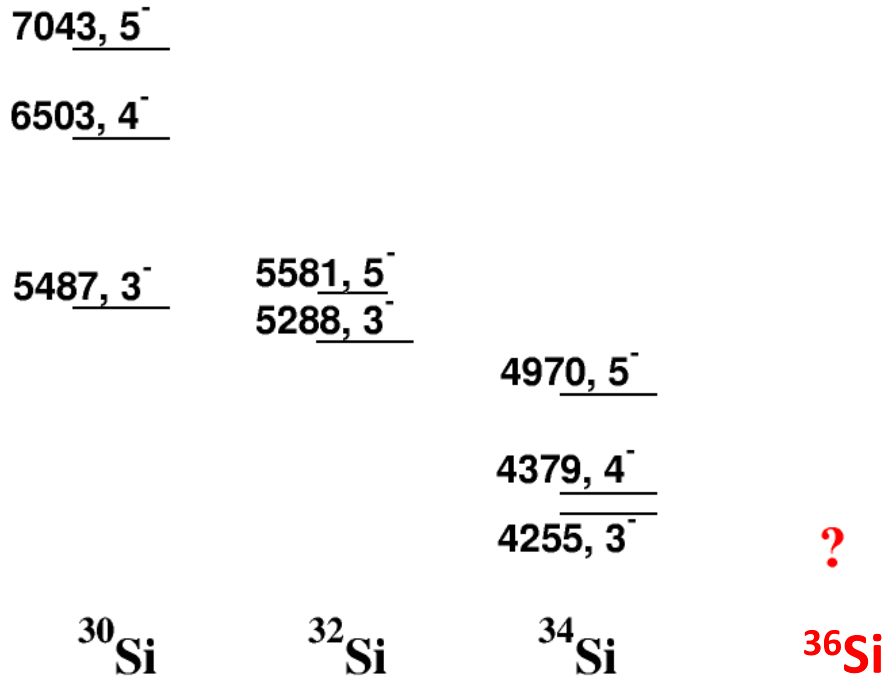


- Negative parity trend of even-mass Si isotope shows evidence of N=20 shell gap evolution.
- How about N>20? No negative parity level is known for ^{36}Si.
- β-decay of ^{36}Al (g.s.) will populate them.

Experiment at FRIB

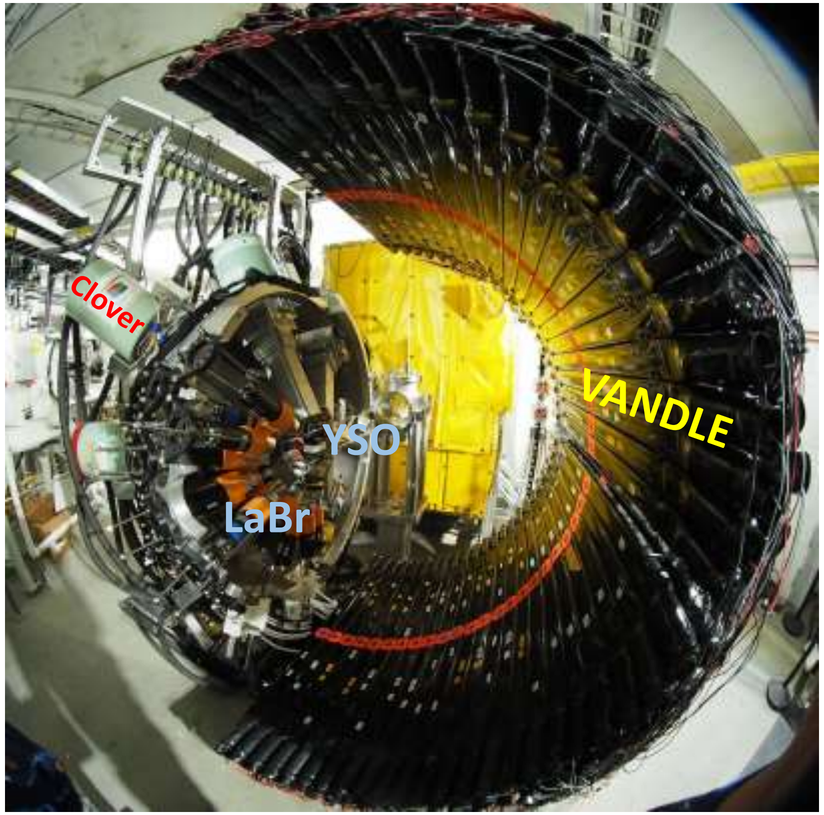


Photo credit: FDSi collaboration

- **FDSi: FRIB Decay Station initiator.**
- **Primary beam ^{48}Ca impinged on a ^{9}Be target.**
- **FDSi: YSO implant detector, 11 HPGe, 15 $LaBr_3$ and VANDLE for neutron detection.**
- **Scintillator and PIN for particle identification.**

Experiment at FRIB

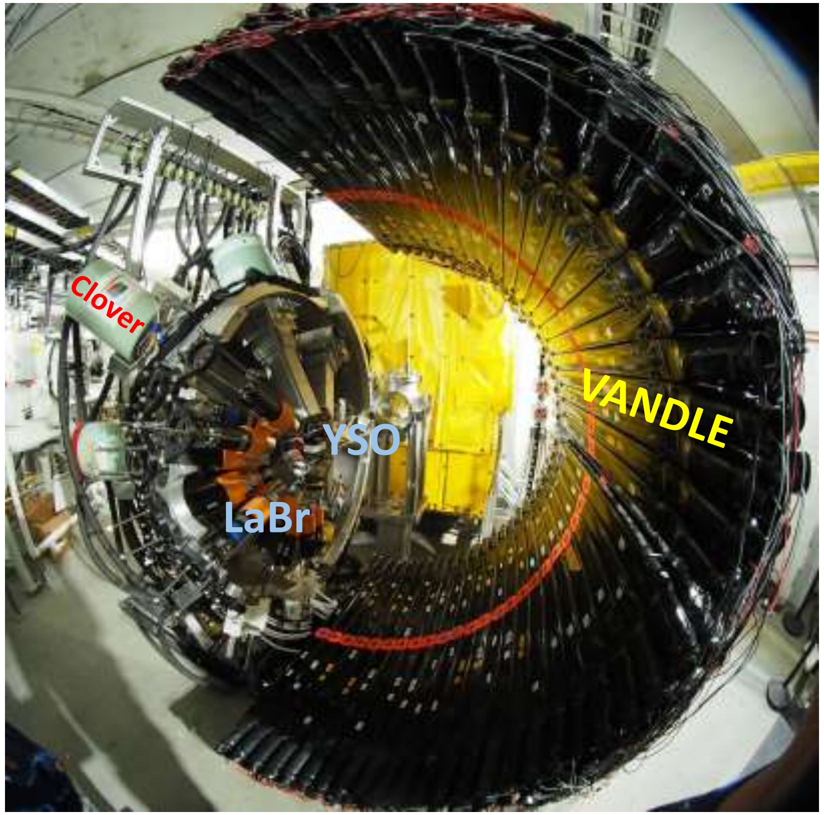
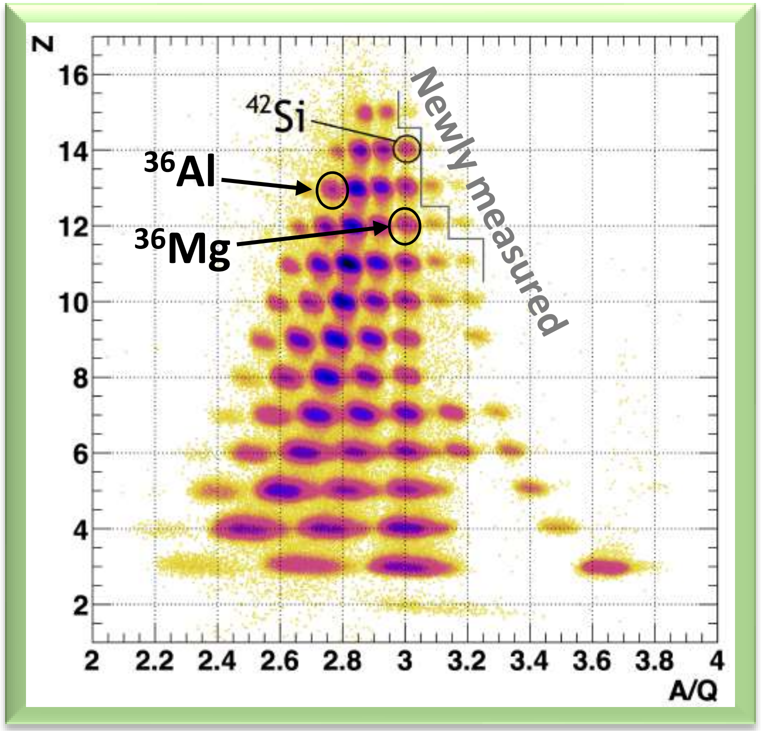


Photo credit: FDSi collaboration

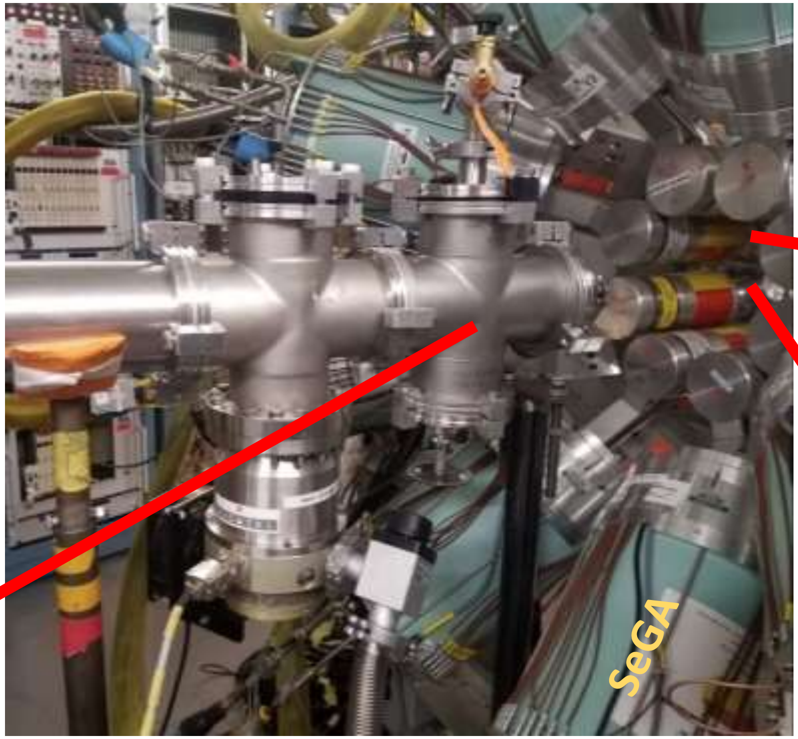
- FDSi: FRIB Decay Station initiator.
- Primary beam ^{48}Ca impinged on a ^{9}Be target.
- FDSi: YSO Implant detector, 11 HPGe, 15 $LaBr_3$ and VANDLE for neutron detection.
- SiPM and PIN for particle identification.

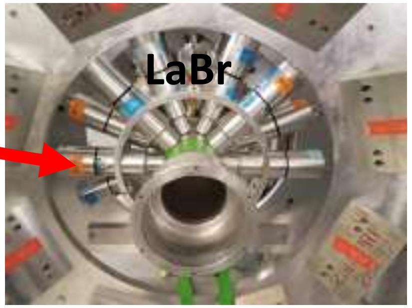
- PID from the first FRIB experiment.
- Center of the secondary beam was ^{42}Si.
- ^{36}Mg and ^{36}Al were populated whose β-decay descendant nuclei are not well known.



H.L.Crawford *et al.*, Phys. Rev. Lett. 129, 21250

Experiment at NSCL

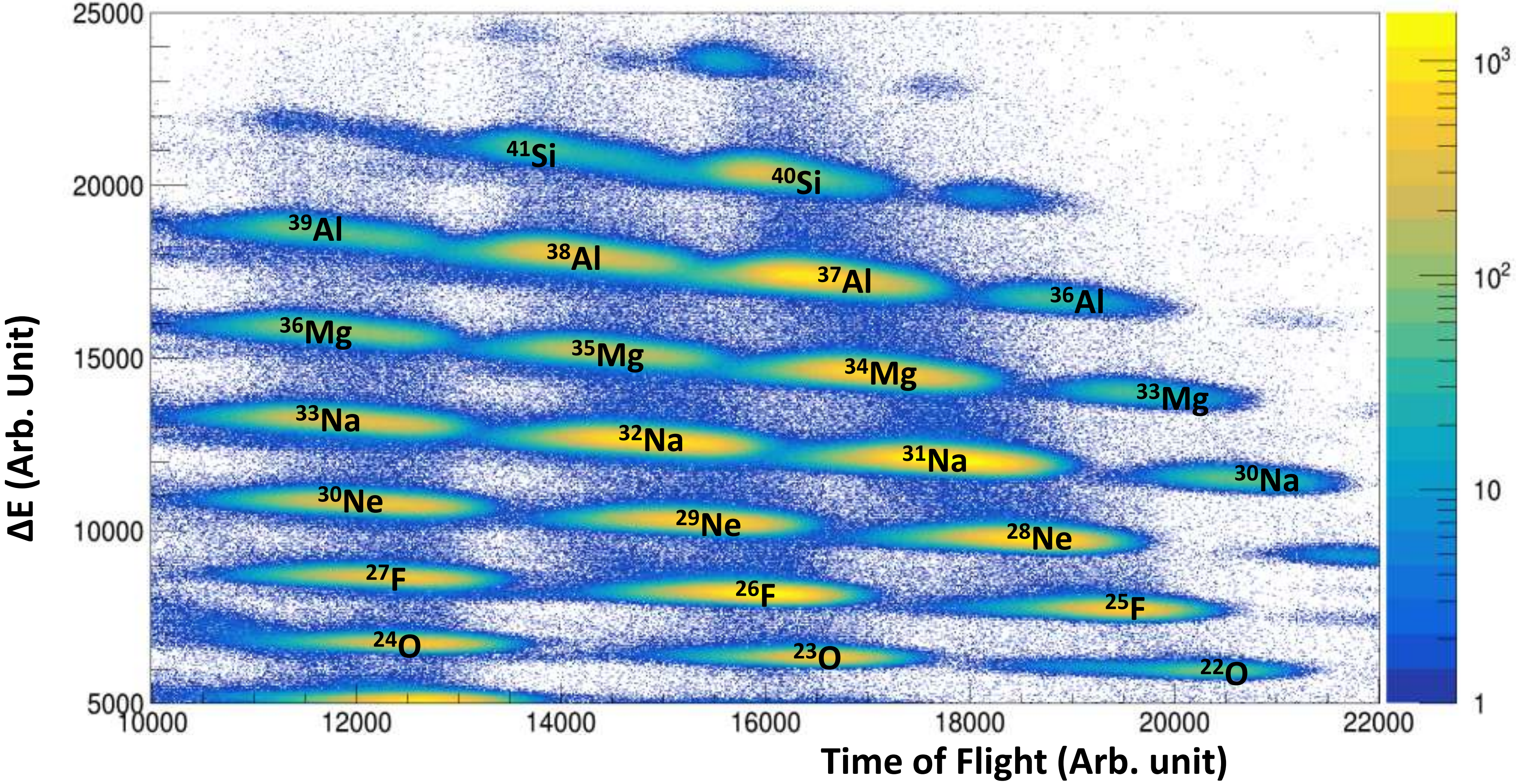




- NSCL β-decay station.
- Primary beam ^{48}Ca impinged on a ^{9}Be target.
- $CeBr_3$ implant detector, 16 SeGA, 15 $LaBr_3$ detectors.
- Two PIN detectors for particle identification.
- Cocktail bean center was ^{33}Na.

Picture credit: T. Ogunbeku.

Particle ID (NSCL)



X-axis: Time of flight between the scintillator at the A1900 focal plane and the PIN 1.

Y-axis: energy lost by the ions in PIN 1.

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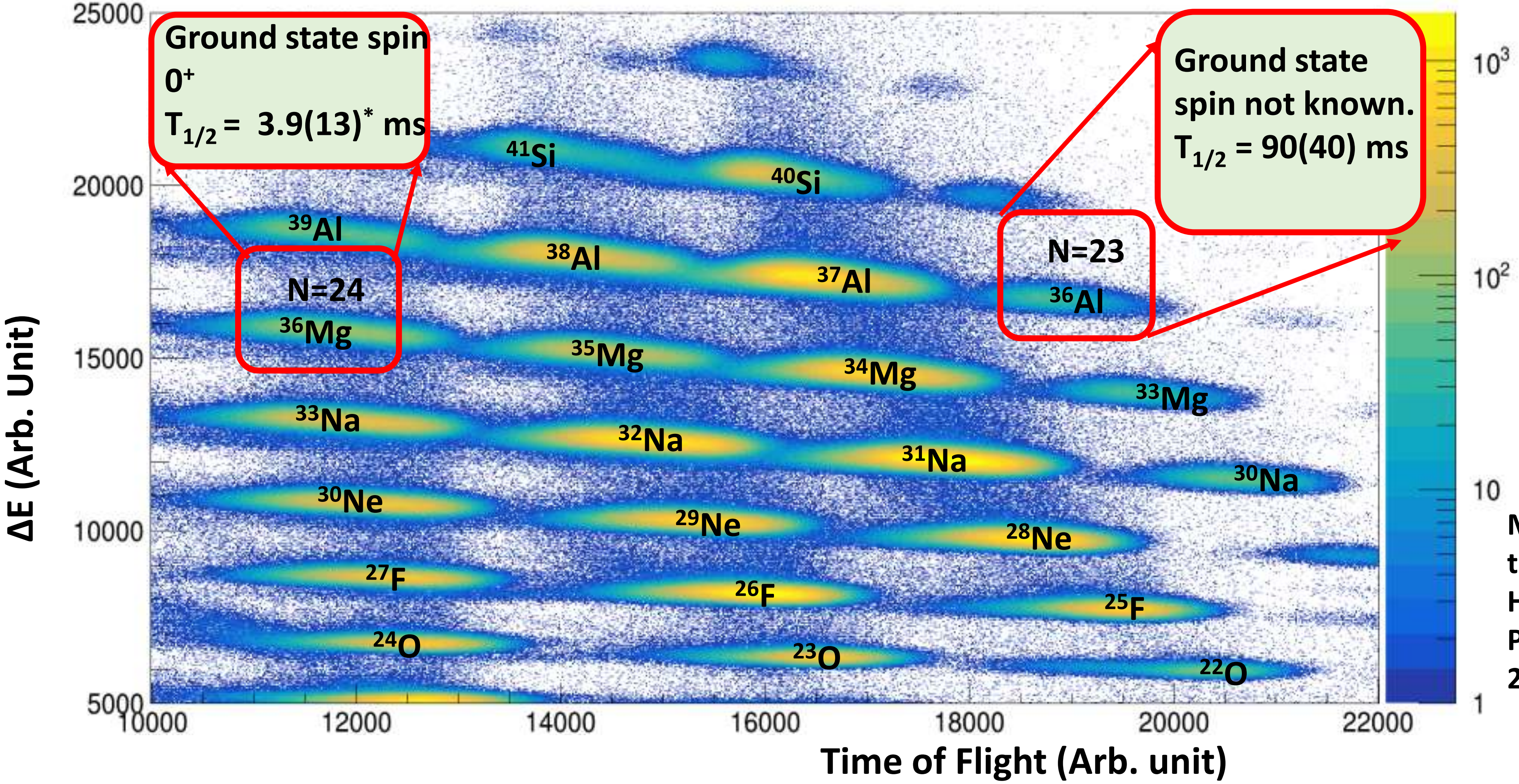

X-axis: Time of flight between the scintillator at the A1900 focal plane and the PIN 1.

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Measured 7.2(12) ms in the FRIB experiment H.L.Crawford *et al.* Phys. Rev. Lett. 129, 21250.

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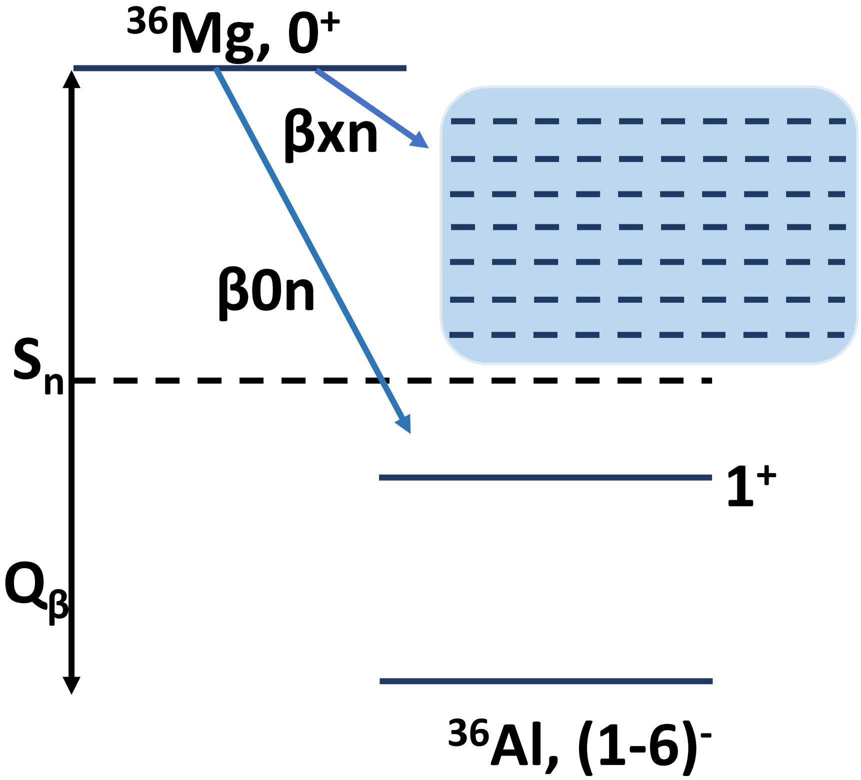
Half-lives reported from www.nndc.bnl.gov

β^- decays of ^{36}Mg and ^{36}Al

Preferentially populates 1^+ state of ^{36}Al via allowed β decay



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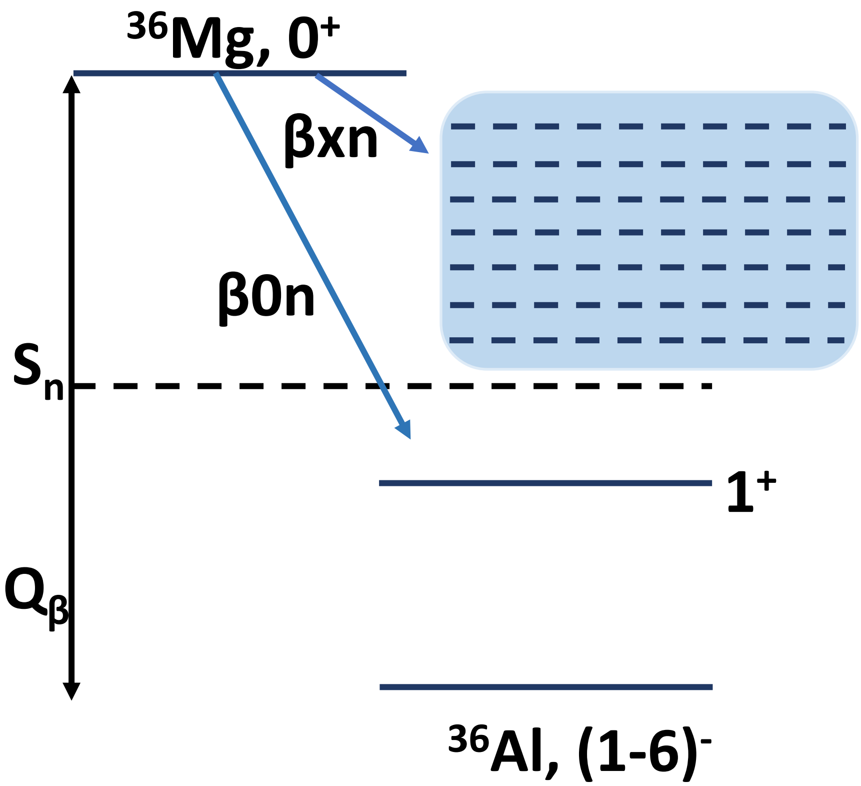
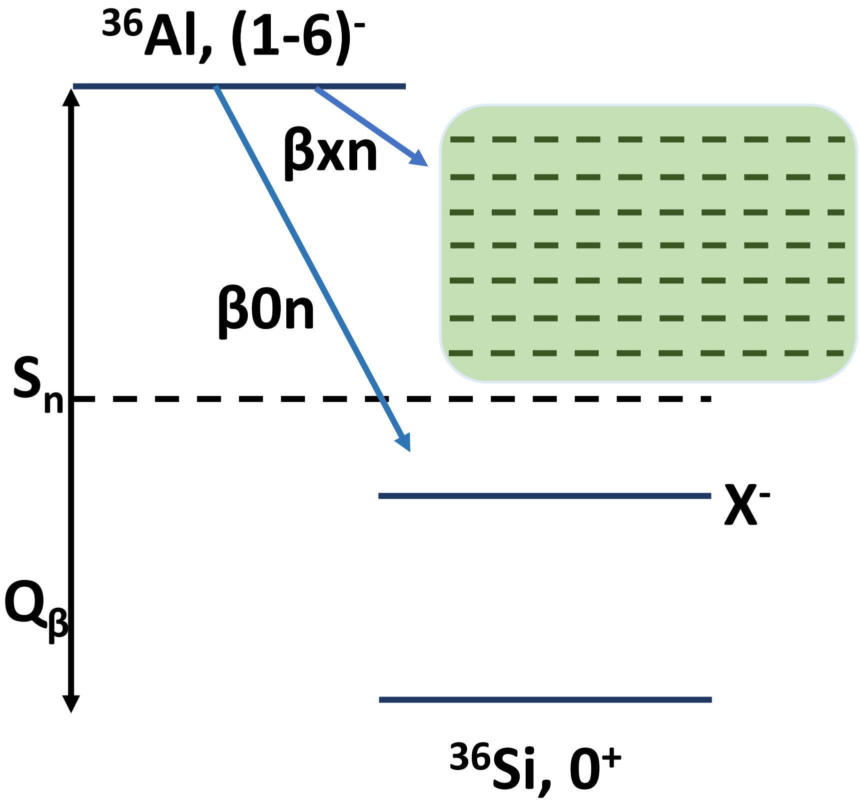


Preferentially populates negative parity states of ^{36}Si via allowed β decay



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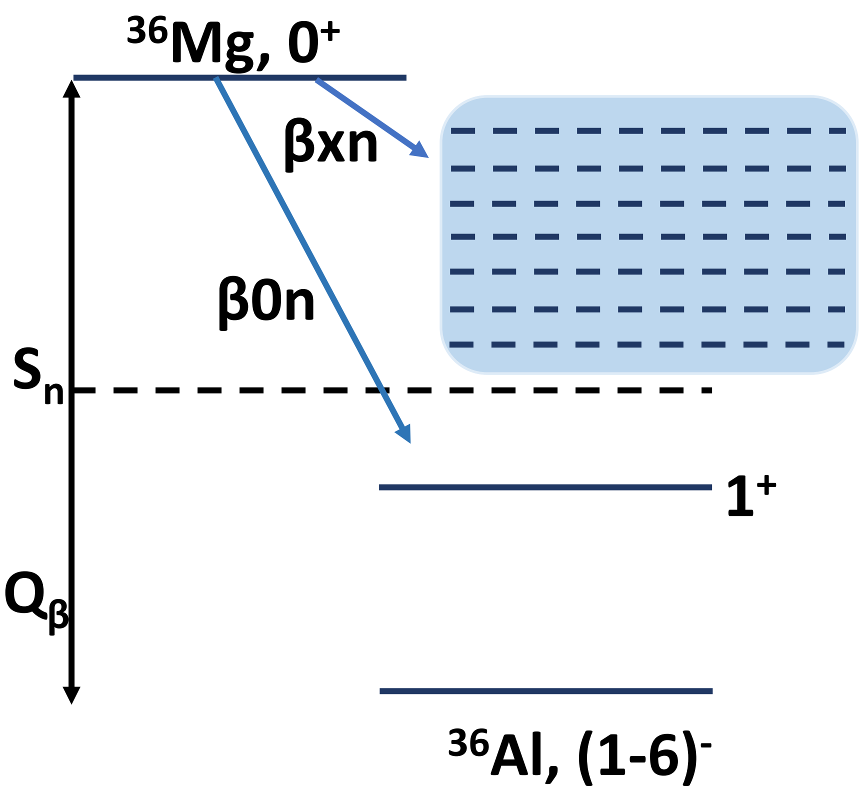
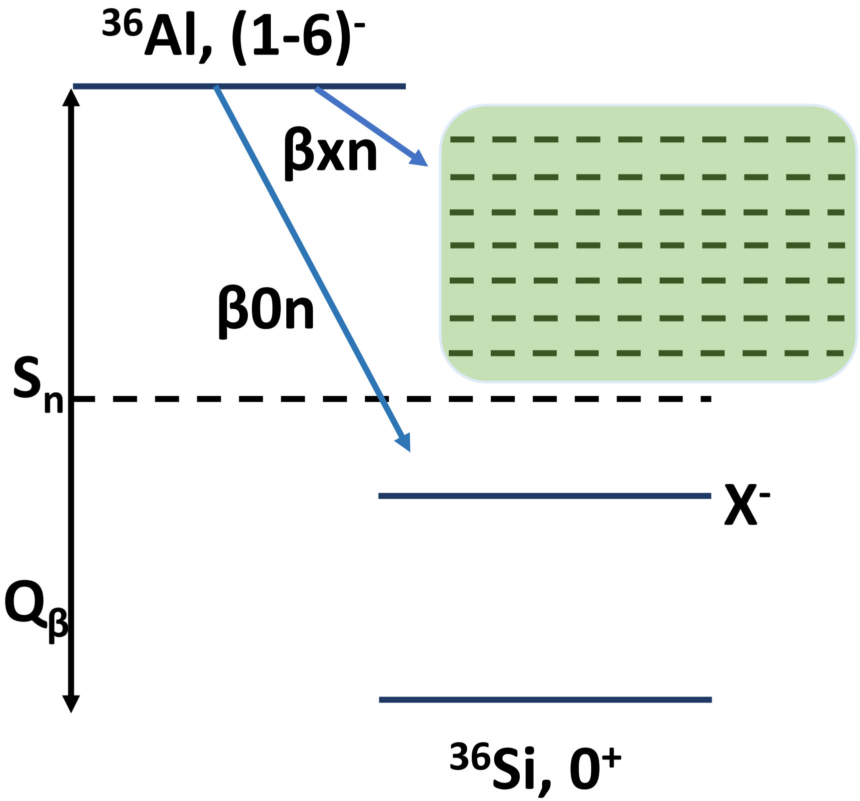
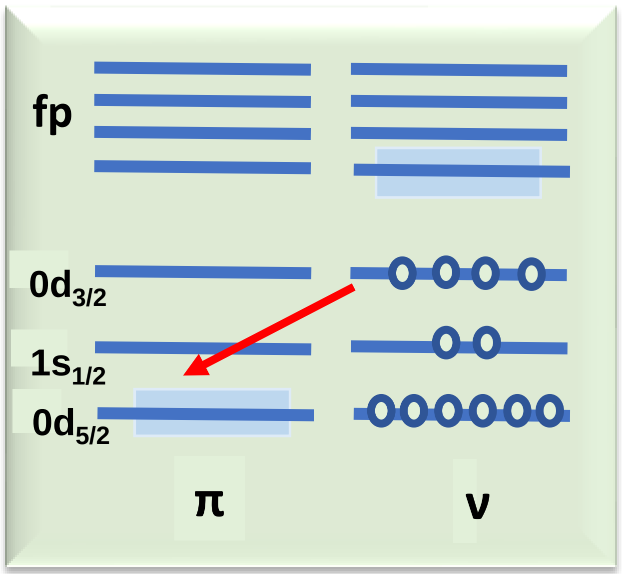


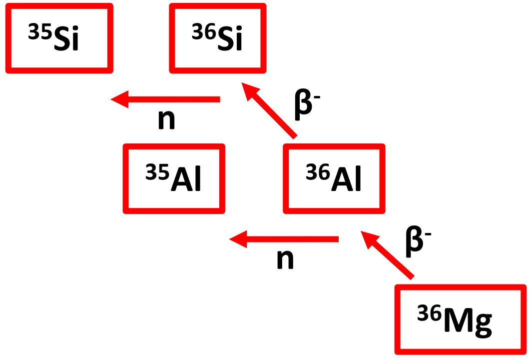
Preferentially populates negative parity states of ^{36}Si via allowed β decay



- Valence protons in sd shell, neutrons in fp shell.
- Populate opposite parity states of the first descendant via allowed β decay.



β-decay of ^{36}Mg



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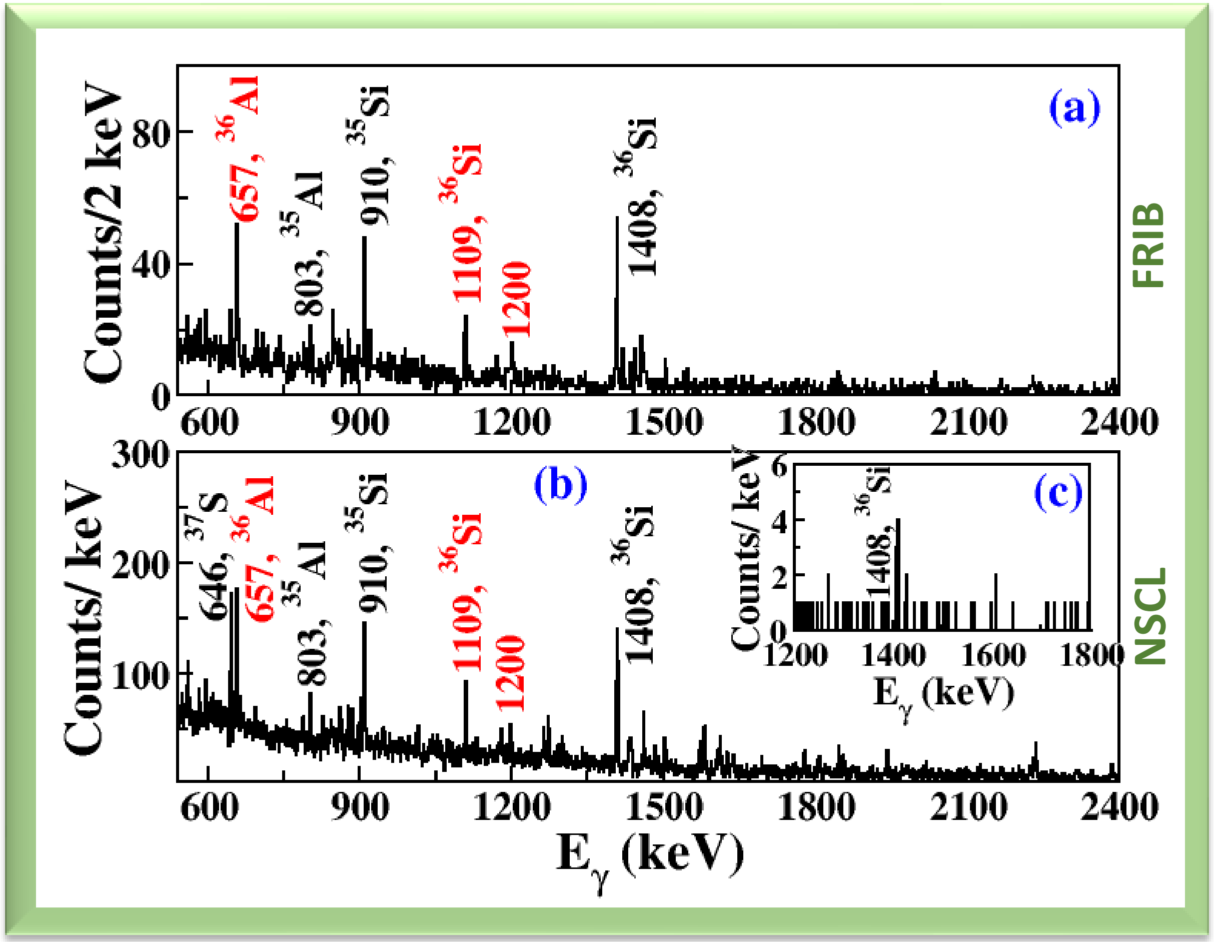
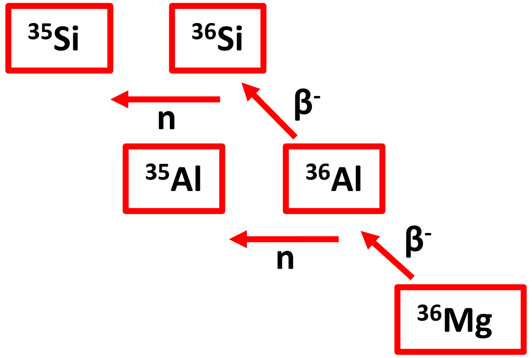
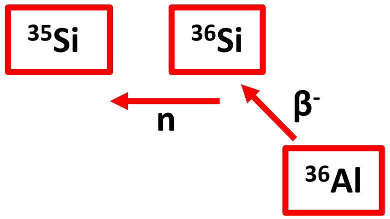


Peaks labeled in red are newly assigned

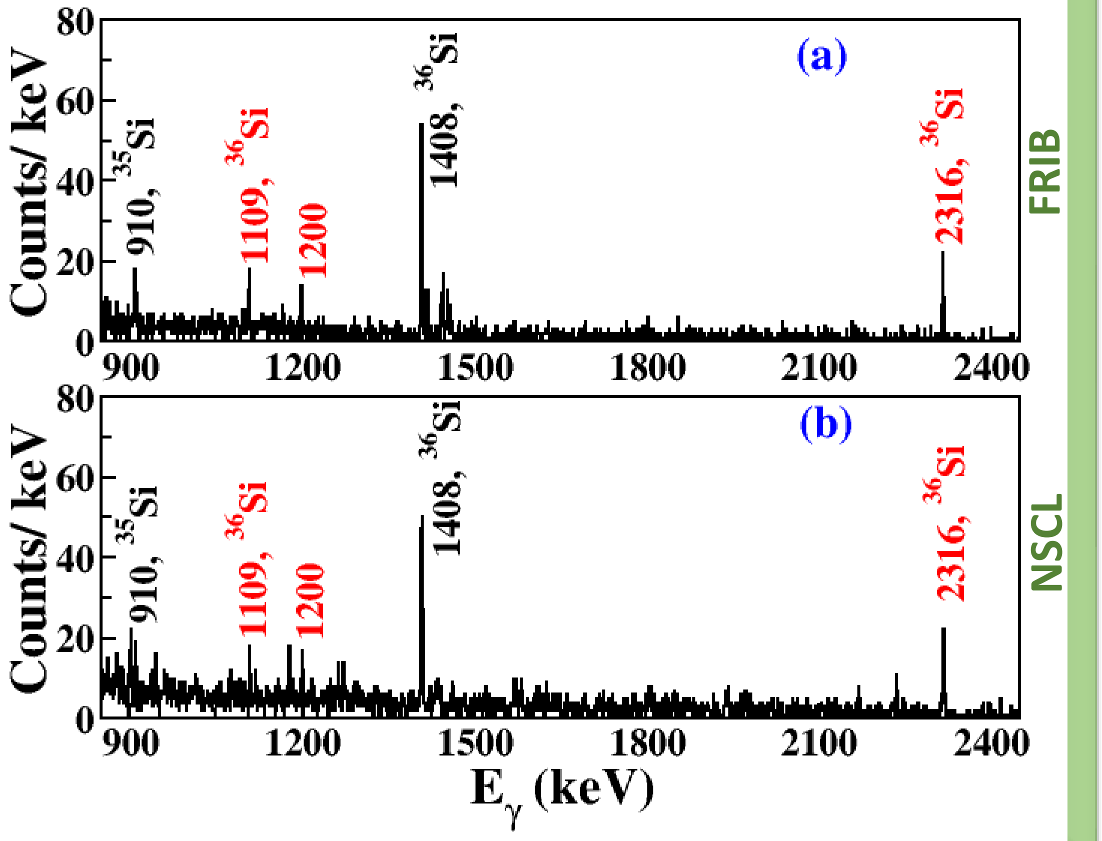


- One γ-ray candidate of ^{36}Al at 657 keV.
- Observe ^{36}Si 2^+ to g.s. transition and a new candidate at 1109 keV.
- γ-γ coincidence confirms the 1109 keV peak belongs to ^{36}Si.
- Observed descendants from the β-delayed neutron emissions.

β-decay of ^{36}Al

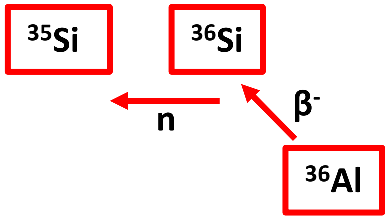


β-decay of ^{36}Al



Peaks labeled in red are newly assigned

- Observed ^{36}Si 2^+ to g.s. transition at 1408 keV and a new candidate at 2316 keV.
- Weak presence of the 1109 keV peak.



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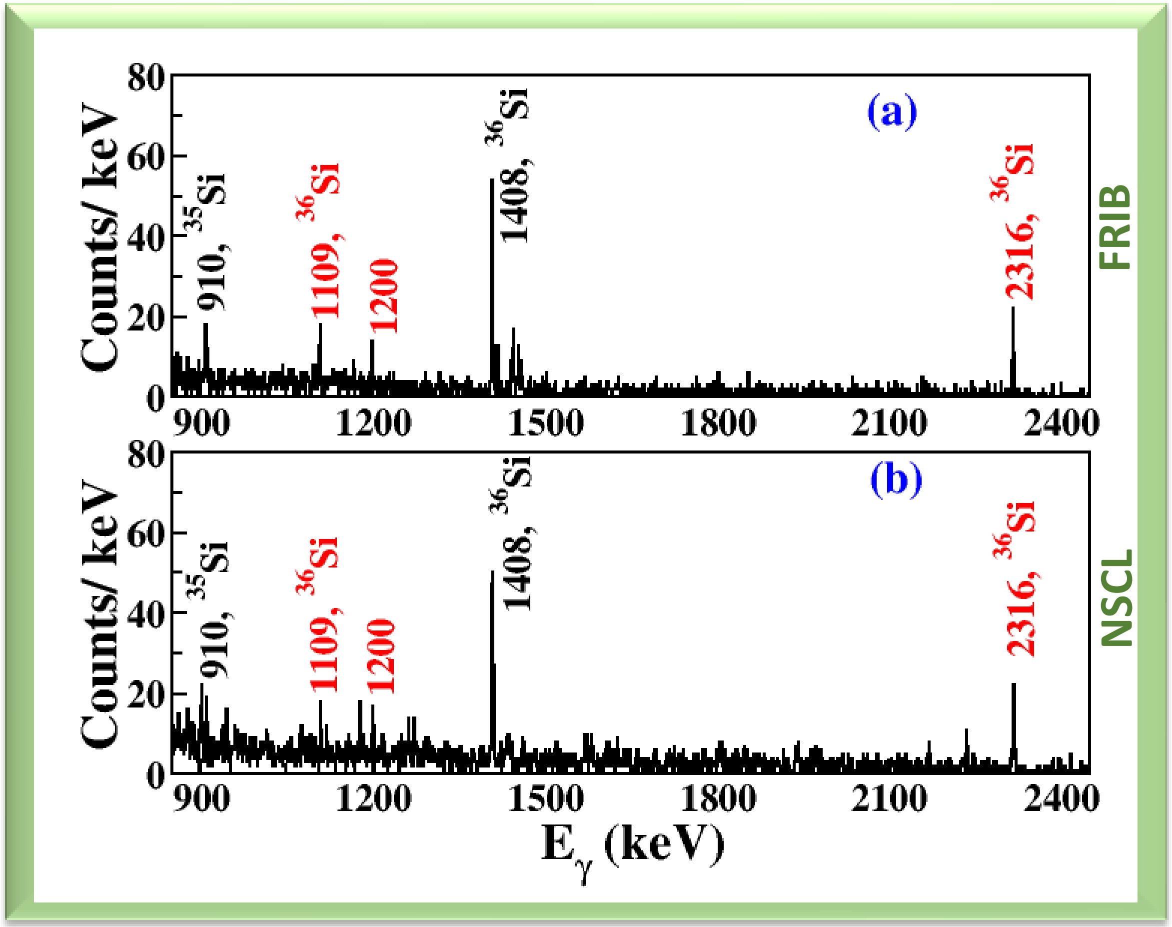

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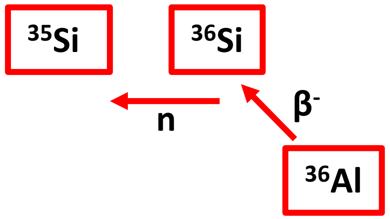
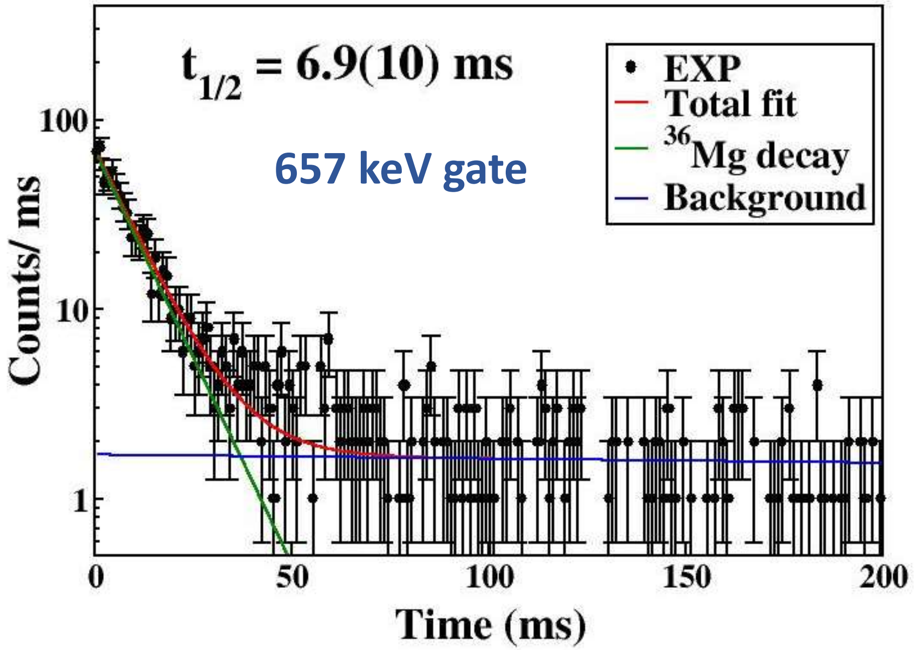


- Discrepancy in the relative intensities between 1109 and 1408-keV peaks.
- Absence and presence of 2316 keV peak in two β-decay paths.
- Indication of a β-decaying isomer in ^{36}Al.

Half-lives of ^{36}Mg and ^{36}Al

NSCL data

^{36}Mg decay half-life



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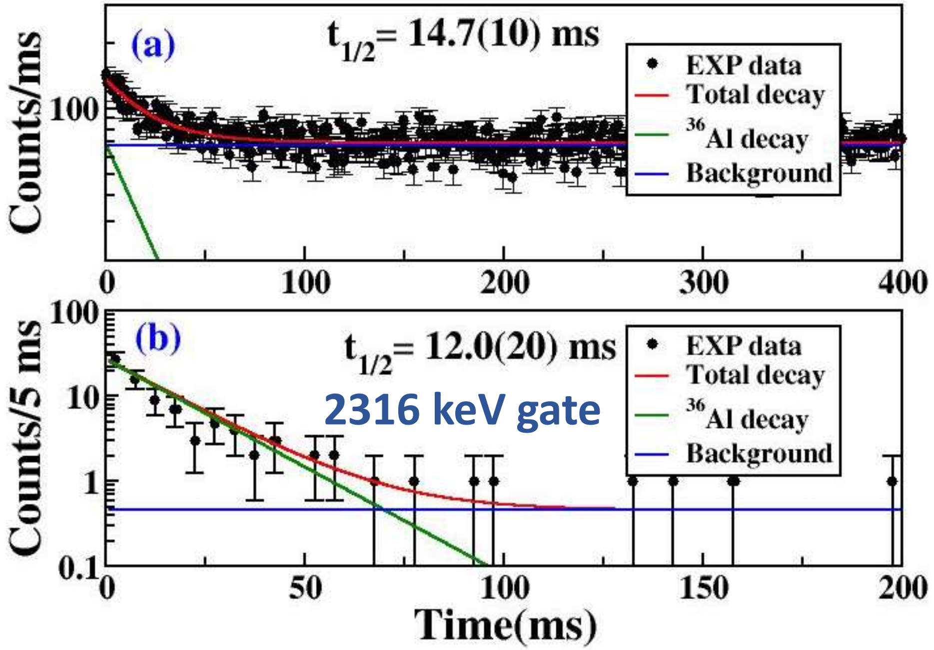

- Half-life of ^{36}Mg extracted as 6.9(10) ms from the 657 keV γ-gated time distribution.
- Half-life extracted for ^{36}Al was 14.7(10) ms and 12.0(20) ms from the full time distribution and the 2316 keV γ-gated time distributions
- Half-life of ^{36}Al was reported before as 90(40) ms.

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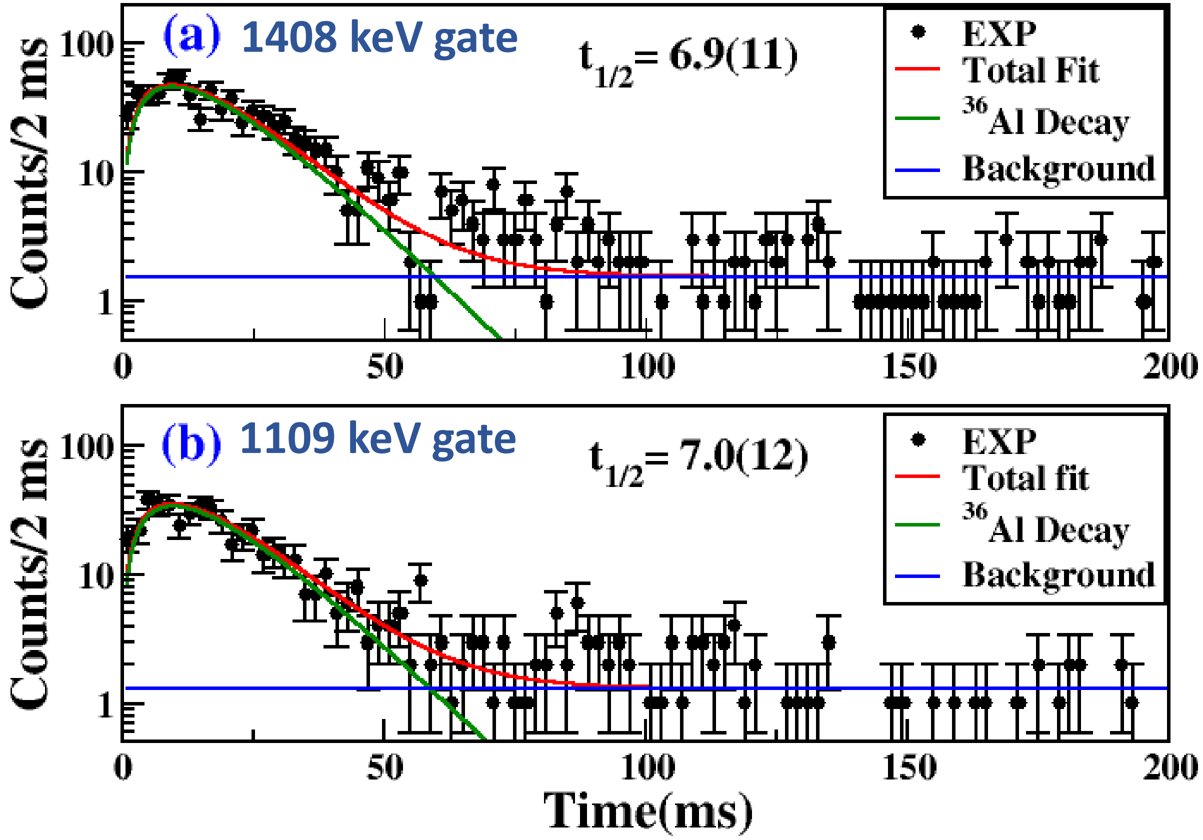
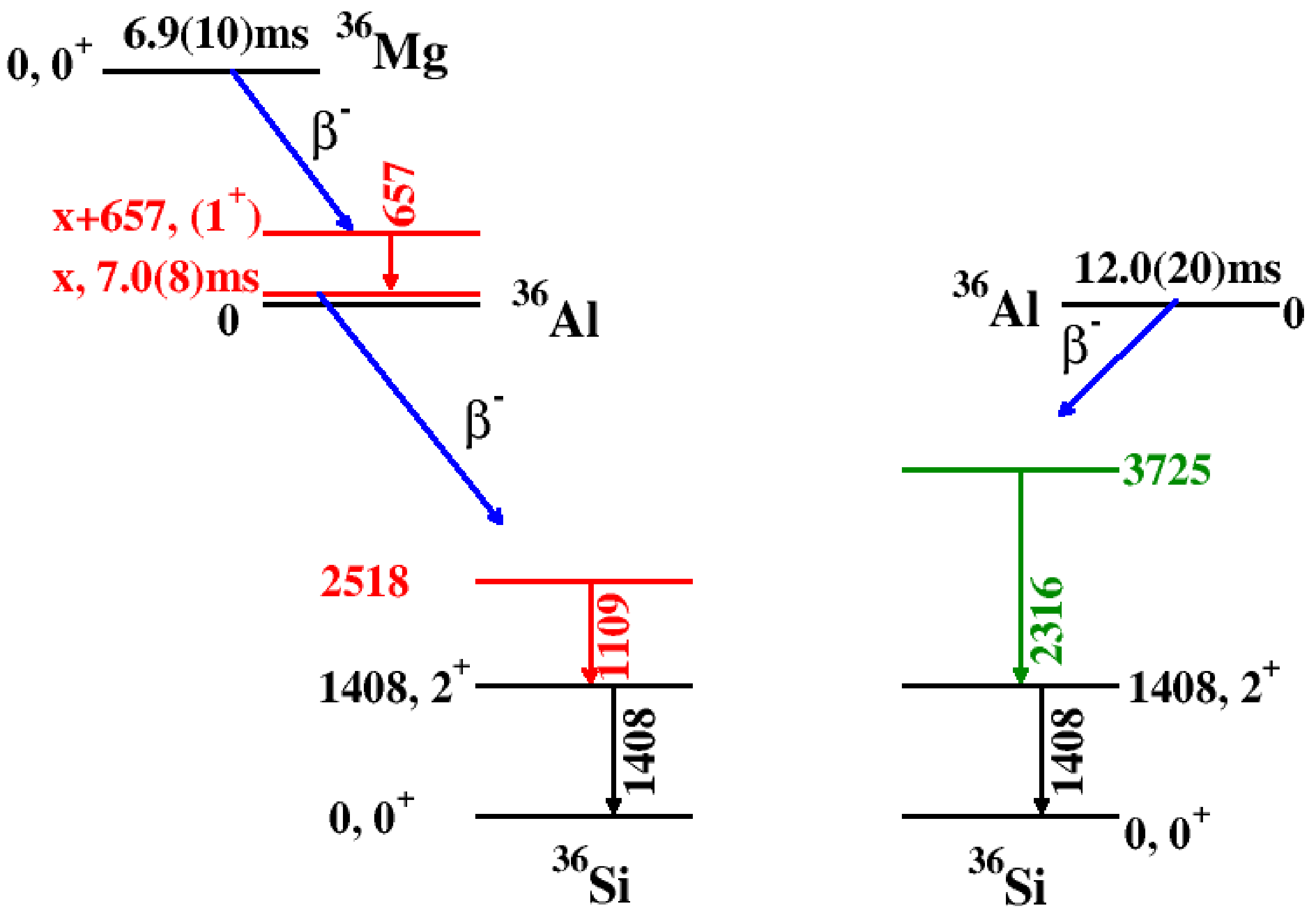
Half-life of ^{36}Al Isomer

NSCL data



- **Half-life of the isomer in 36Al has been measured from the γ transition gated time distribution.**
- **From the 1408 keV gate, half-life is extracted as 6.9(11) ms.**
- **From the 2316 keV gate, half-life is extracted as 7.0(12) ms.**

Proposed Decay Schemes of Mass A=36

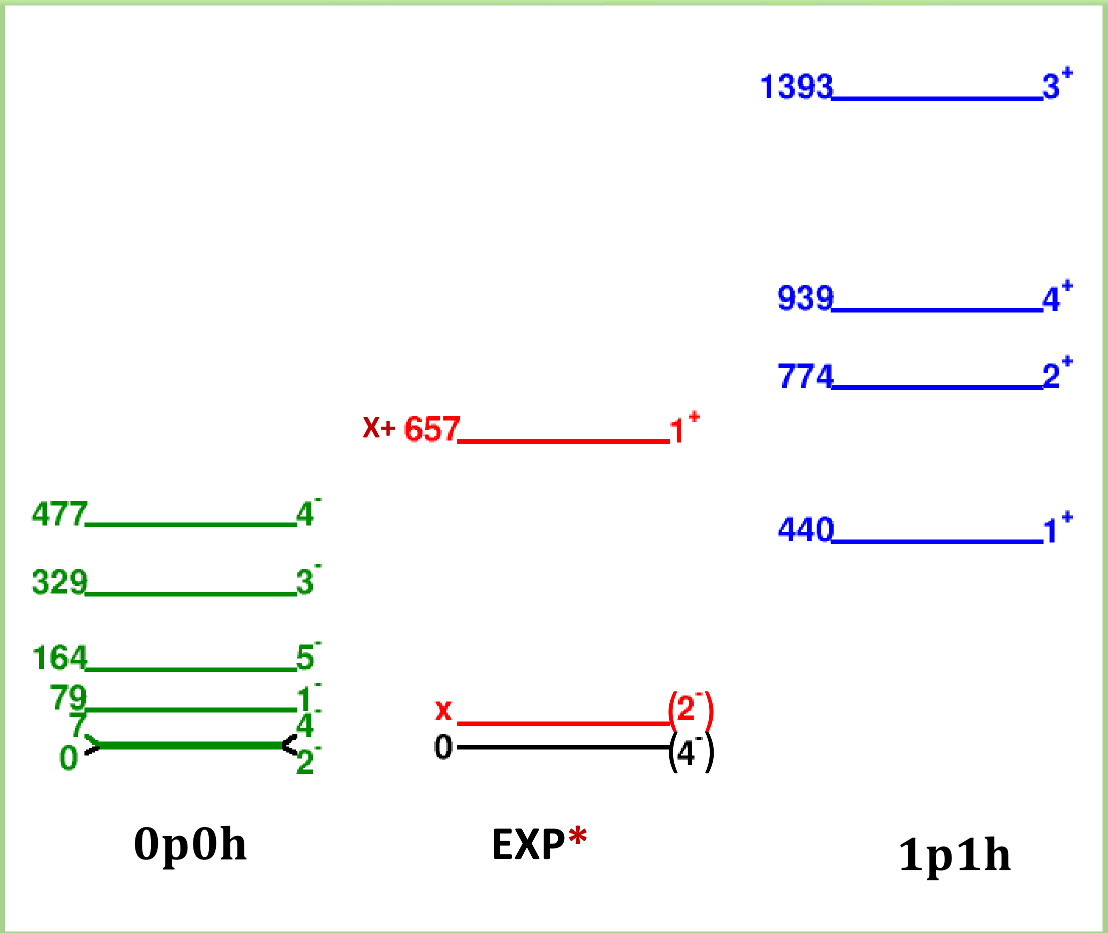


- β-decay of ^{36}Mg populates the 1^+ state of ^{36}Al which decays via isomeric state.
- The isomeric state decays via β-particle and populates 2518 keV state of ^{36}Si.
- β-decay of ^{36}Al ground state populates 3725 keV state of ^{36}Si.
- 3725 keV state will be of negative parity if populated by the allowed β transition.

Relative ordering of g.s. and isomeric state in ^{36}Al could not be determined.

R.S.Lubna *et al.*, submitted to PRC

Nuclear Shell-model Predictions, ^{36}Al

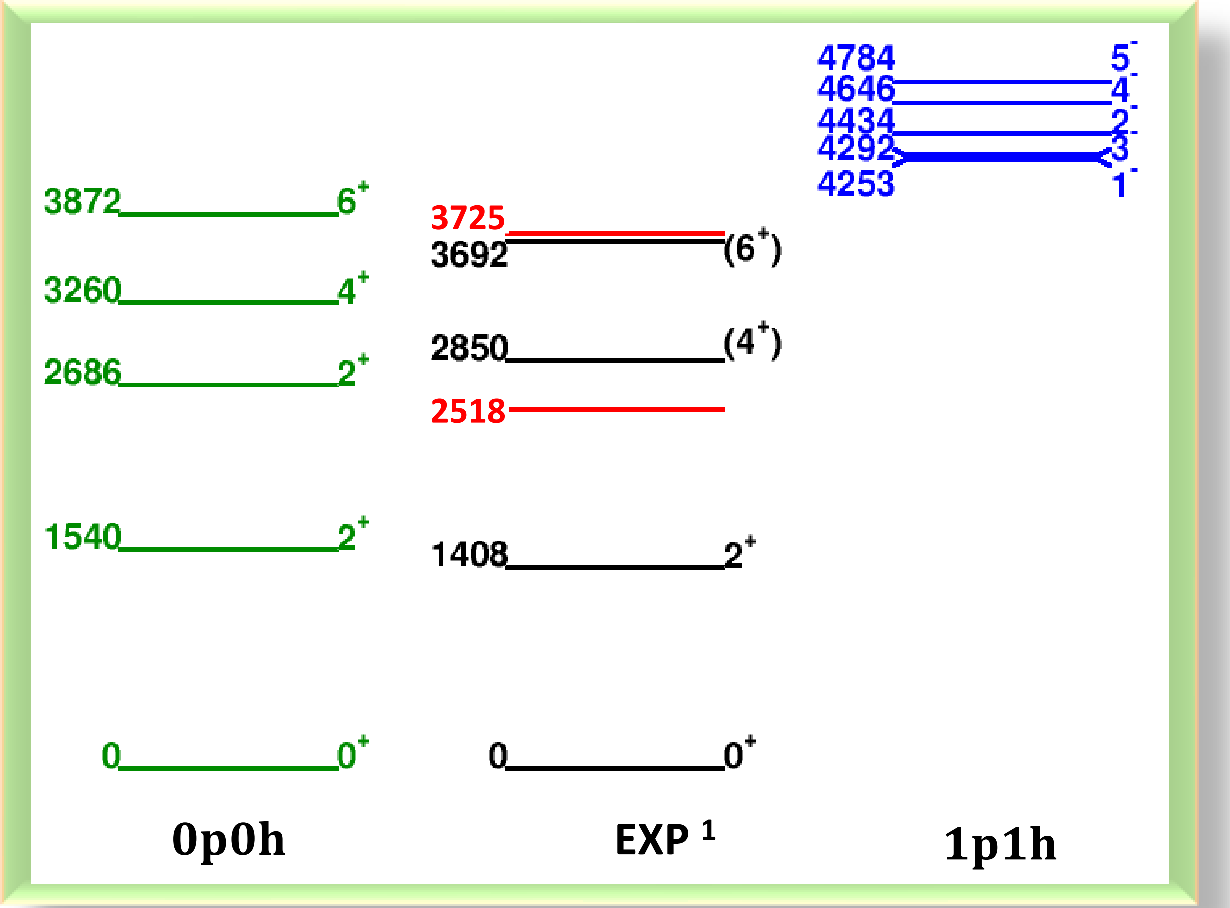


- Shell model calculations performed by using FSU[1] interaction.
- Unmixed 0p0h (negative) and 1p1h (positive) calculations were performed to predict states of ^{36}Al.
- Predicted 2^- and 4^- levels closely spaced in energies, one of them can be the ground state.
- 1p1h excitation calculates the lowest states as 1^+ with 440 keV.

*Black: previously confirmed
Red: Suggested from this work

1. R.S.Lubna *et al.*, Phys. Rev. Research 2, 043342 (2019).

Nuclear Shell-model Predictions, ^{36}Si

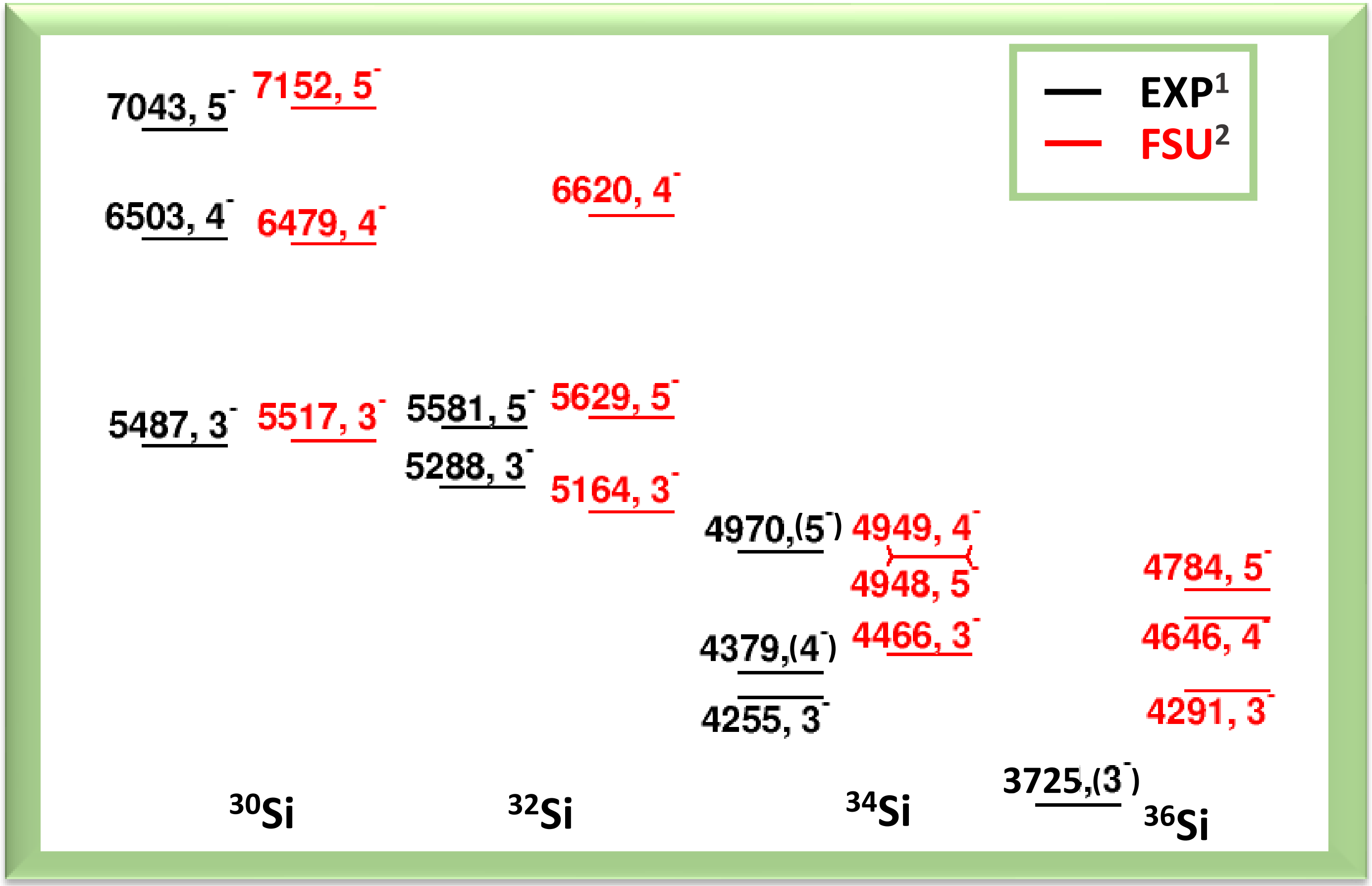


- Shell model calculations performed by using FSU[2] interaction.
- No mixing was allowed to calculate the positive and negative parity states.
- The first predicted negative parity state is above 4 MeV.
- No good negative parity candidate for the 2518 keV.
- Predicted 2^+ 2686 keV level can be the theoretical counterpart the 2518 keV state. This can be populated by a forbidden β-decay or fed by a state above.

*Black: previously confirmed
Red: Suggested from this work

1. Experimental levels were compiled from https://www.nndc.bnl.gov/
2. R.S.Lubna *et al.*, Phys. Rev. Research 2, 043342 (2019).

Systematic of the Negative-parity States of Even–mass Si Isotopes



- Experimentally observed negative-parity states of even-mass Si isotopes compared with that predicted by using FSU interaction.
- Trends are well reproduced by the calculations.
- According to the trend, the first negative parity of ^{36}Si is expected to be around 4 MeV.
- Do we have intruder/ opposite parity states for the higher mass isotopes?
- Are we ready to populate them and interpret their structure with the existing theoretical models?

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1. Experimental levels, except for that of ^{36}Si, were compiled from https://www.nndc.bnl.gov/
2. R.S.Lubna *et al.*, Phys. Rev. Research 2, 043342 (2019).

Summary

- **Investigated structure of ^{36}Al via β-decay of ^{36}Mg.**
- **Strong indication of a long-lived β-decaying isomeric state.**
- **Predictions with the FSU interaction supports the existence of an isomer and well predicts the 1^+ state.**

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- **Investigated structure of ^{36}Si via β-decay of ^{36}Mg and ^{36}Al.**
- **More precise half-life measured.**
- **Negative parity intruder state was suggested to be around 4 MeV.**
- **Theoretical predictions made for the systematic of Si isotopes supports the argument.**

Summary

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- More precise half-life measured.
- Negative parity intruder state was suggested to be around 4 MeV.
- Theoretical predictions made for the systematic of Si isotopes supports the argument.

Future:

- More exciting data coimg from FRIB, are we ready?.
- Experimental data will provide stringent test to the theoretical models as well as will be invaluable inputs to improve them.

Thank You

Collaboration:

R. S. Lubna,[1] S. N. Liddick,[1,2] T. H. Ogunbeku,[1,3] A. Chester,[1] J. M. Allmond,[4] Soumik Bhattacharya,[5] C. M. Campbell,[6] M. P. Carpenter,[7] K. L. Childers,[8,2] P. Chowdhury,[9] J. Christie,[10] B. R. Clark,[3] R. M. Clark,[6] I. Cox,[10] H. L. Crawford,[6] B. P. Crider,[3] A. A. Doetsch,[1,11] P. Fallon,[6] A. Frotscher,[6] T. Gaballah,[3] T. J. Gray,[4] R. Grzywacz,[10] J. T. Harke,[12] A. C. Hartley,[1,2] R. Jain,[1,11] T. T. King,[4] N. Kitamura,[10] K. Kolos,[12] F. G. Kondev,[7] E. Lamere,[9] R. Lewis,[8,2] B. Longfellow,[8,11,12] S. Lyons,[8,*] S. Luitel,[3] M. Madurga,[10] R. Mahajan,[1] M. J. Mogannam,[1,2] C. Morse,[13] S. K. Neupane,[10] W.-J. Ong,[12] D. Perez-Loureiro,[10] C. Porzio,[6] C. J. Prokop,[14] A. L. Richard,[8,†] E. K. Ronning,[1,2] E. Rubino,[1,†] K. Rykaczewski,[4] D. Seweryniak,[7] K. Siegl,[10] U. Silwal,[3] M. Singh,[10] D. P. Siwakoti,[3] D. C. Smith,[3] M. K. Smith,[8] S. L. Tabor,[5] T. L. Tang,[5] Vandana Tripathi,[5] A. Volya,[5] T. Wheeler,[1,11] Y. Xiao,[3] and Z. Xu[10]

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[10] *Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37966, USA*
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[13] *Brookhaven National Laboratory, Upton, New York 11973, USA*
[14] *Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA*

Thank You for Your Attention

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Discussions with B. A. Brown (FRIB, MSU) are gratefully acknowledged.

Back Up

Half-lives and P_n of ^{36}Mg and ^{36}Al measured at RIKEN

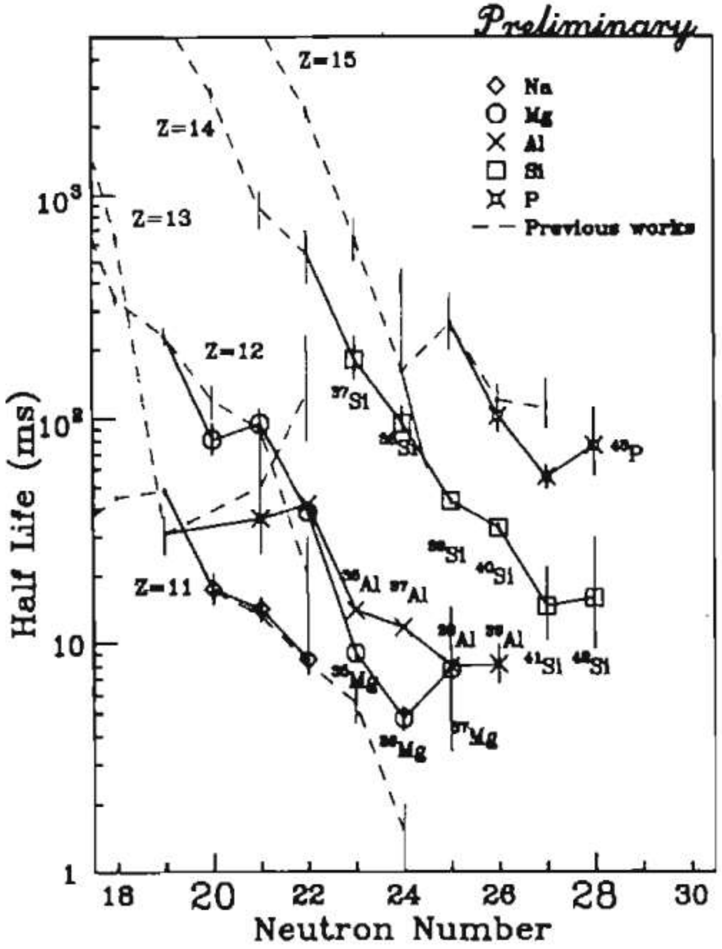
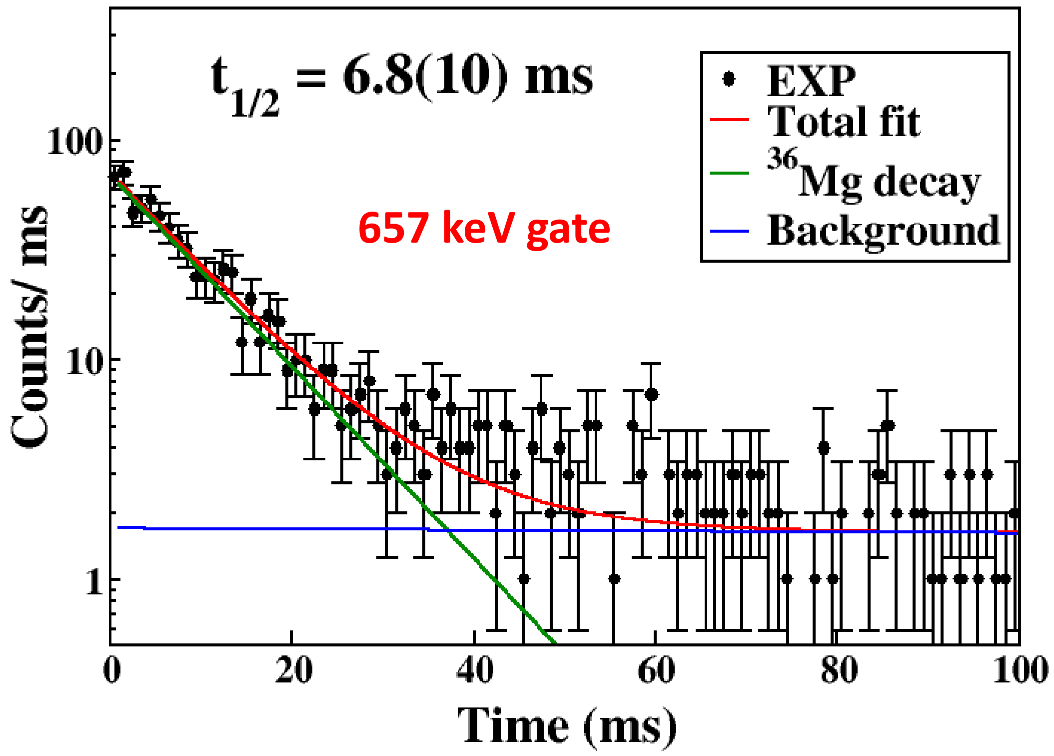
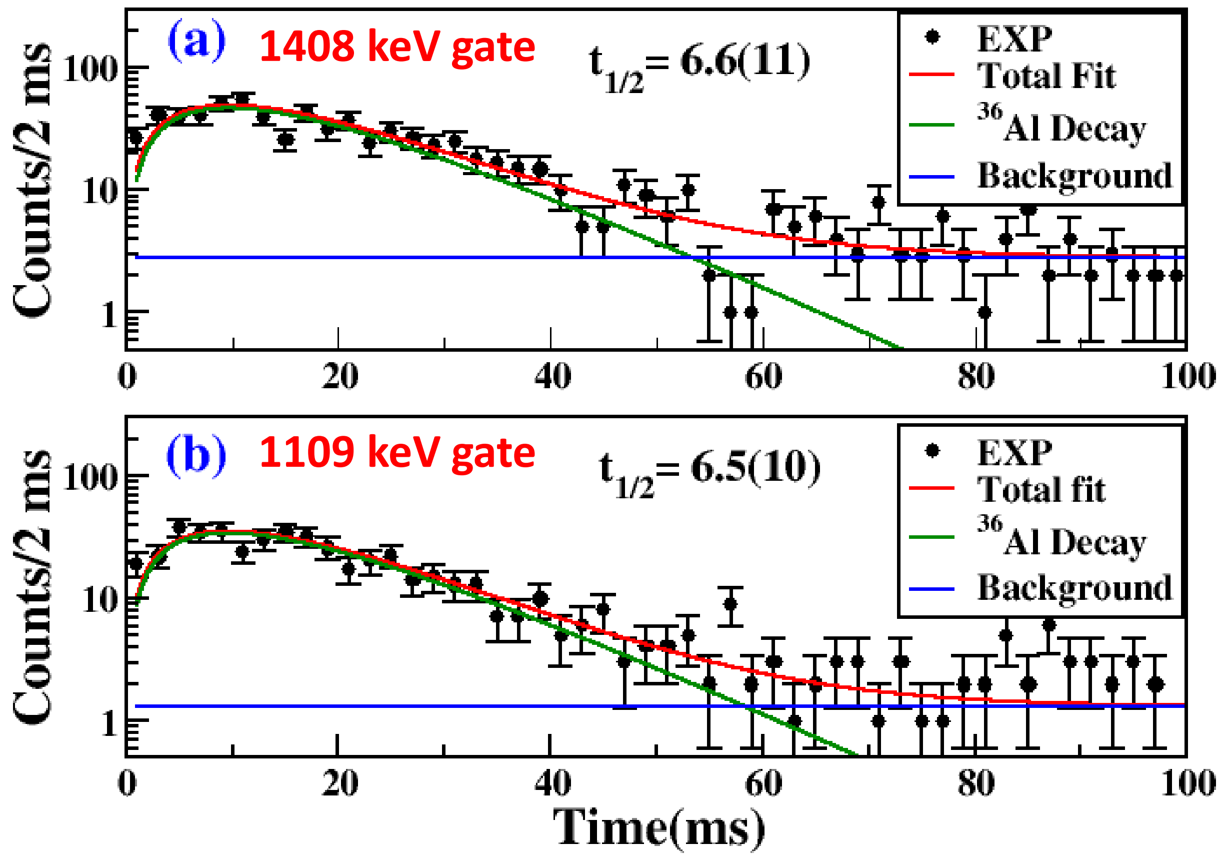


Table 1. Preliminary results on β-delayed neutron emission probabilities P_n.

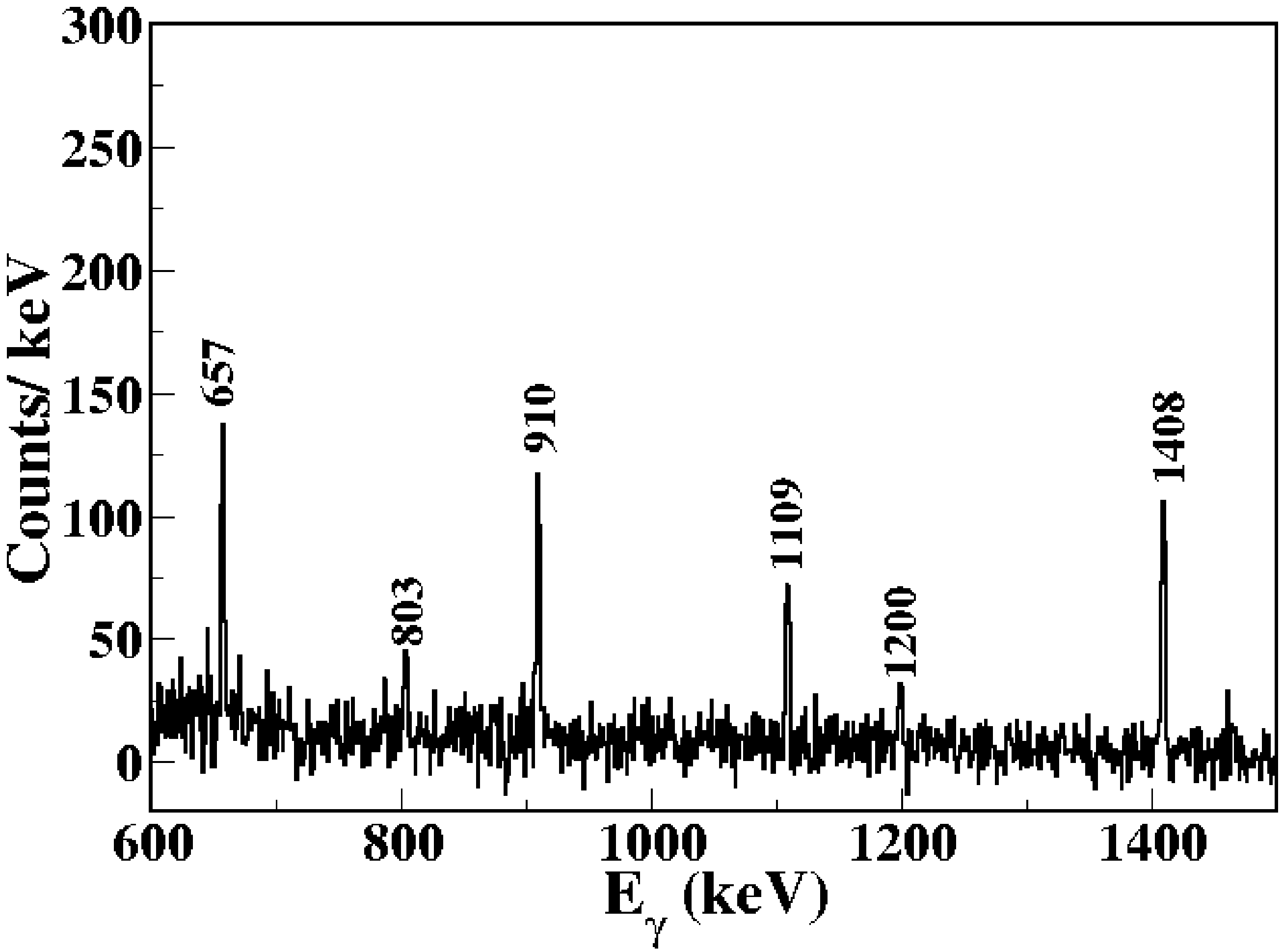
nucleus	P_n (%)	nucleus	P_n (%)
^{31}Na	82 ± 42	^{37}Al	55 ± 11
^{32}Na	59 ± 17	^{38}Al	84 ± 19
^{33}Na	136 ± 34	^{39}Al	97 ± 22
^{32}Mg	6 ± 4	^{37}Si	15 ± 8
^{33}Mg	50 ± 18	^{38}Si	28 ± 7
^{34}Mg	58 ± 12	^{39}Si	60 ± 13
^{35}Mg	52 ± 11	^{40}Si	53 ± 12
^{36}Mg	48 ± 12	^{41}Si	103 ± 48
^{34}Al	30 ± 6	^{41}P	71 ± 21
^{35}Al	43 ± 9	^{42}P	57 ± 13
^{36}Al	55 ± 11	^{43}P	84 ± 47

Half-lives of ^{36}Mg and ^{36}Al Isomer for 100 ms Correlation



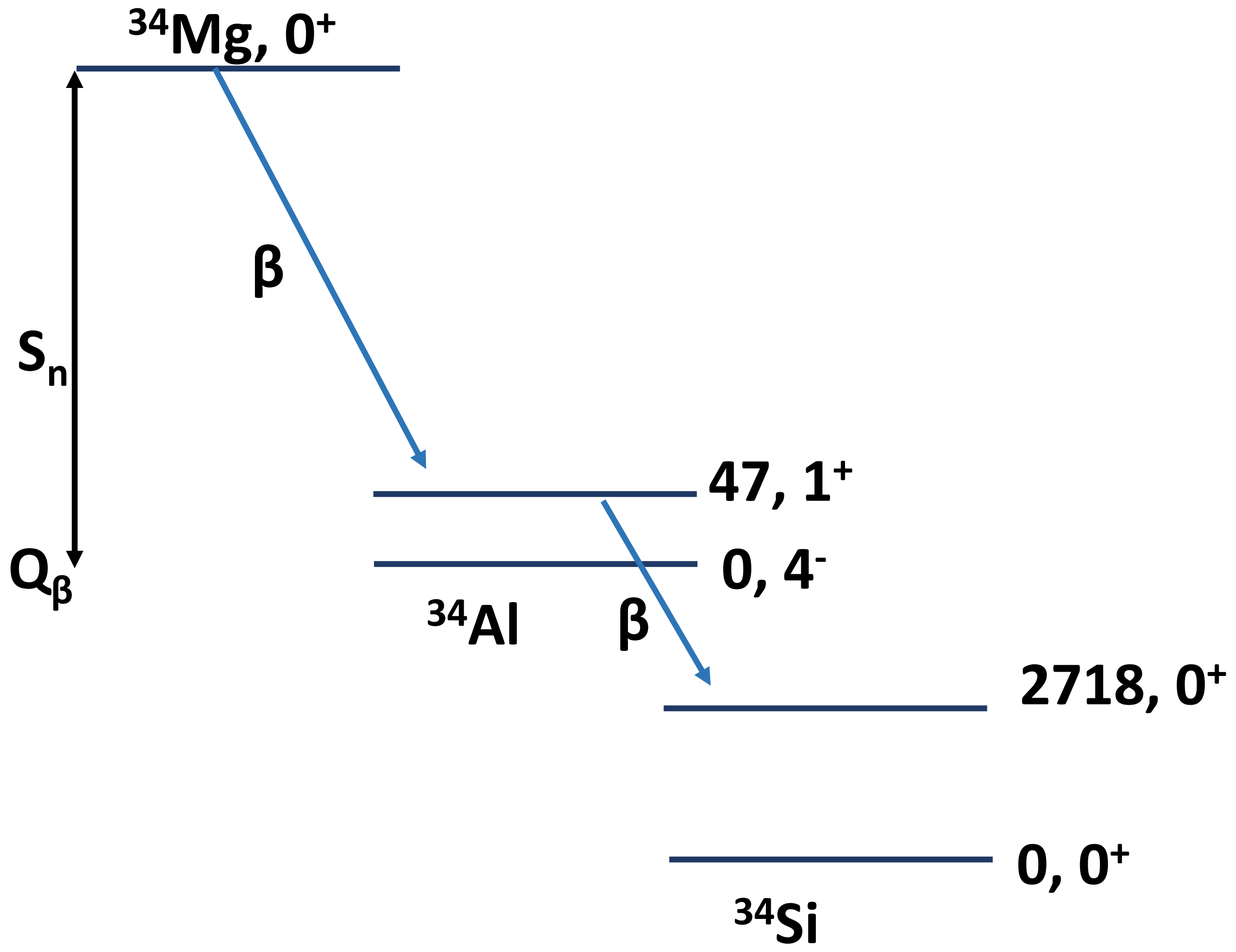


^{36}Mg β-delayed γ-ray spectrum (NSCL)

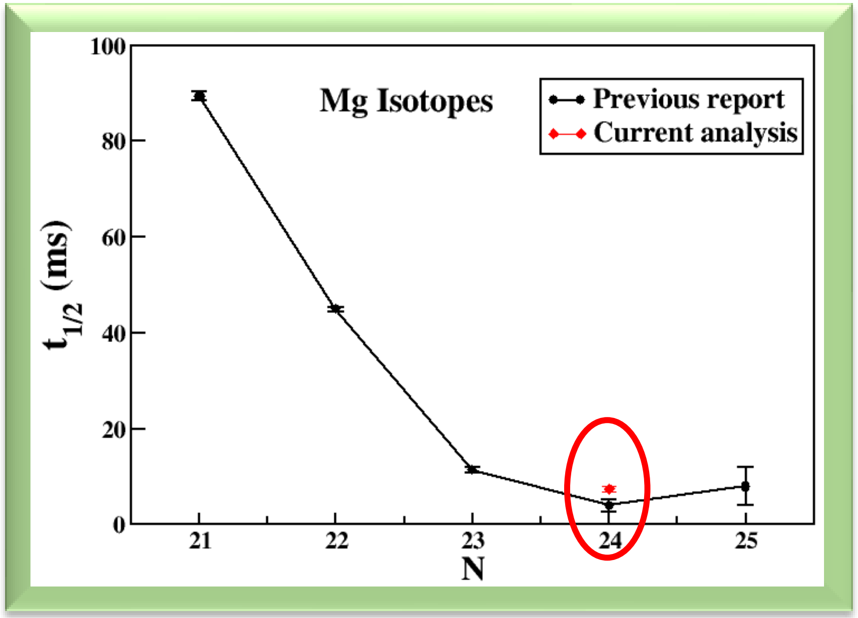


Background subtracted

^{34}Mg -> ^{34}Al -> ^{34}Si

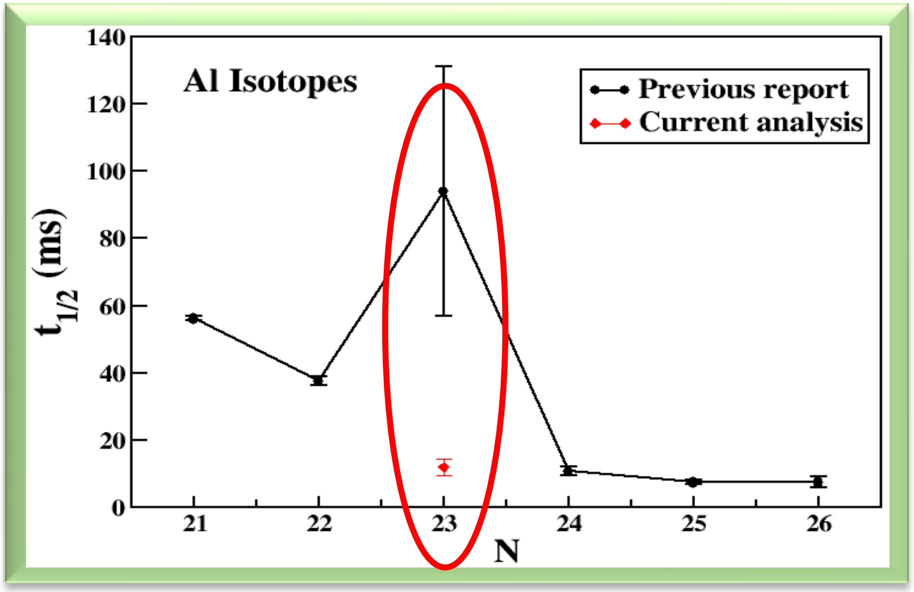


Mg and Al Half-lives Systematics



- In Mg isotopes, the half-lives decreases for the increasing ratio of N/Z.
- The measured half-life in the current analysis follows the trend.

- Al isotopes also follow the trend of more exotic nuclei have shorter half-lives, except for ^{36}Al.
- The current measured half-life is far different from the previously measured one but falls right on the trend with the other Al isotope half-lives.



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National Science Foundation
Michigan State University

The previously measured half-lives were compiled from https://www.nndc.bnl.gov/

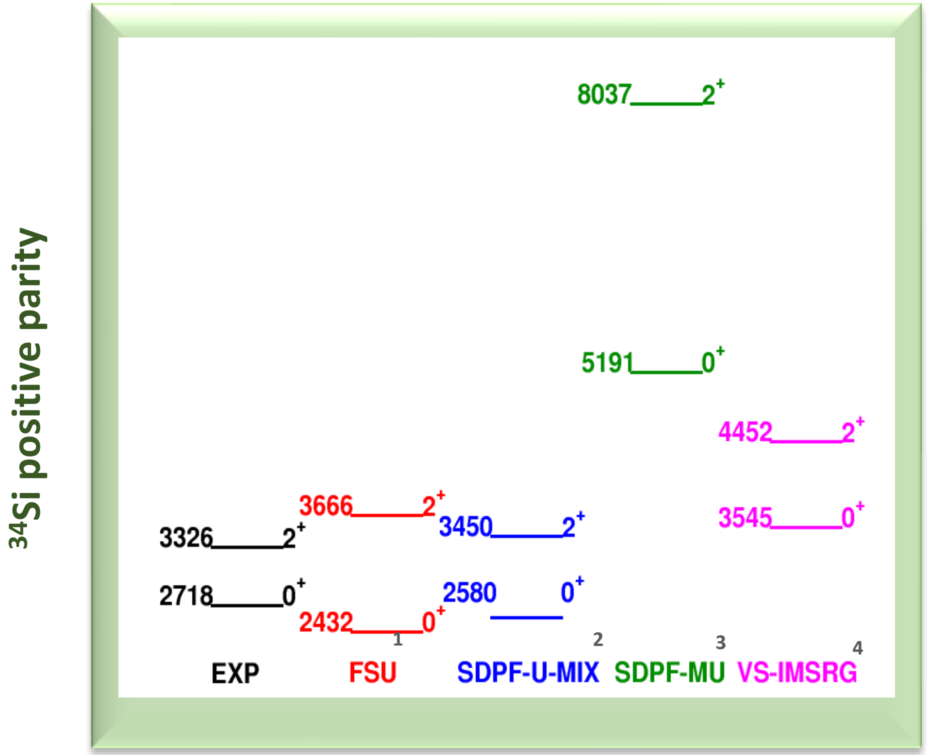
Areas of γ-peaks

Decaying parent	γ-transition	Area
^{36}Mg	1109	237
	1408	373
	2316	134
^{36}Al	1109	80
	1408	126
	2316	45

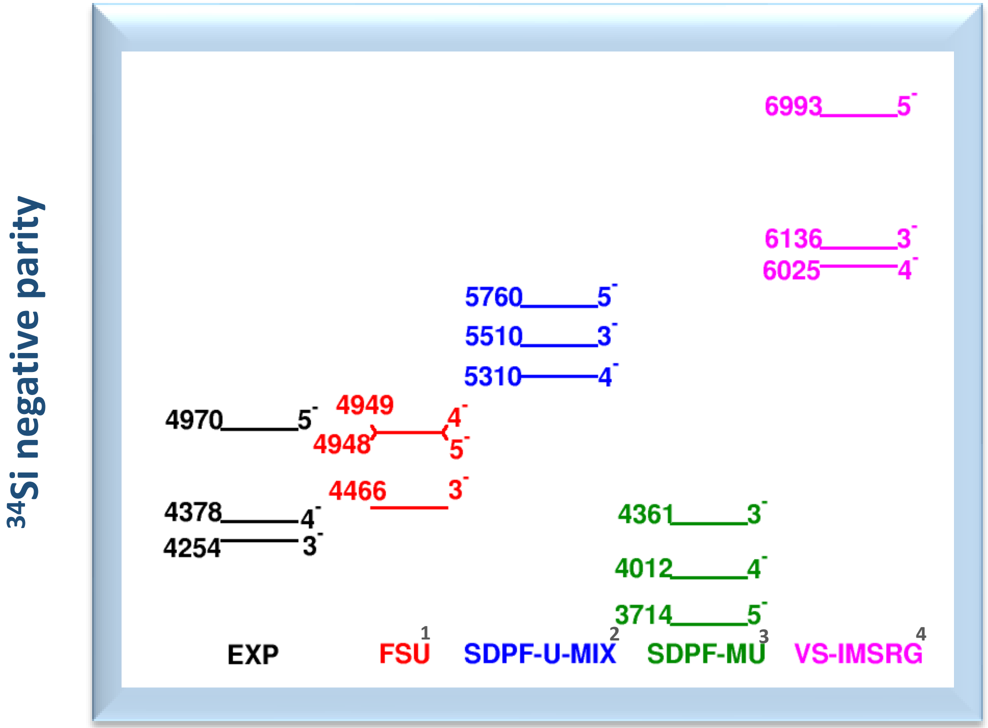
Expected counts

decay	gate keV	peak keV	area gate coincidence spectrum	eff_gate	eff_peak	expected area peak
36Mg	657	910	156.00	0.04	0.04	5.66
	1408	2316	228.49	0.03	0.02	4.89
	1408	1109	228.49	0.03	0.03	7.59
36Al	1408	1109	118.87	0.03	0.03	3.95
	1408	2316	118.87	0.03	0.02	2.54

^{34}Si: Transitional Nucleus along N = 20



- Compared the experimental levels with some modern theoretical models.
- FSU, SDPF-U-MIX and VS-IMSRG well predicts the first excited 0+ and 2+ with the $2\hbar\omega$ excitation.

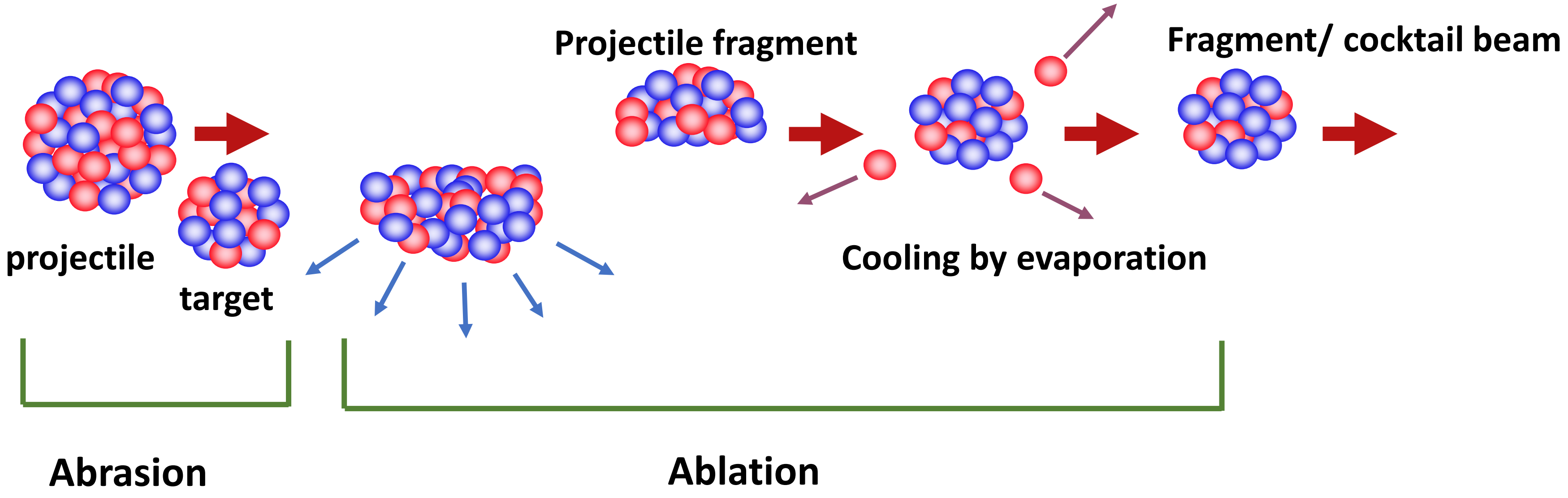


- The first negative parity 3^-, 4^-, 5^- states are dominated by the $1\hbar\omega$ excitation with the dominant configuration $\left(\nu d_{\frac{3}{2}}\right)1 \otimes \left(\nu f_{\frac{7}{2}}\right)1$

1. Phys. Rev. Research 2, 043342 (2019).
2. Phys. Rev. C 100, 034306 (2019).
3. Phys. Rev. C 86, 051301(R) (2012).

Rare Isotopes via Projectile Fragmentation

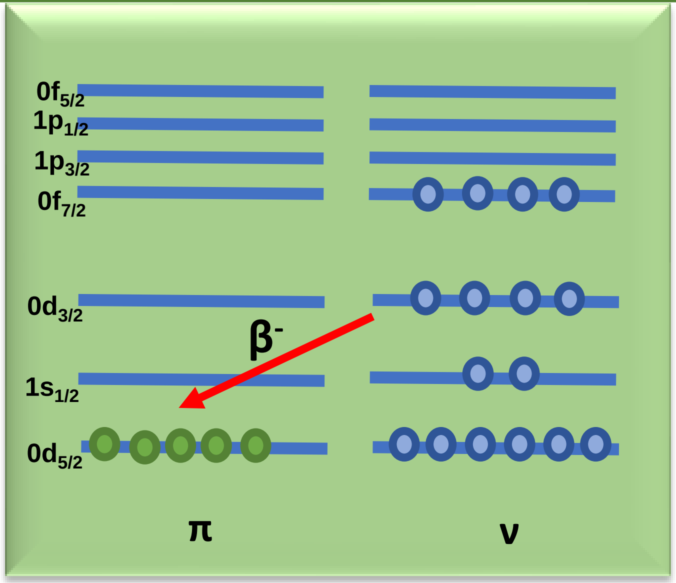
- Isotope production process during projectile fragmentation.



- Produce exotic isotopes.
- Production occurs at very high energies (~100 MeV/nucleon).
- Many isotopes are produced simultaneously.

β⁻ decays of ³⁶Mg and ³⁶Al

Ground State (g.s.) configuration of ³⁶Mg, Spin 0⁺

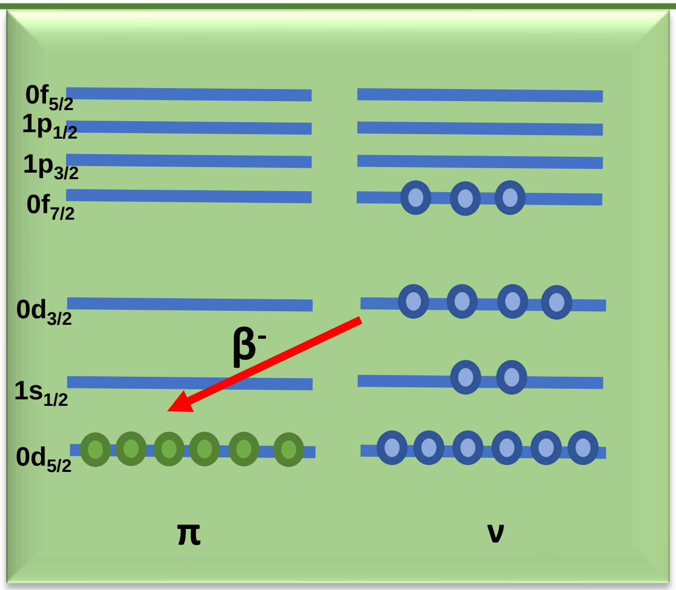


$$\nu 0d_{3/2} \overset{\beta^-}{\rightarrow} \pi 0d_{5/2}$$

Strongly populates 1⁺ (intruder) state of ³⁶Al via allowed β transition

$$\frac{5}{2} \otimes \frac{3}{2} \rightarrow 1^+$$

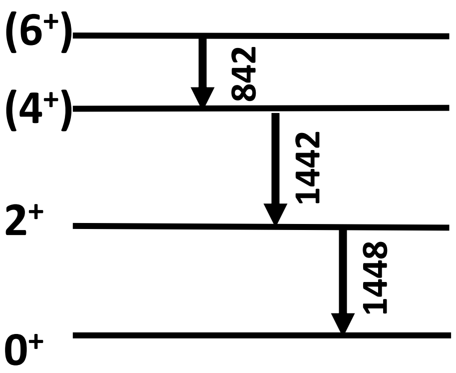
Ground State (g.s.) configuration of ³⁶Al. Spin, $\frac{5}{2} \otimes \frac{3}{2} \rightarrow 1^- - 6^-$



$$\nu 0d_{3/2} \overset{\beta^-}{\rightarrow} \pi 0d_{5/2}$$

Populates intruder, negative parity states of ³⁶Si via allowed β transition. Levels of ³⁶Si will also be populated from the β decay of ³⁶Mg.

- **With N>20, both will populate the intruder states of the first descendant nuclei.**
- **No experimental information on ³⁶Al is available except for the half-life.**
- **No experimental information on ³⁶Si from the β-decay of ³⁶Al is available.**



³⁶Si known level scheme of γ-transitions

NSCL
FRIB
U.S. Department of Energy Office of Science
National Science Foundation
Michigan State University

The experimental level energies of ³⁶Si were compiled from https://www.nndc.bnl.gov/