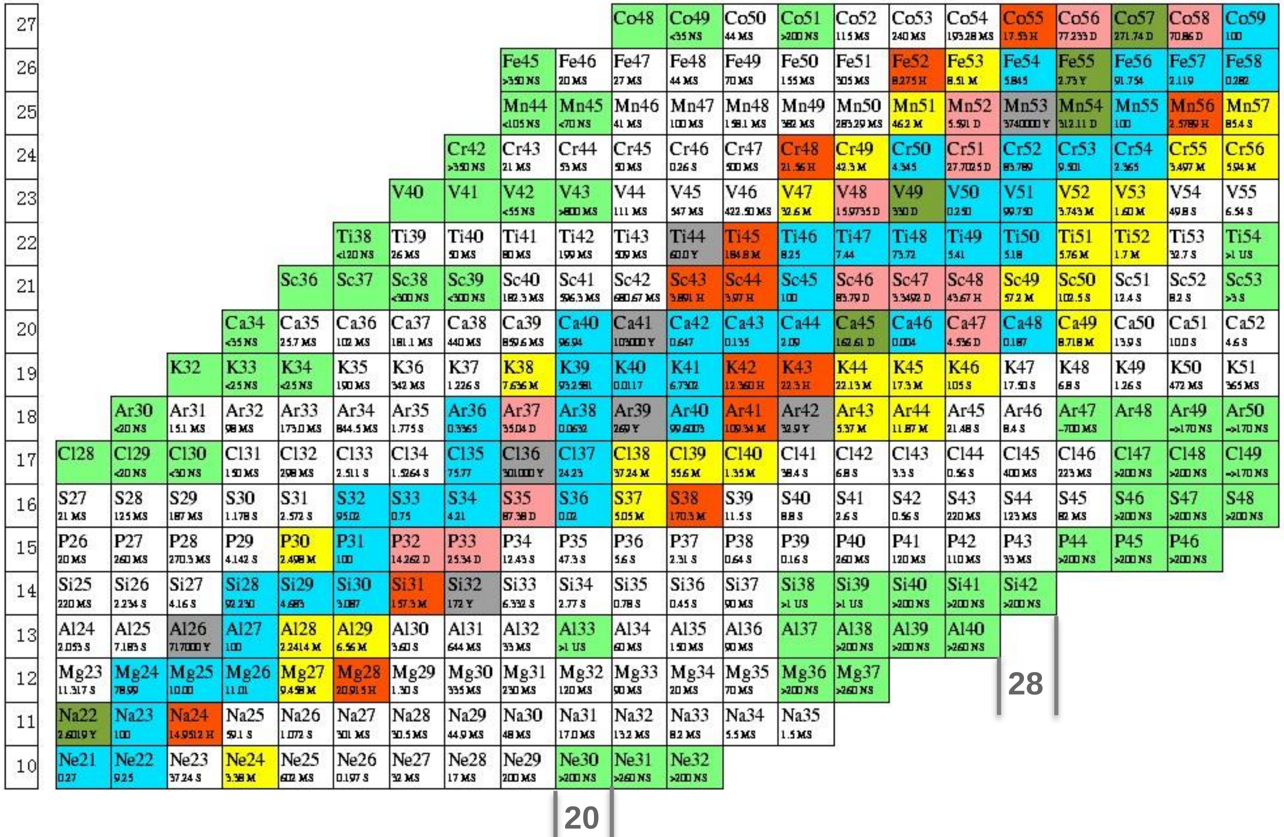
Early FRIB experiments: Explore Structural Properties of Exotic Nuclei via β decay and transfer Reactions

Rebeka Sultana Lubna

Facility for Rare Isotope Beams

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.

Outline



http://www.nuclear.csdb.cn/nuclear/index.asp

- **Isotopes with Z <= 20 and n > 20.**
- **Rich testing ground for the models to assess the structural evolution.**
- **Evolution near N = 28 shell gap.**

Outline

- Shape-coexistence with the FRIB Decay Station (FDS, current FDSi).
- Single-particle strength distribution via particle transfer reactions, (d, p) and (d, t) with the SOLenoid spectrometer Apparatus for Reaction Studies (SOLARIS).
- Phenomenological shell-model interaction.

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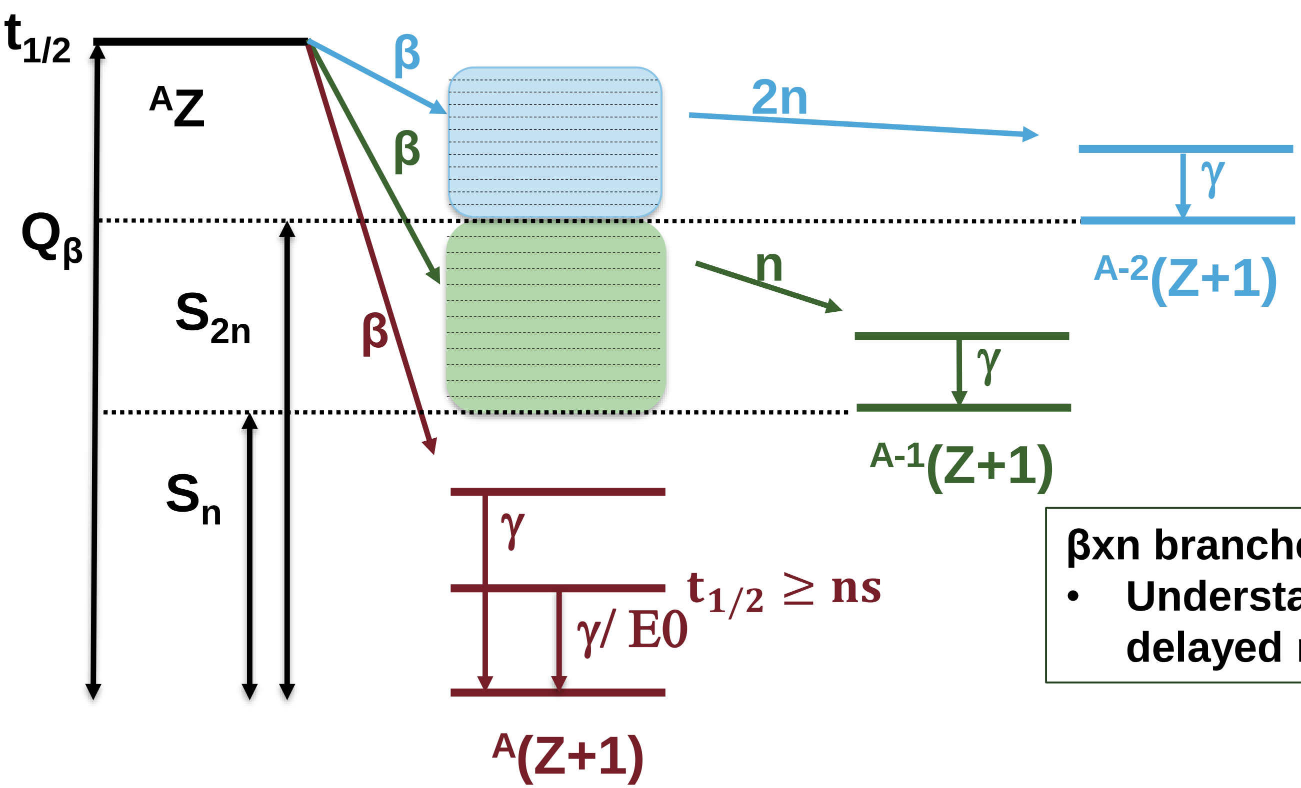
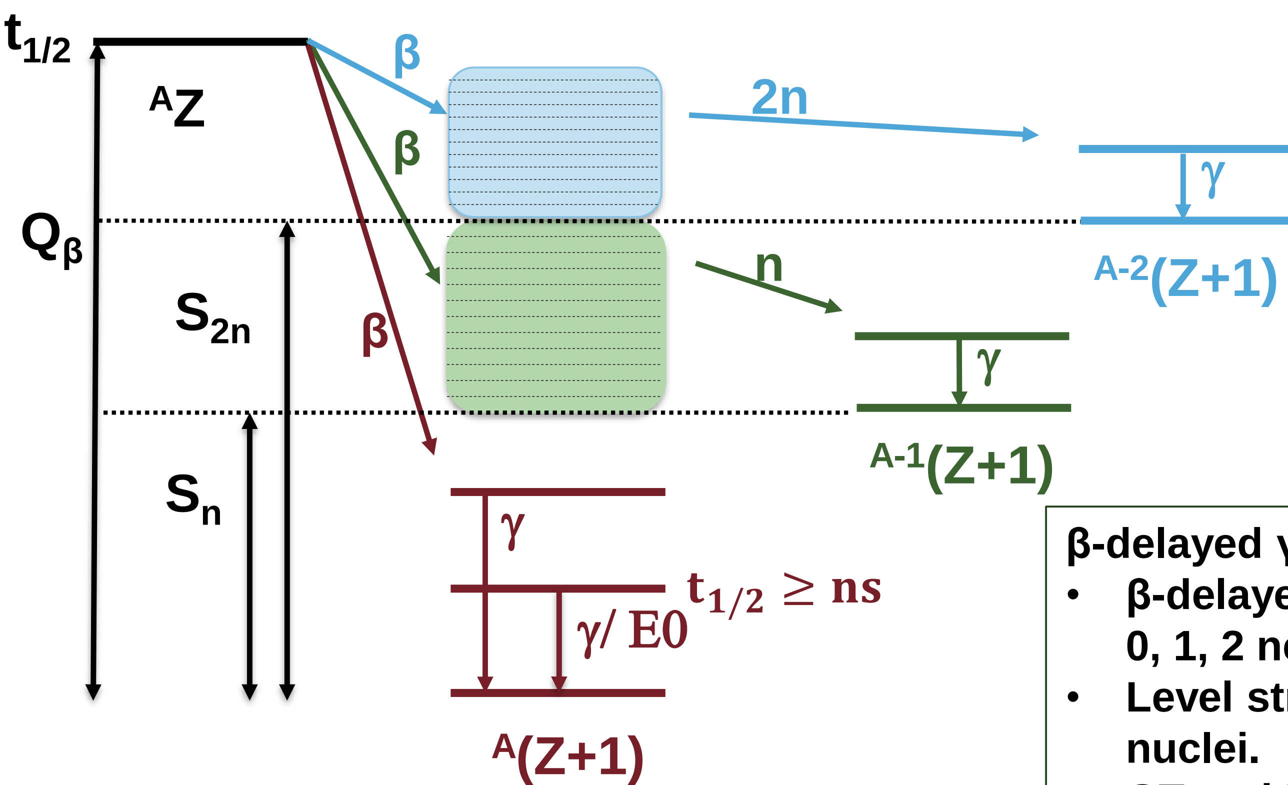
Measurements from β decay



βxn branches:

- **Understand the process of β-delayed neutron emission.**

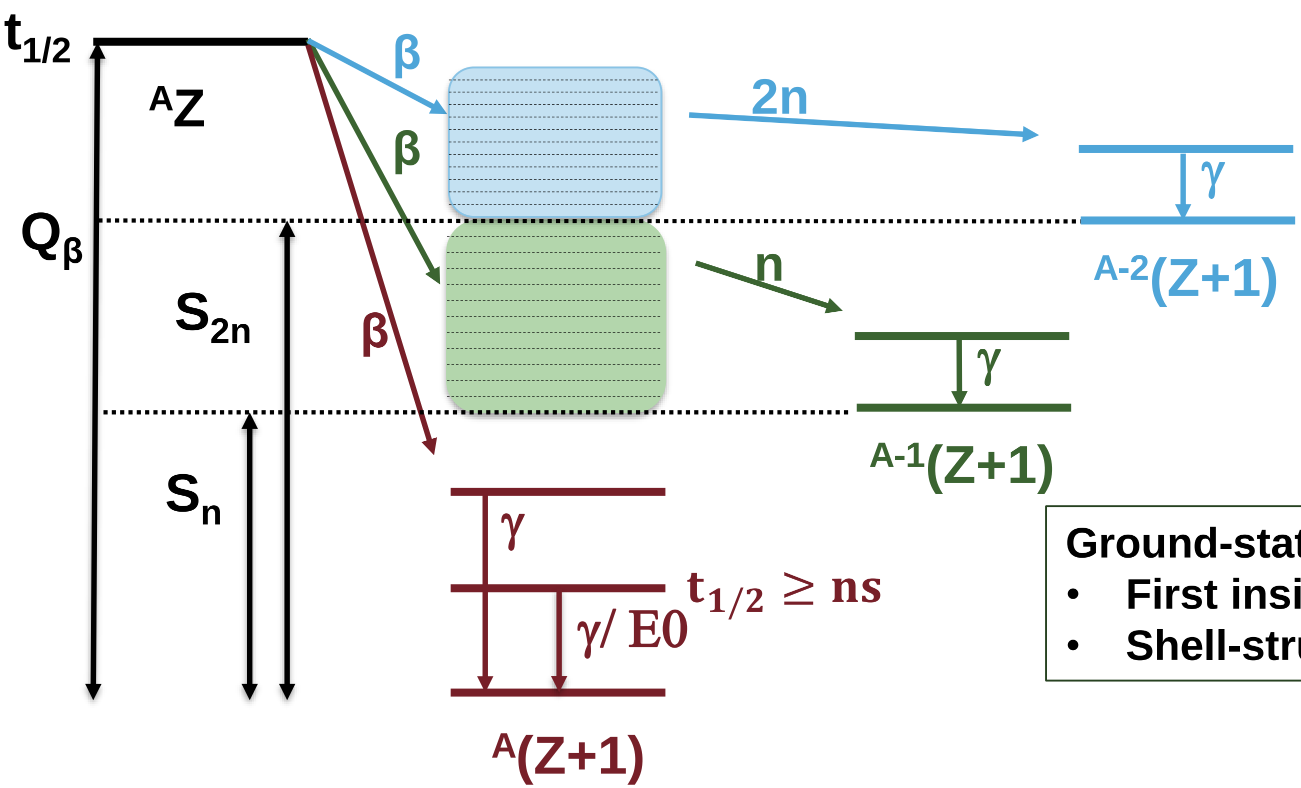
Measurements from β decay



β-delayed γ transitions:

- **β-delayed γ rays accompanied with 0, 1, 2 neutrons.**
- **Level structure of the descendant nuclei.**
- **GT and FF transition strength.**

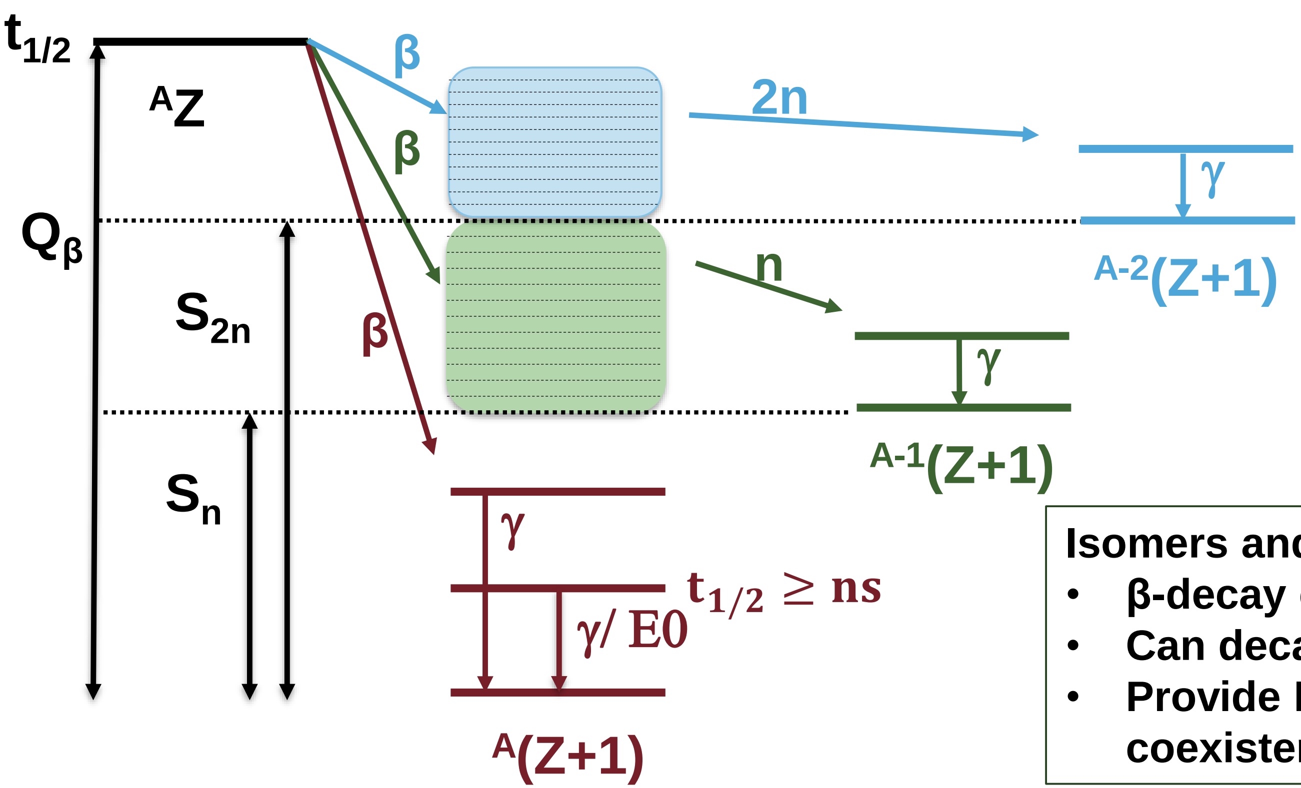
Measurements from β decay



Ground-state half-life:

- First insight into the structure.
- Shell-structure and evolution.

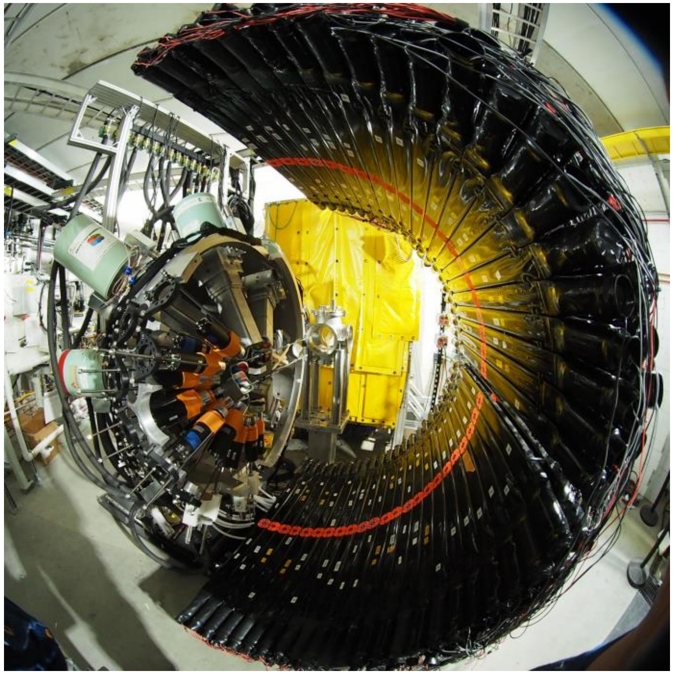
Measurements from β decay



Isomers and Shape co-existence:

- **β-decay can populate isomers.**
- **Can decay via β, γ or IC/ IPF.**
- **Provide Insight into shape coexistence.**

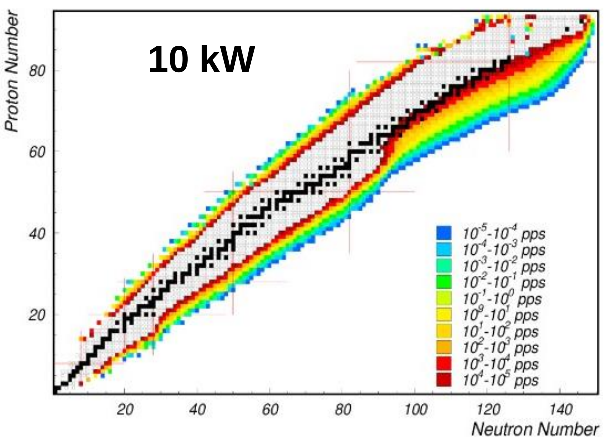
FRIB Decay Station, FDS (current FDSi)

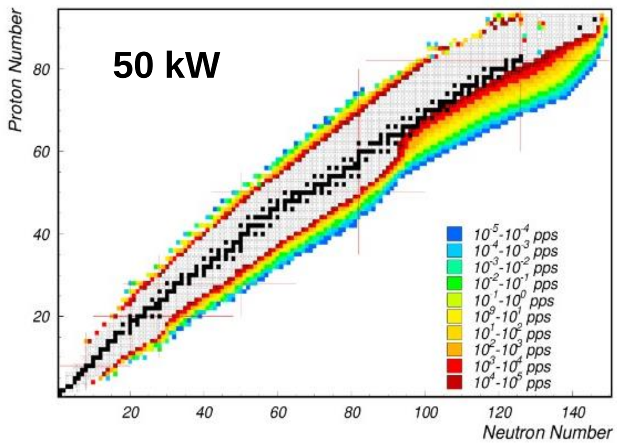


- **Measurements from the decay experiments with the fast beam delivered.**
- **A high-efficiency multi-detection system.**
- **γ-ray spectroscopy with HPGe and LaBr3, VANDLE, implantation detector.**

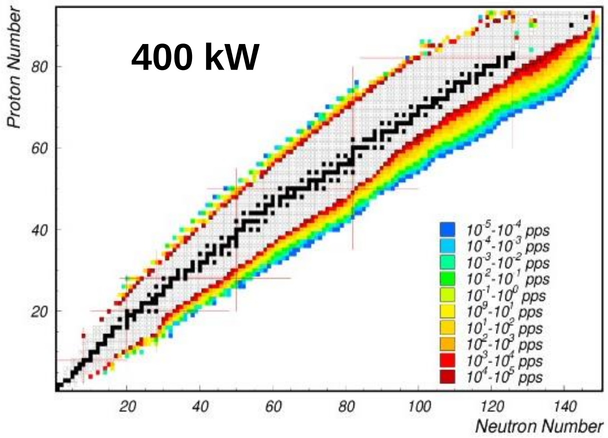
Photo credit: FDSi collaboration

Discovery Potential





FRIB fast-beam rates estimated at different stages.



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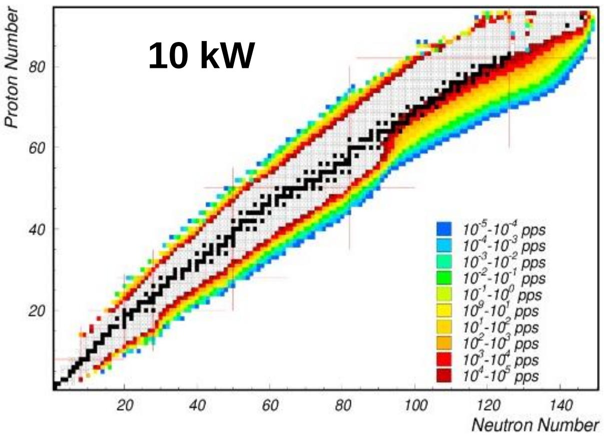

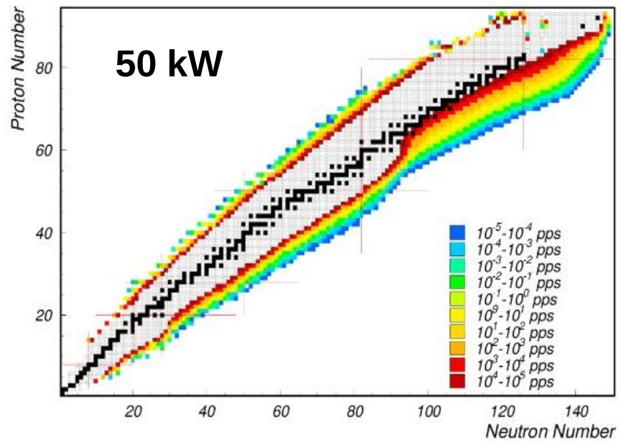

- **Rate requirements from different decay spectroscopy.**
- **Requirements will be reduced for enhanced efficiency.**

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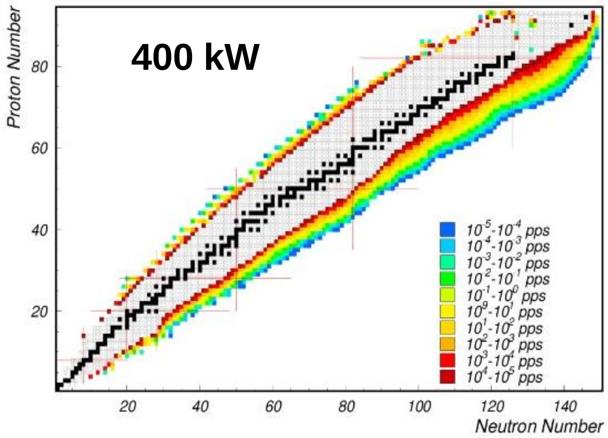
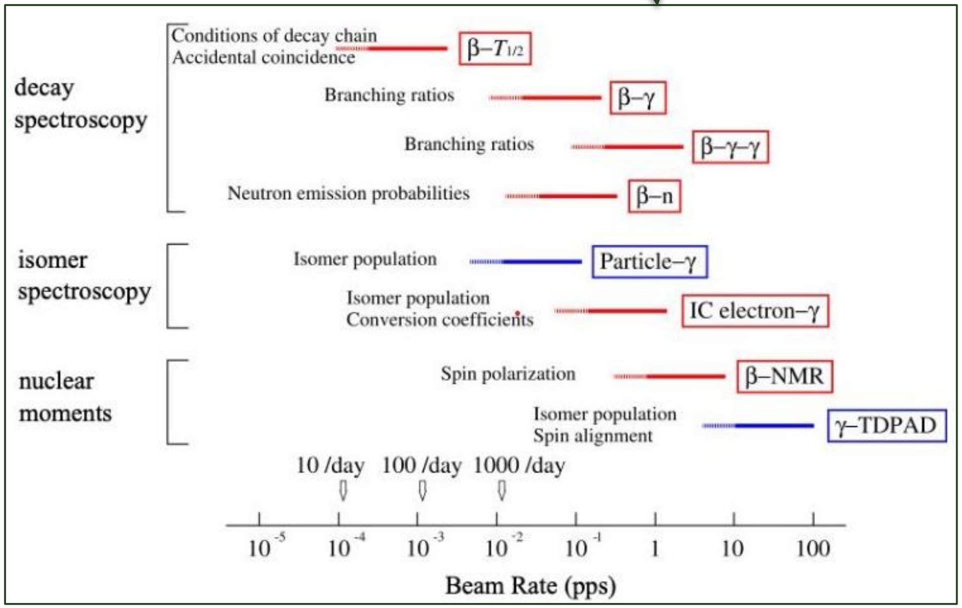
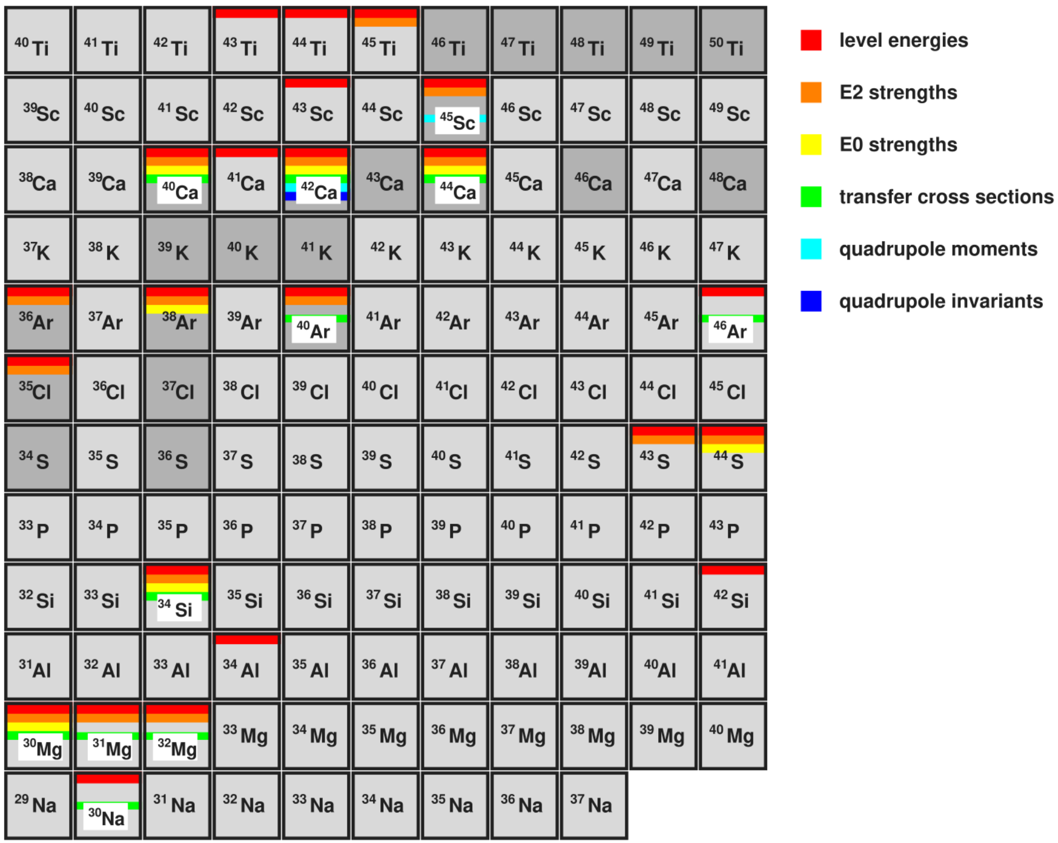




Identification of isomers: Shape Coexistence

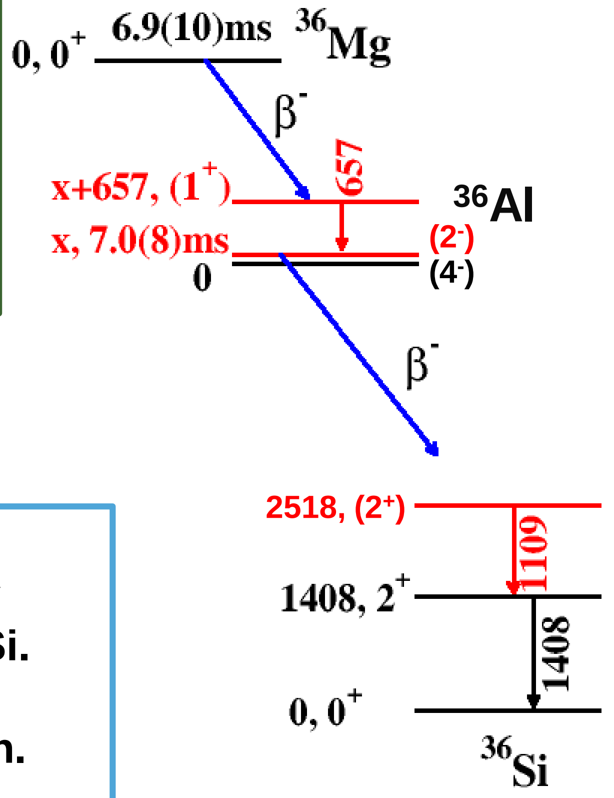


- **Low-lying states with different shapes correspond to different configurations.**
- **Isomers can be attributed to the shape coexistence.**
- **Discovery potential with the beams delivered to the FDS.**

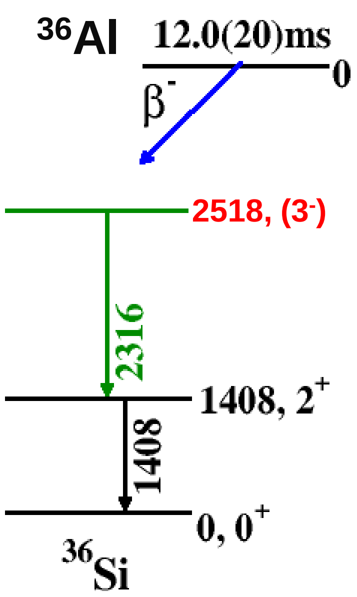
https://doi.org/10.1016/j.ppnp.2021.103931

Identification of β-decaying isomers

- A β-decaying isomer in ^{36}Al.
- Spin-parity all based on shell model.
- β-decaying isomer in this region only seen in Al.



Implantation and Ge detectors



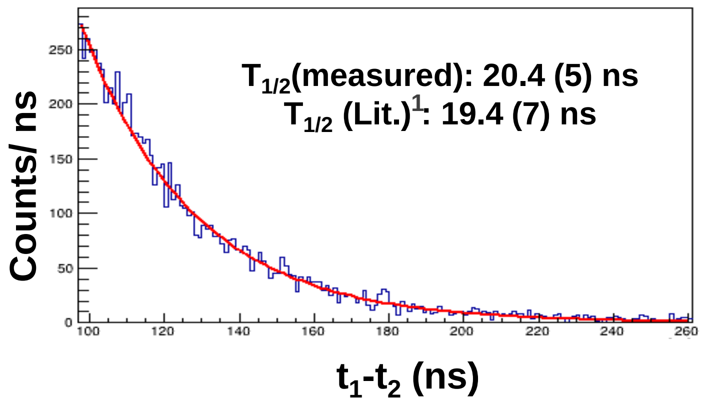
Future:
- Determine spins with γ-γ angular correlation in ^{34}Si.
- Constrain the parent spin.

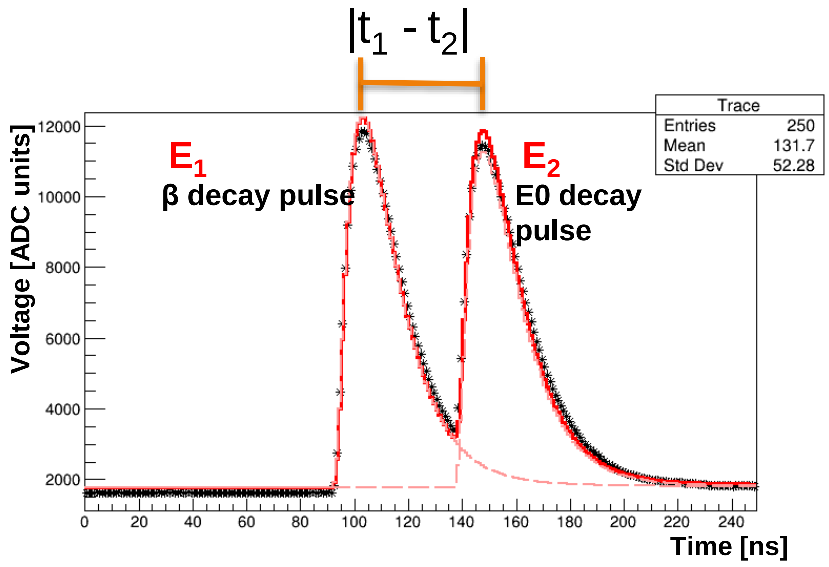
R.S.Lubna, submitted to Phys. Rev. C

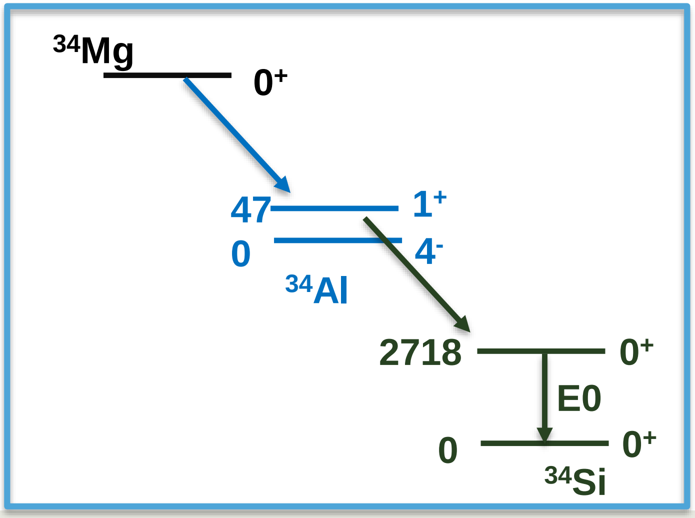
Identification of isomers due to E0 transition

- **β decay of ^{34}Mg.**
- **Time delay between a β-decay electron and IPF electron from ^{34}Si 2718 keV level.**

Implantation detector





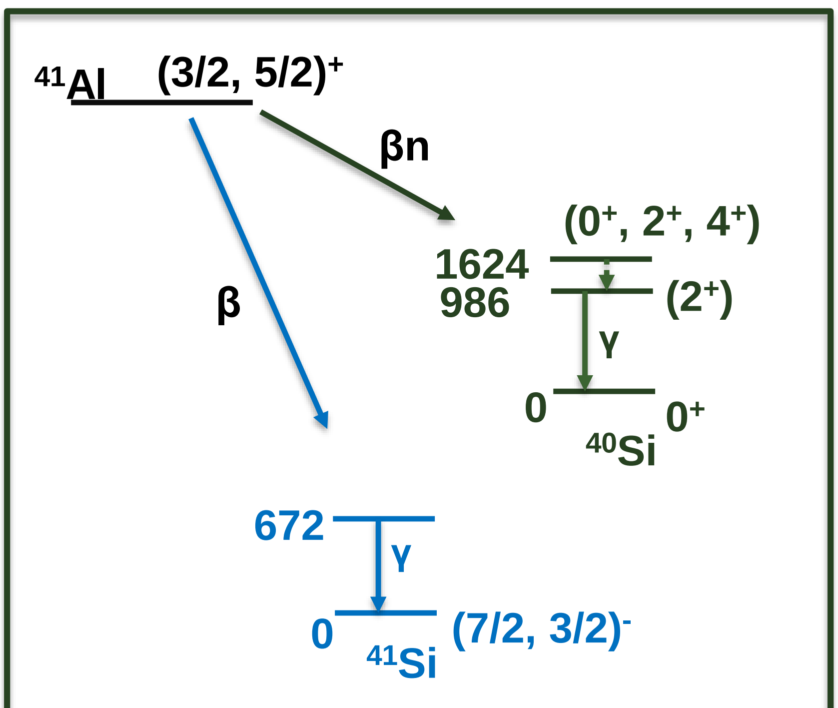


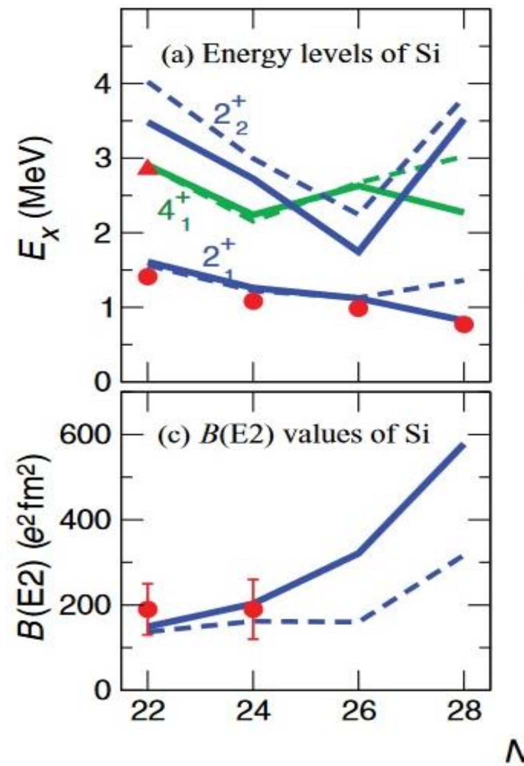
Half-life Pictures: T. Ogunbeku.

1. *Phys. Rev. Lett. 109, 092503*

Shape Coexistence through E0 transition

- Excited 0^+ levels are good probe for shape coexistence.
- Prospects to study more shape-coexisting 0^+ levels in more exotic nuclei with higher rates.





- SDPF-MU[2] successfully predicts first excited 2^+ along the Si Isotopic chain.
- How well 0^+ levels can be predicted.

1. *Experimental levels from https://www.nndc.bnl.gov/*
2. *Phys. Rev. C 86, 051301(R) (2012).*

Outline

- Shape-coexistence with the FRIB Decay Station (FDS, current FDSi).
- **Single-particle strength distribution via particle transfer reactions, (d, p) and (d, t) with the SOLenoid spectrometer Apparatus for Reaction Studies (SOLARIS).**
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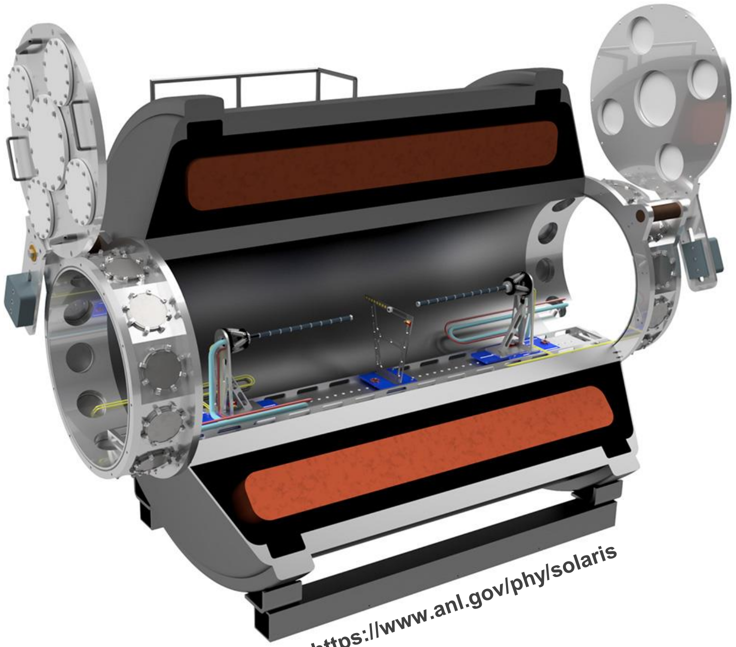
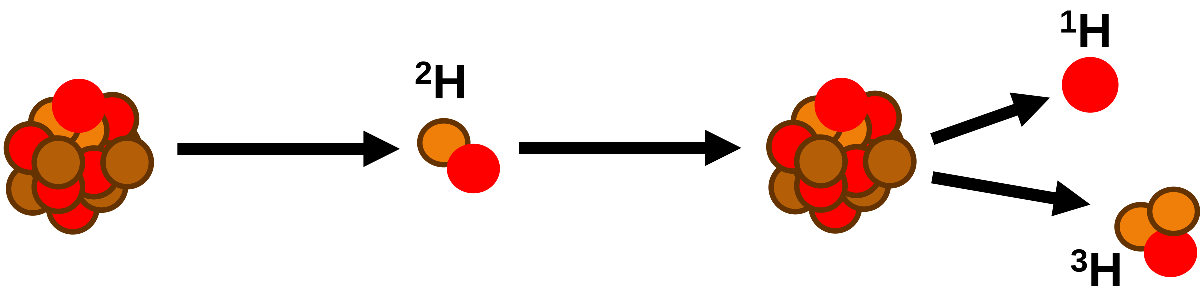
Solenoid Spectrometer, SOLARIS



- **Facilitate the measurements from direct reaction with the Re-accelerated beams.**
- **Work with inverse kinematic, doesn't suffer from the lack of stable target.**
- **Can measure (d, p) and (d, t) simultaneously.**
- **Discovery potential with the beams provided by the FRIB.**

Particle transfer reactions, simultaneous (d, p) and (d, t) measurements



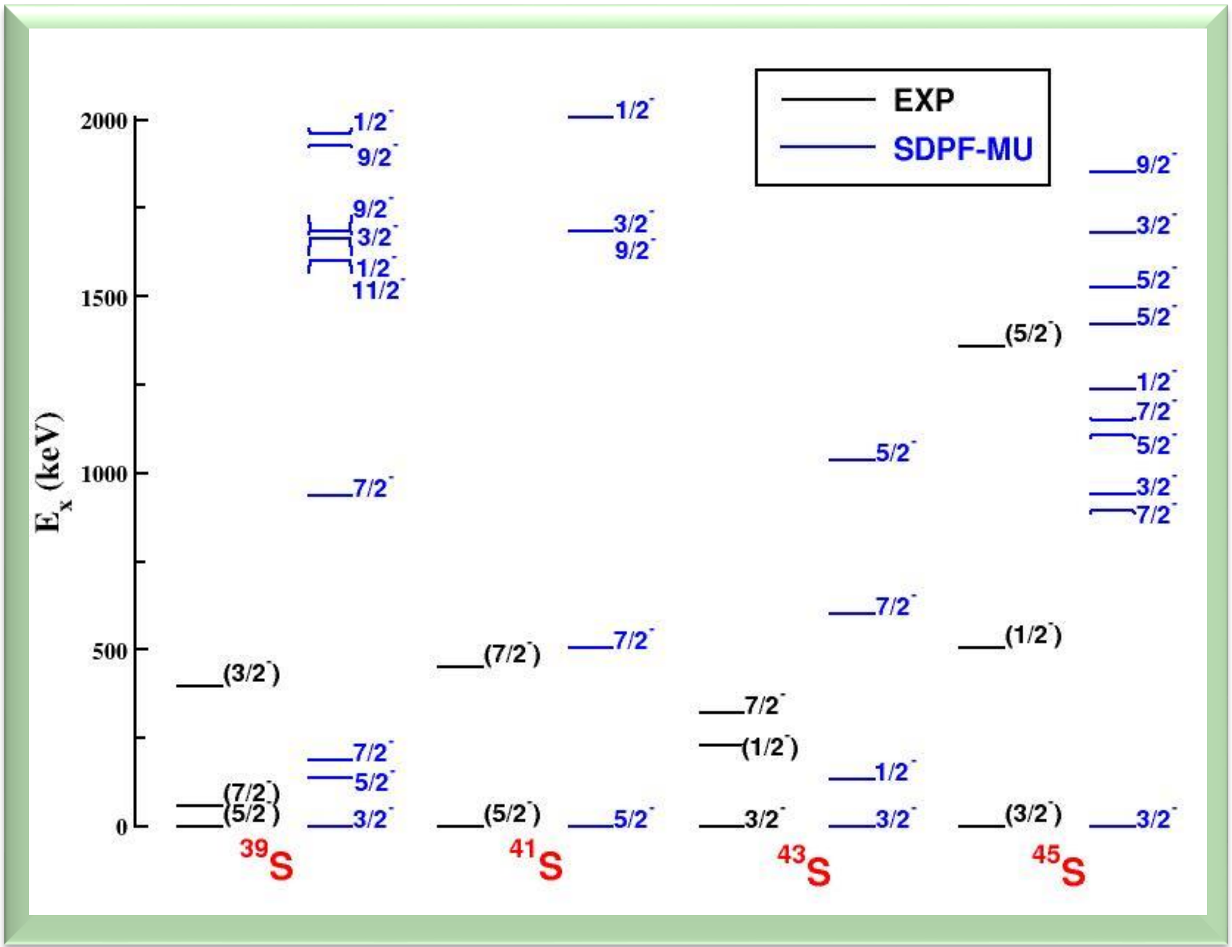
- **Single particle properties near N = 28 deformed region is not well probed.**
- **Spectroscopic factors will assess the fragmentation of single particle strengths.**
- **Effective Single Particle Energy (ESPE) with simultaneous (d, p) and (d, t).**

Particle transfer reactions, simultaneous (d, p) and (d, t) measurements

- **Two experiments approved in FRIB PAC II, focused on the simultaneous (d, p) and (d, t) measurements to probe the fragmentation of the single particle strengths.**
- ***^{40}S(d, p) (d, t)^{41}S, ^{39}S* and *^{42}S (d, p) (d, t) ^{43}S, ^{41}S*.**[1]
- ***^{46}Ca(d, p) (d, t) ^{47}Ca, ^{45}Ca*.**[2]

1. **R.S.Lubna *et al* , FRIB PAC II approved proposal.**
2. **A.J. Mitchell et al, FRIB PAC II approved proposal.**

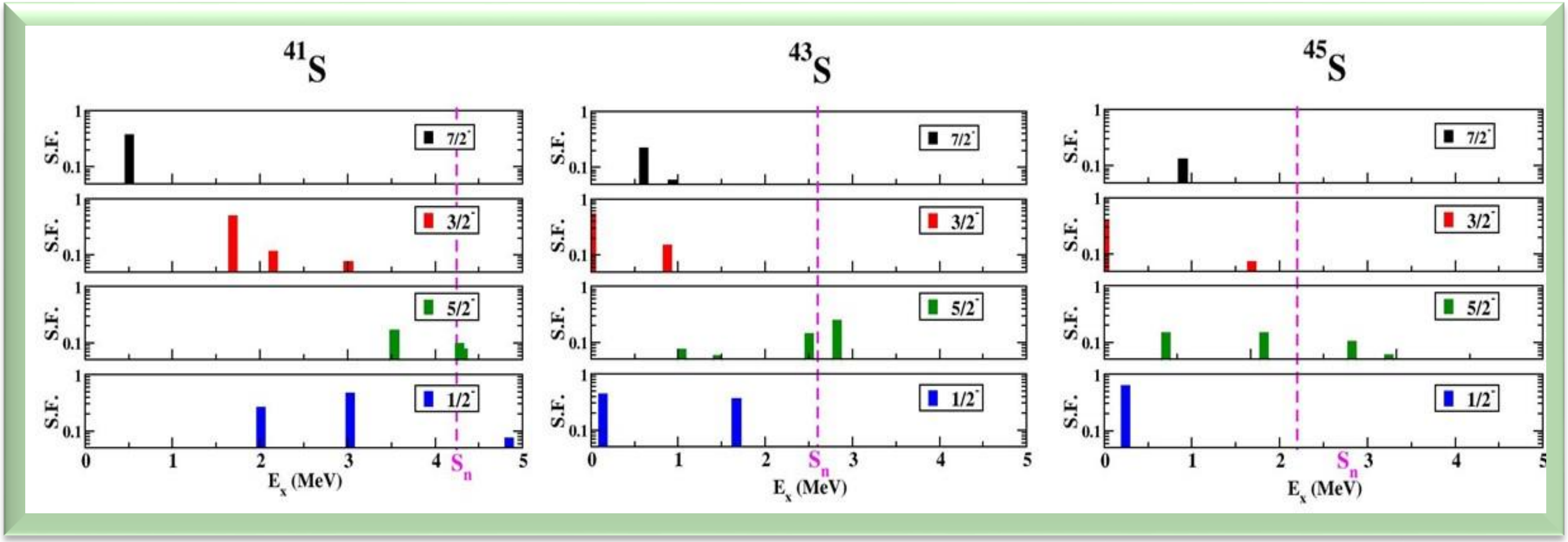
Particle transfer reactions, (d, p) and (d, t): Future



- **S isotopes near N = 28 are well known for deformation.**
- **^{41}S and ^{43}S will be investigated via (d, p) and (d, t) reactions.**
- **^{45}S assigned solely based on theory.**

1. R.S.Lubna *et al,* FRIB PAC II approved proposal.

Particle transfer reactions, (d, p) and (d, t): Future



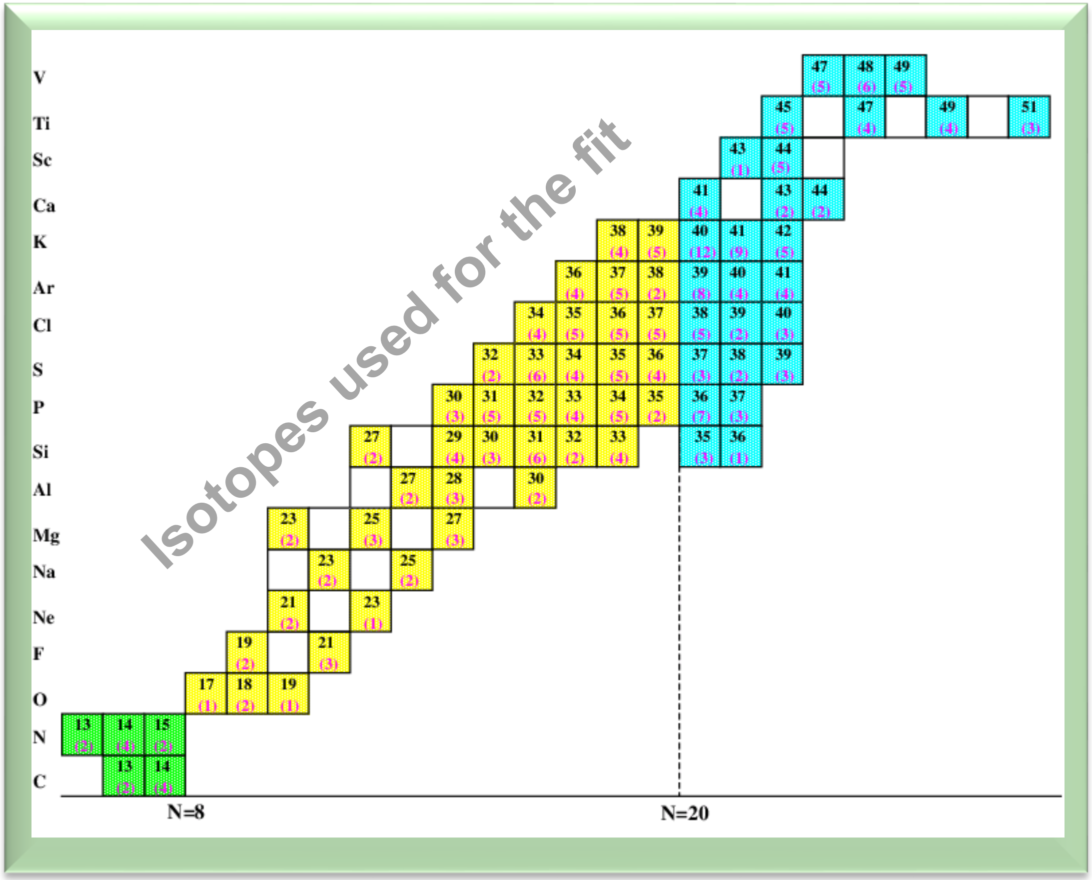
- Spectroscopic factors predicted by model.[2]
- Whether theory can predict the spectroscopic factors properly for ^{41}S and ^{43}S.
- *^{44}S(d, p)(d, t)^{45}S* will provide stringent test to the models with the ultimate beam rates provided by the FRIB.

1. R.S.Lubna *et al,* FRIB PAC II approved proposal.
2. *Phys. Rev. C 86, 051301(R) (2012).*

Outline

- Study of β-decay half-life, strength distribution(GT, FF) and shape-coexistence with the FRIB Decay Station (FDS, current FDSi).
- Single-particle strength distribution via particle transfer reactions, (d, p) and (d, t) with the SOLenoid spectrometer Apparatus for Reaction Studies (SOLARIS).
- **Phenomenological shell-model interaction.**

Phenomenological model: Data can be invaluable



- FSU[1] shell-model within the *spsdfp* model-space using the data fitting procedure.
- Hamiltonians from the existing models were used as a starting point
- Data fitting performed within the *p-sd-fp* model-space.
- A total of 70 parameters fitted by using 270 experimentally observed levels.

1. *Phys. Rev. Research 2, 043342 (2020)*

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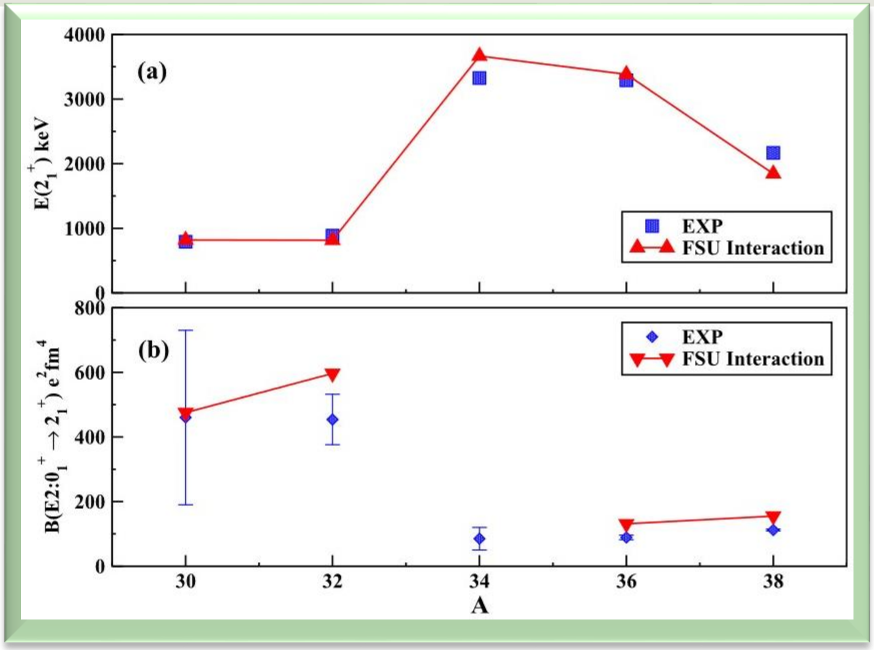
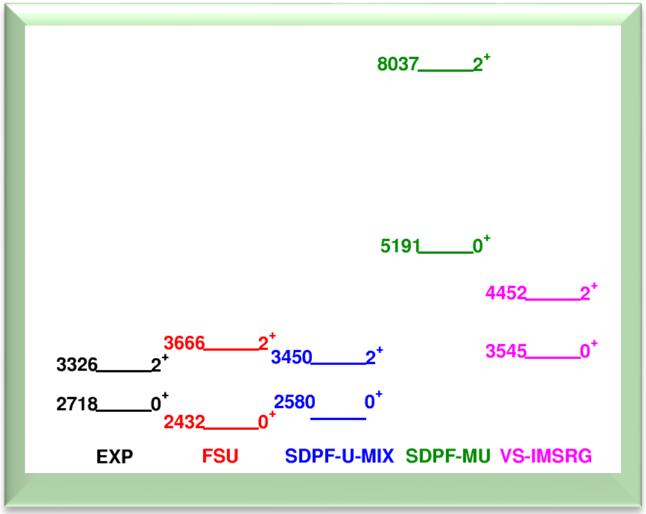


- Reproduce N = 20 IoI phenomena successfully.
- Successful in reproducing opposite parity levels.

^{34}Si positive parity



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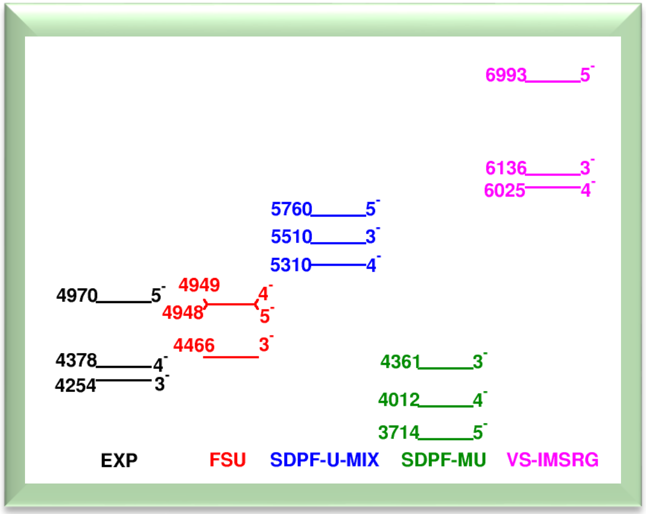

1. *Phys. Rev. Research 2, 043342 (2020).*
2. *Phys. Rev. C 100, 034306 (2019).*
3. *Phys. Rev. C 86, 051301(R) (2012).*
4. *Phys. Rev. C 102, 034320 (2020).*

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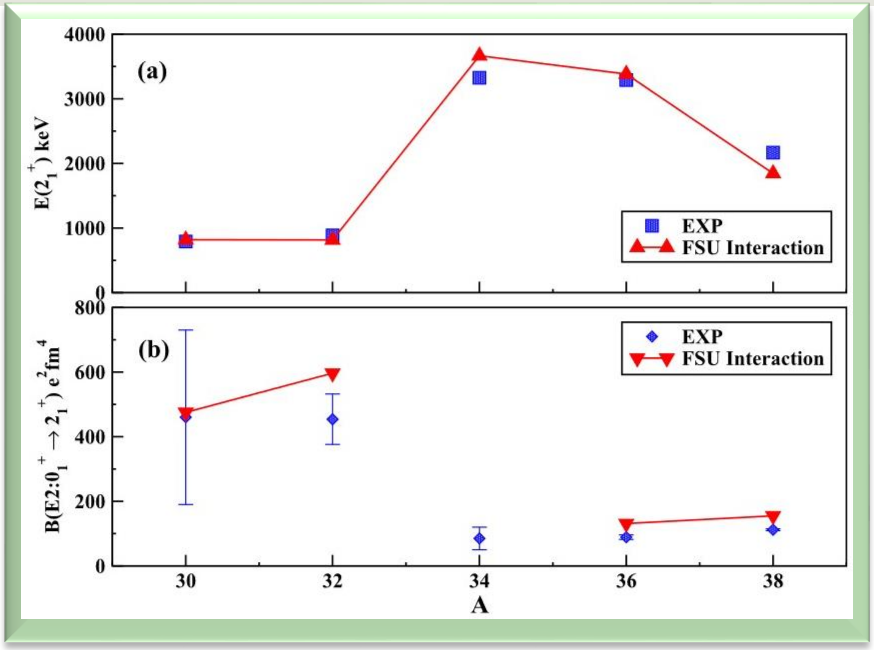

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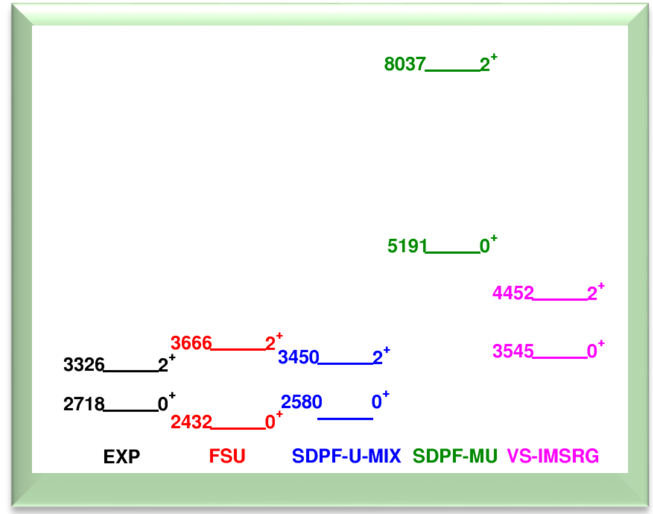

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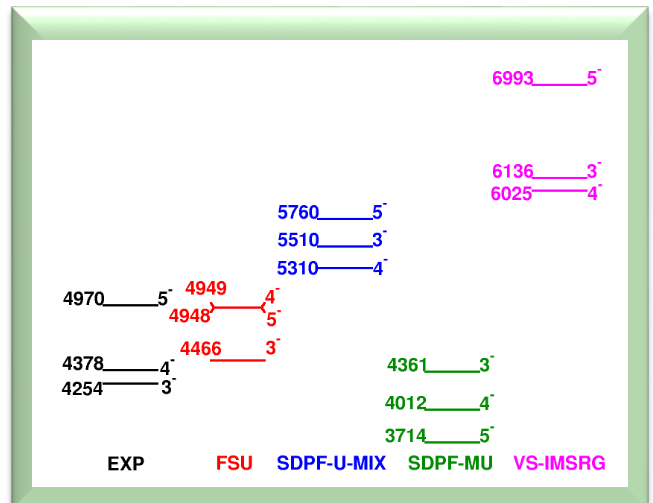

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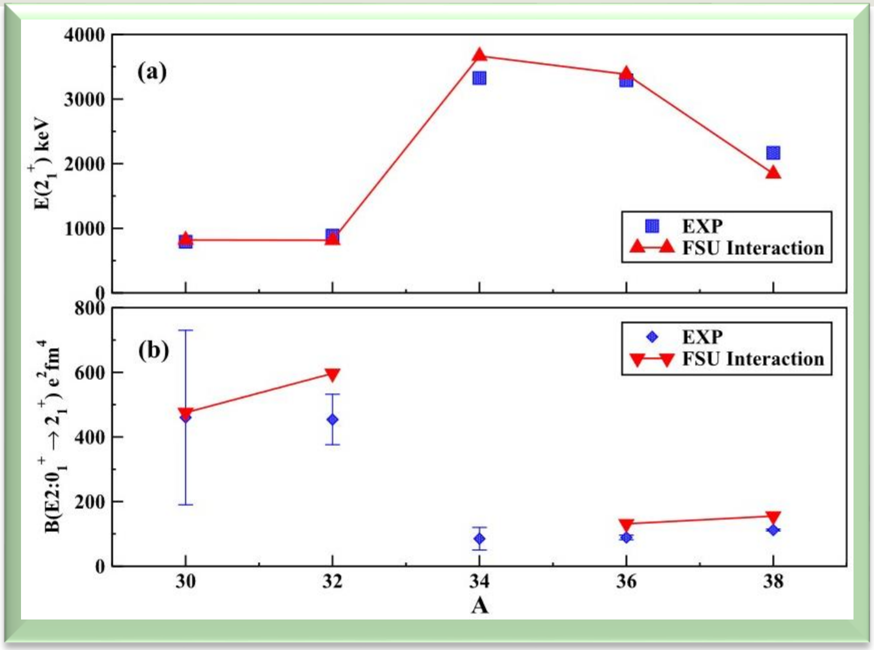

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- **Fit more parameters.**
- **Introduce mixing.**
- **Expand model space.**

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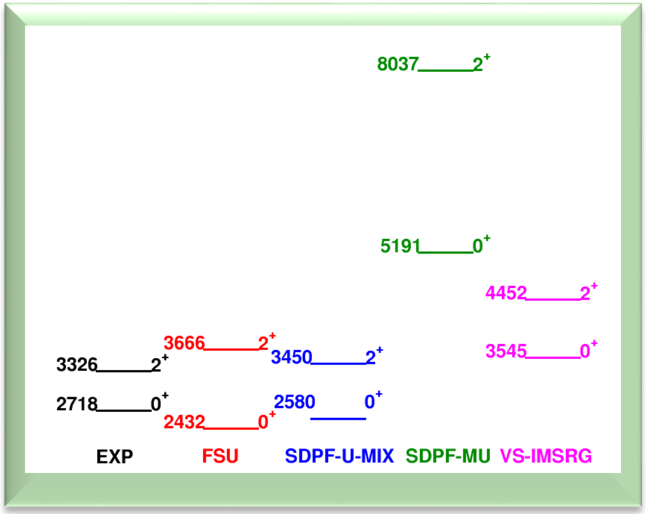

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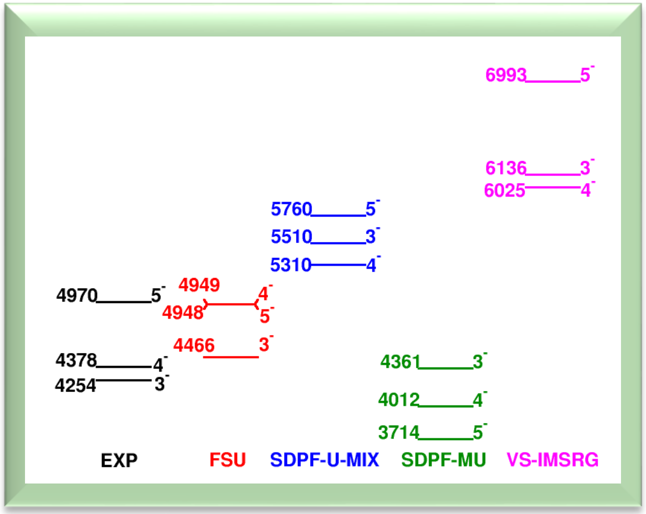

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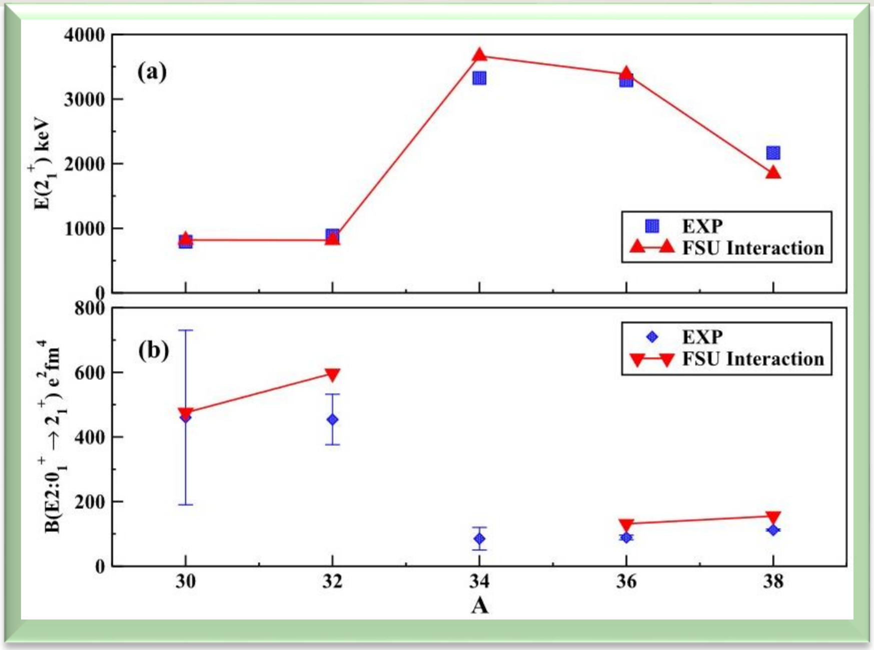

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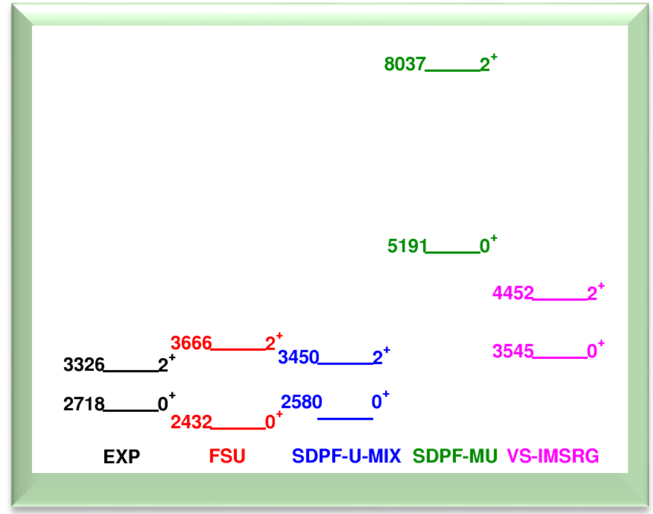

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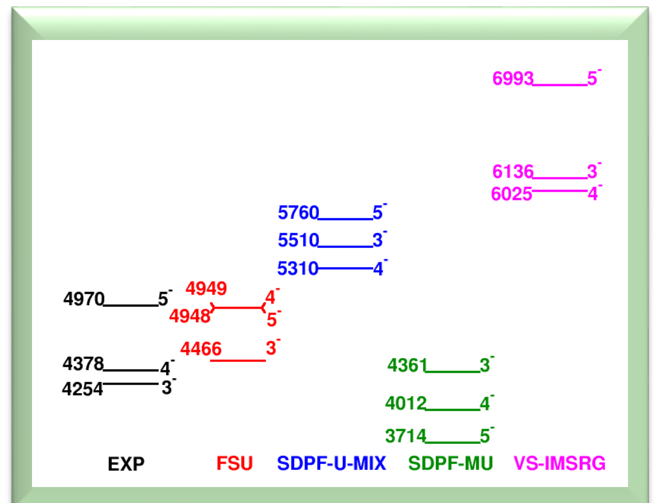

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Need more experimental data

FRIB Facility for Rare Isotope Beams
U.S. Department of Energy Office of Science
Michigan State University

1. *Phys. Rev. Research 2, 043342 (2020).*
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Conclusion

- **β decay can be used to study shape coexistence.**

- **With the FRIB enhanced beams rates of the exotic nuclei, we aim to populate and study 0^+ excited levels with the FDS.**

- **Do we have a consistent model that can interpret their configurations?**

Conclusion

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- With the FRIB enhanced beams rates of the exotic nuclei, we aim to populate and study 0^+ excited levels with the FDS.
- Do we have a consistent model that can interpret their configurations?

- (d, p) will provide single-particle strength distribution for the nuclei in deformed region.
- Simultaneous (d, p) and (d, t) will probe the occupancy of the initial isotope.
- FRIB Re-accelerated beam to SOLARIS will study the fragmentation of the single-particle strength.
- Need models that can explain consistently the properties extracted. .

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- Need models that can explain consistently the properties extracted. .

- Data will provide stringent test and challenges to the models.
- Data can be used as invaluable inputs to the phenomenological model.

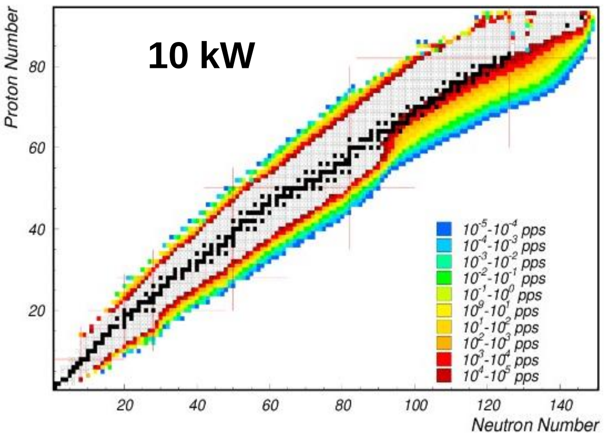
Thank you

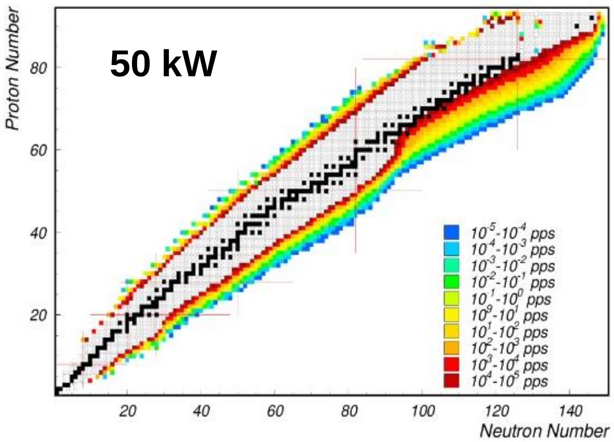
Acknowledgement:

U.S. Department of Energy, Office of Science, Office of Nuclear Physics, Contract No DE-SC0020451.

Backup

Discovery Potential





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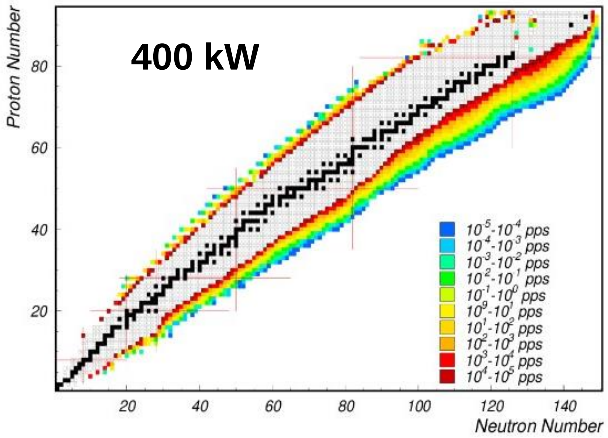
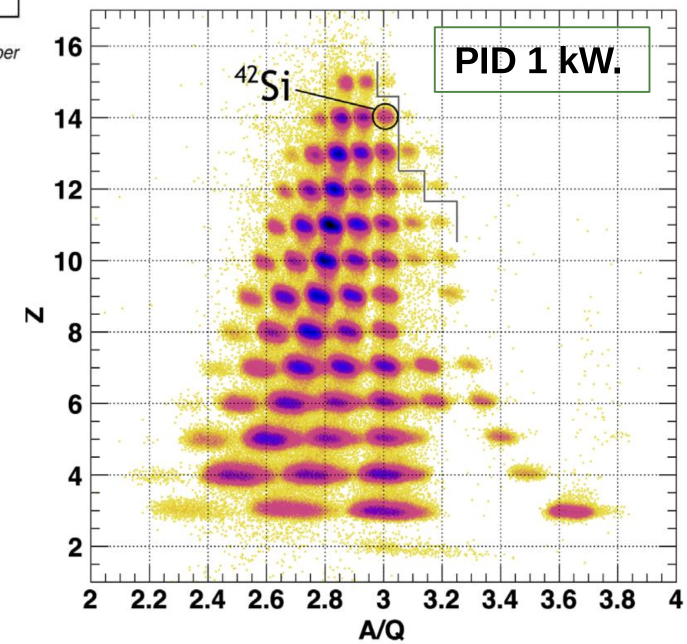


https://fds.ornl.gov/wp-content/uploads/2020/09/FDSi-Proposal-May2020.pdf

- **Ultimate power 400 kW.**



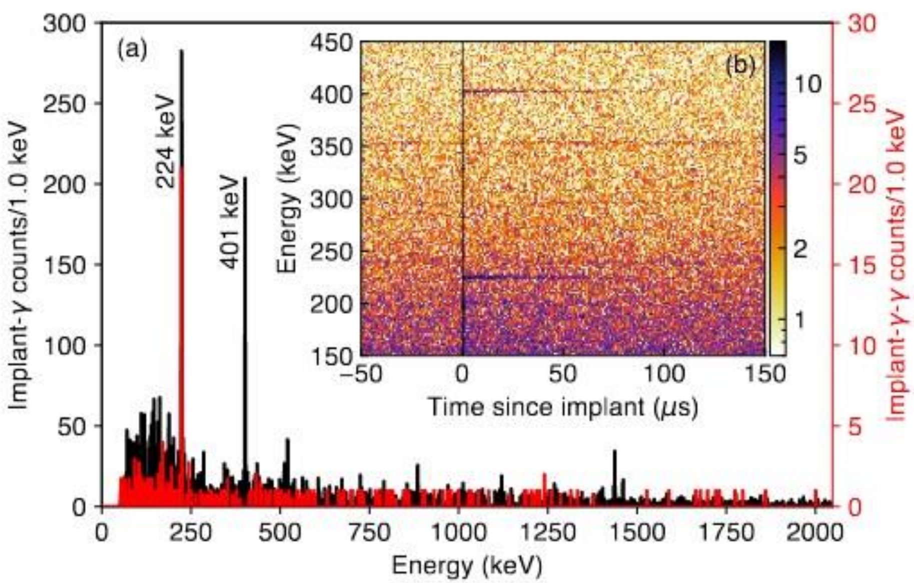
Phys. Rev. Lett. 129, 21250

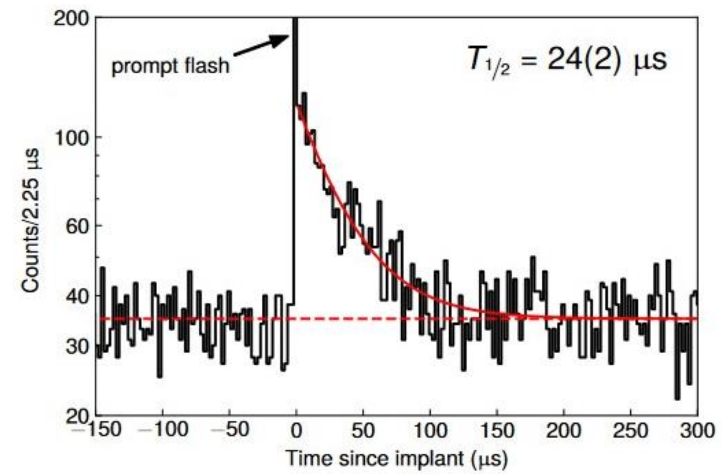
Identification of isomers (µs)

Implantation and Ge detectors

<u>µs isomer:</u>

- A µs isomer present in ^{32}Na beam.
- Confirmed for the delayed γ ray emitted.





- Spin-parity could not be determined.
- Theory suggested either 6^- or 0^+.
- Need more theoretical guidance along with the experimental confirmation.

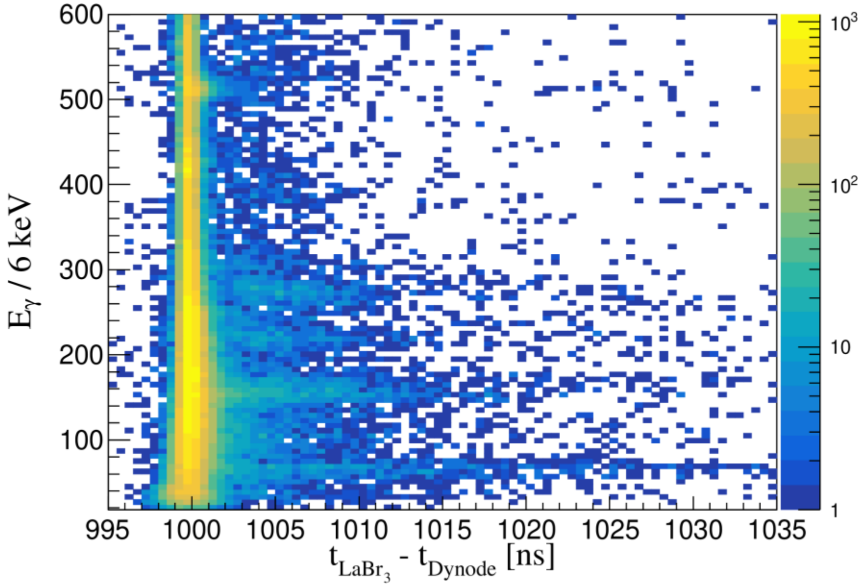
T.J.Gray, accepted, Phys. Rev. Lett.

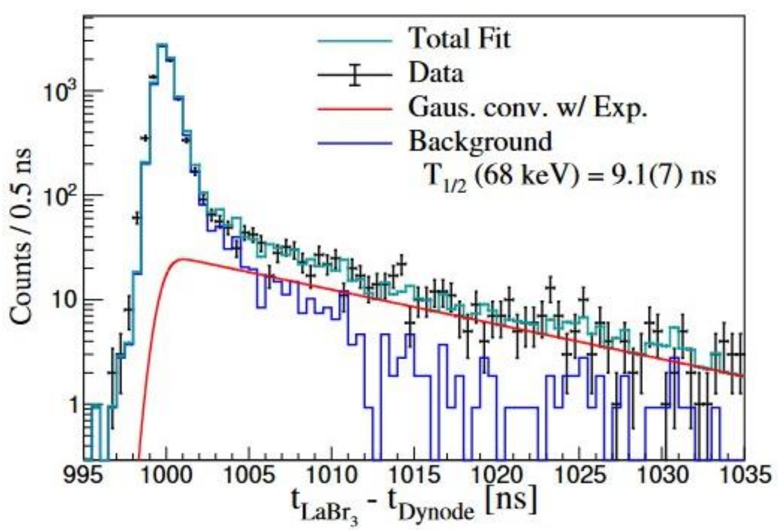
Identification of isomers (ns)

Implantation, Ge and LaBr detectors

<u>**~1-100 ns:**</u>

- **Measure time delay between isomeric state following β decay and γ emission in coincidence**





T. Ogunbeku, submitted, Phys. Rev. C

Identification of isomers (ms)

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ms Isomers:

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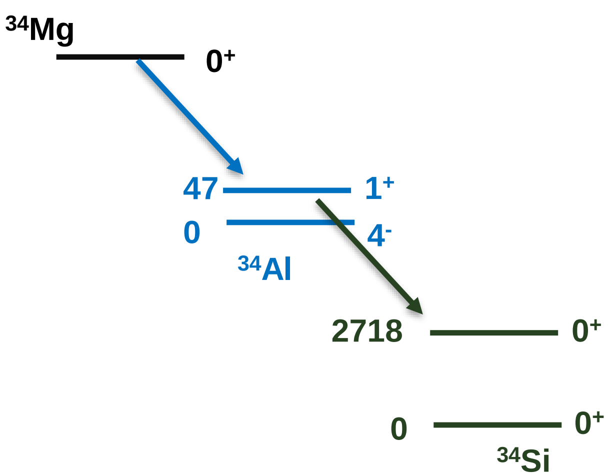
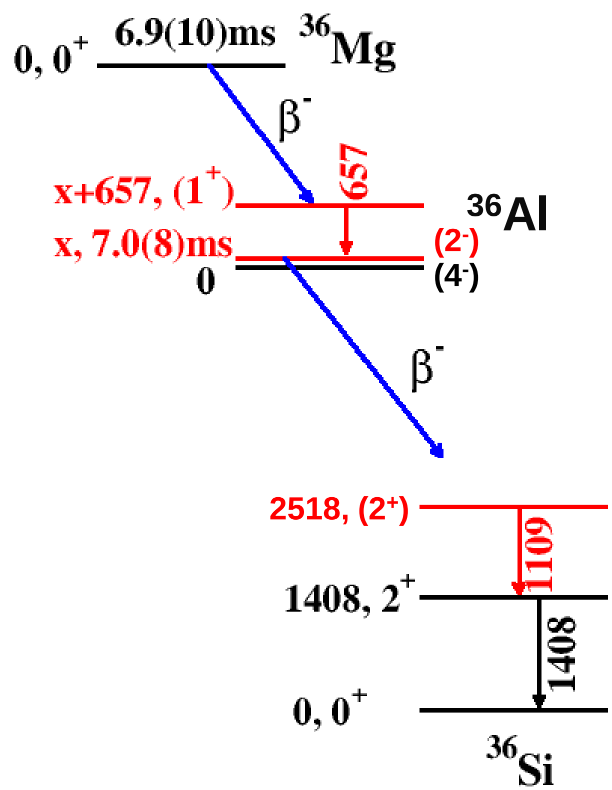
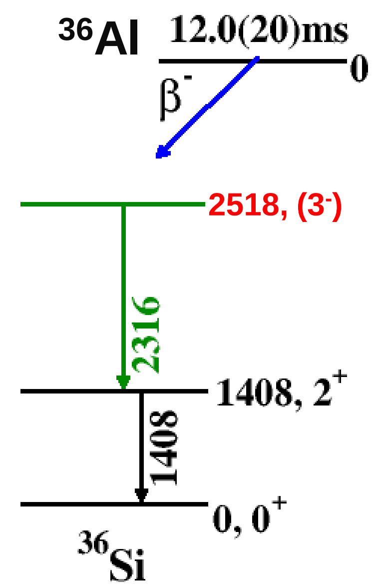
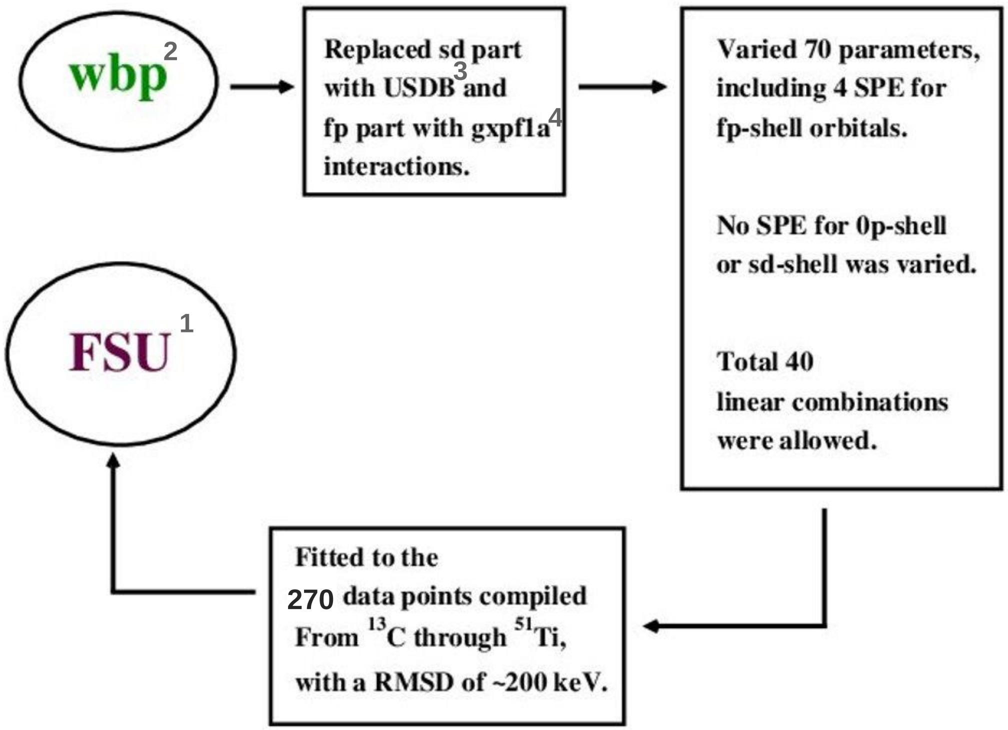
- Spin-parity all based on shell model.
- β-decaying isomer in this region only seen in Al, need explanations.







Phenomenological model: Data can be invaluable



- FSU[1] shell-model within the *spsdfp* model-space using the data fitting procedure.
- Hamiltonians from the existing models were used as a starting point
- Data fitting performed within the *p-sd-fp* model-space.
- A total of 70 parameters fitted by using 270 experimentally observed levels.

1. *Phys. Rev. Research 2, 043342 (2020)*
2. Phys. Rev. C 46, 923 (1992).
3. *Phys. Rev. C 74, 034315 (2006).*
4. *Eur. Phys. J A 25, 499 (2005).*

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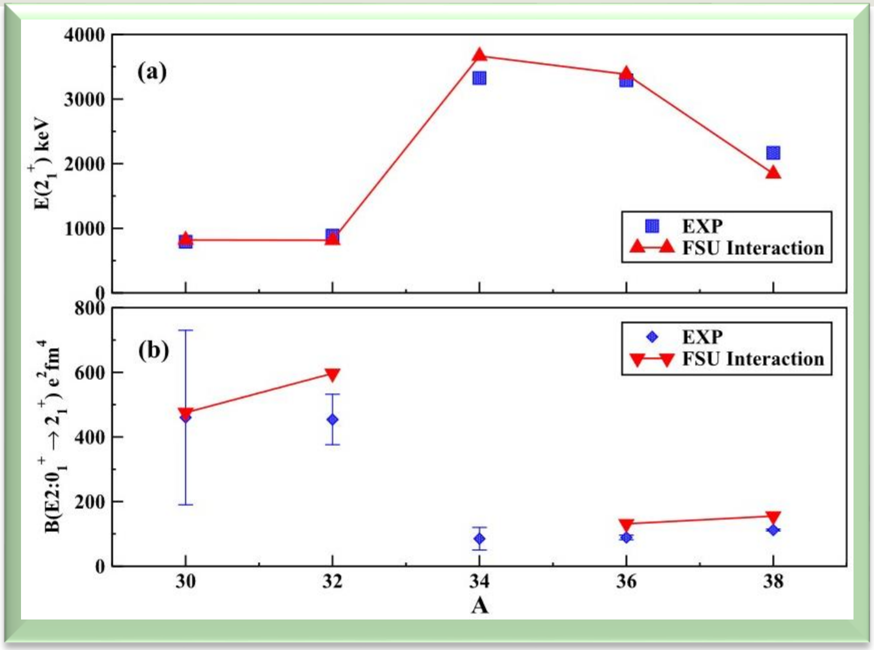

- **Reproduce N = 20 IoI phenomena successfully.**
- **Satisfactory predictions of spectroscopic factors.**

Nucleus	J^π	Energy EXP	Energy Th	(2J+1)SF EXP	(2J+1)SF Th
^{25}Ne	$7/2^-$	4030	3957	5.8	4.5
	$3/2^-$	3330	3471	3.0	1.9
	$3/2^+$	2030	2044	1.6	1.8
^{27}Ne	$7/2^-$	1740	1634	2.8	3.9
	$3/2^-$	765	858	2.6	2.4
	$3/2^+$	0	0	1.7	2.8
^{25}Mg	$7/2^-$	3971	3902	2.2-3.3	3.9
	$3/2^-$	3413	3525	0.9-1.2	1.5
	3/2+	974	1098	0.8	0.9
^{27}Mg	$7/2^-$	3761	3827	4.6	3.5
	$3/2^-$	3559	3644	1.6	2.2
	3/2+	984	994	2.4	1.56
^{29}Mg	$7/2^-$	1430	1719	3.0	4.4
	$3/2^-$	1094	1396	0.4	2.0
	$3/2^+$	0	0	1.2	1.8
^{29}Si	$7/2^-$	3623	3684	7.0	4.5
	$3/2^-$	4934	4373	2.2	2.3
	$3/2^+$	1273	1285	3.0	2.7
^{31}Si	$7/2^-$	3134	2855	4.8	5.6
	$3/2^-$	3533	3435	1.6	2.8
	$3/2^+$	0	0	2.8	2.4
^{33}Si	$7/2^-$	1435	1452		6.0
	$3/2^-$	1981	1944		2.9
	$3/2^+$	0	0		1.4
^{35}Si	$7/2^-$	0	0	4.5	7.4
	$3/2^-$	910	909	2.8	3.7
	$3/2^+$	974	936		
^{33}S	$7/2^-$	2935	2942	4.2	5.8
	$3/2^-$	3221	3386	3.5	2.3
	$3/2^+$	0	0	3.5	2.6
^{35}S	$7/2^-$	1991	2042	5.4	6.4
	$3/2^-$	2348	2409	2.1	2.7
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^{37}S	$7/2^-$	0	0	5.5	7.3
	$3/2^-$	646	573	1.8	3.5
	$3/2^+$	1398	1303		
^{37}Ar	$7/2^-$	1611	1543	6.1	6.3
	$3/2^-$	2491	2679	1.8	2.6
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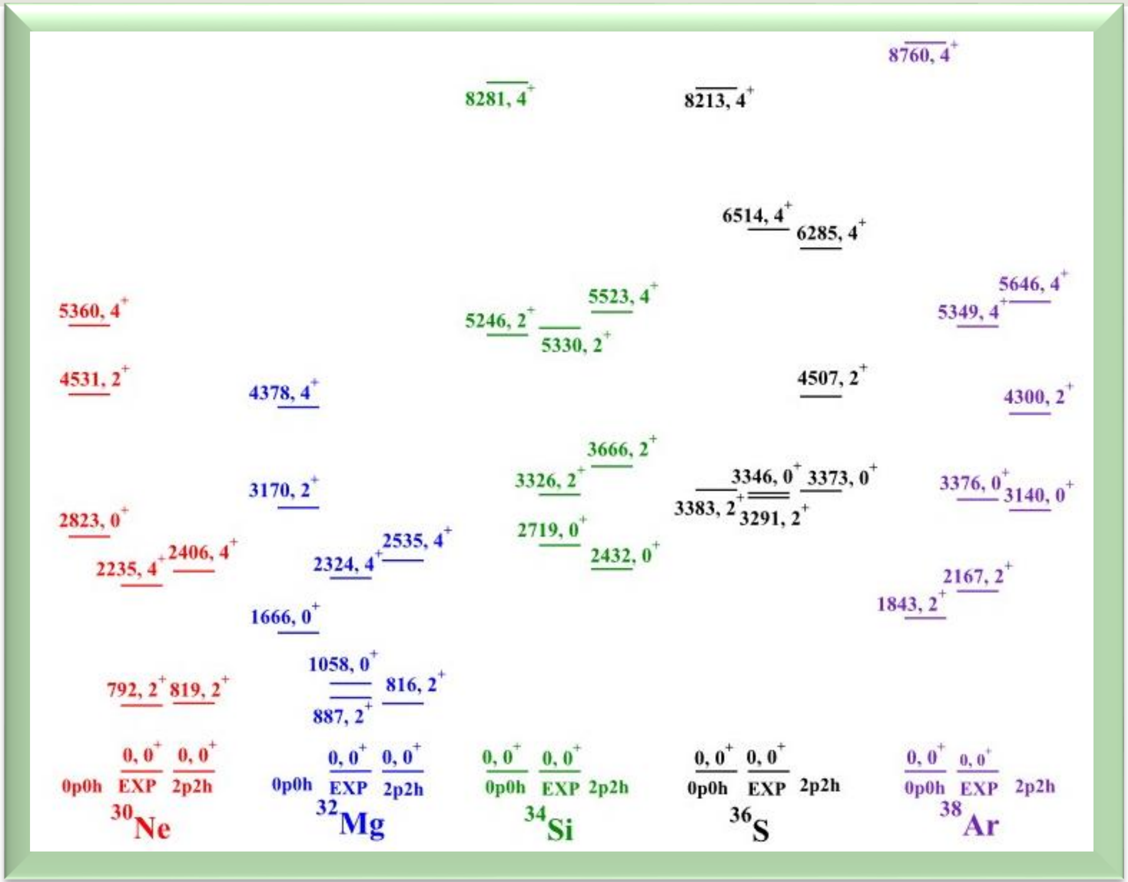
Phenomenological model: Data can be invaluable



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