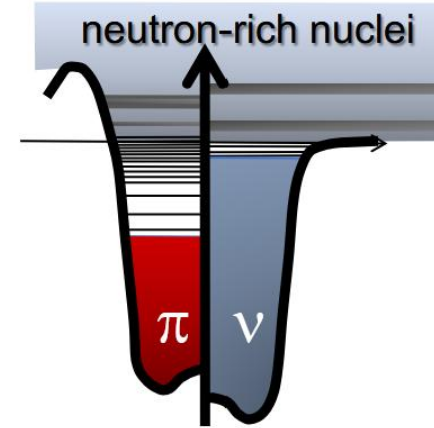
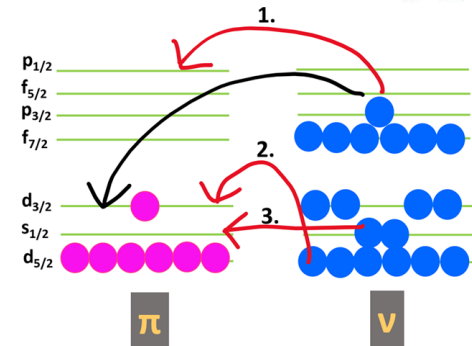


β^- decay of the most exotic isotopes:-

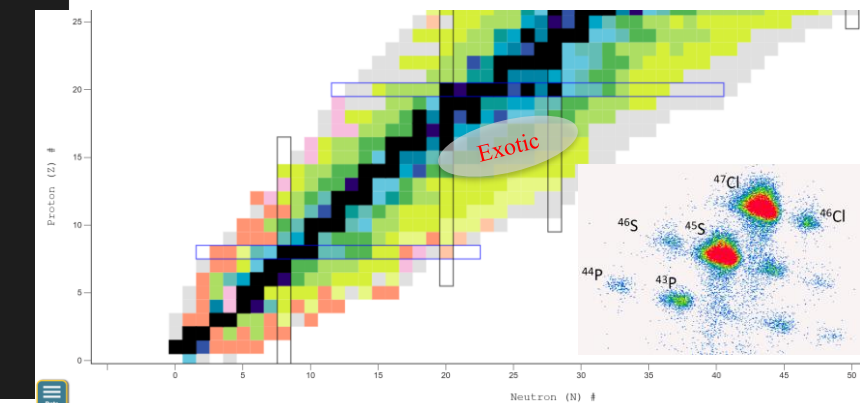
Z: 14-17 & N: 27-30



Vandana Tripathi
FRIB-TA Topical workshop, 2025



Let's visit an exotic neighborhood !



^{37}Si

^{38}Si

^{39}Si

^{40}Si

$^{41}\text{Si}^*$

$^{42}\text{Si}^*$

^{37}Al

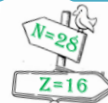


^{43}S

^{44}S

^{45}S

^{46}S



^{45}Cl

^{46}Cl

^{47}Cl

^{42}P

^{43}P

^{44}P



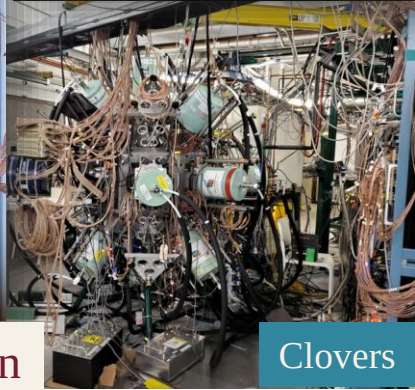
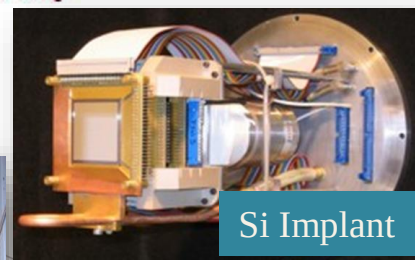
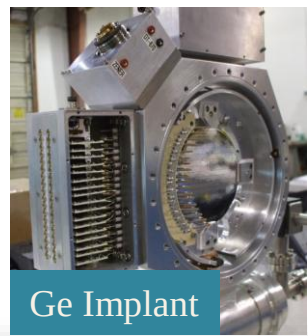
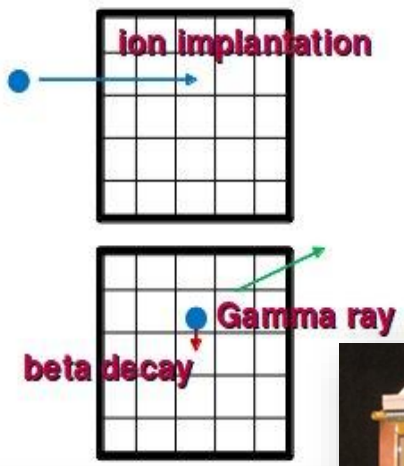
- V. Tripathi et. al., PRC 112, 024320 (2025)
- V. Tripathi et. al., PRC 109, 044320 (2024)
- S. Bhattacharya et. al., PRC 108, 024312 (2023)
- V. Tripathi et. al., PRC 106, 064314 (2022)
- B. Abromeit et. al., PRC 100, 014323 (2019)
- V. Tripathi et. al., PRC 95, 024308 (2017)





Outline of the talk:

- ❑ β -decay of even-even isotopes and the 1^+ states
- ❑ β -decay of odd-A isotopes
- ❑ Role/Influence of First Forbidden Transitions
- ❑ β -delayed neutron emission as a spectroscopy tool



No neutron detection



Systematic shell-model study of β -decay properties and Gamow-Teller strength distributions in $A \approx 40$ neutron-rich nuclei

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(Received 13 March 2018; published 18 May 2018)

Latest calculated data of beta-decay properties of $A \sim 40$ nuclei: update on Phys. Rev. C 97, 054321 (2018):“Systematic shell-model study of β -decay properties and Gamow-Teller strength distributions”

Sota Yoshida¹

¹Institute for Promotion of Higher Academic Education,
 Utsunomiya University, Mine, Utsunomiya, 321-8505, Japan
 (Dated: November 15, 2022)

FSU: Empirical shell-model interaction

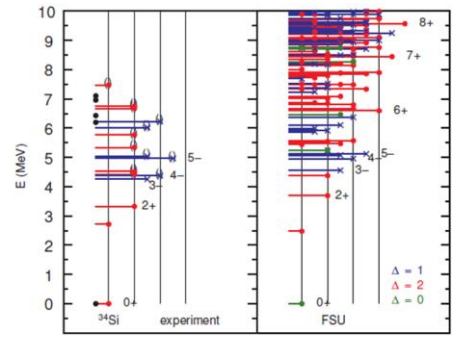


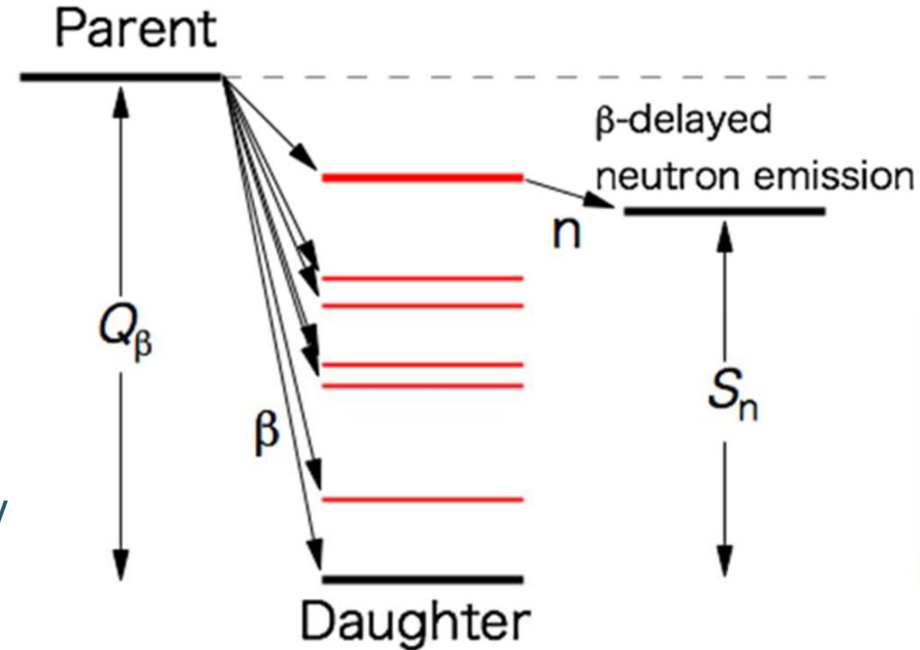
Figure 5. Spectrum of ^{34}Si obtained with the Florida State University (FSU) Hamiltonian [56] compared to experiment. The length of the horizontal lines are proportional to the Gamow-Teller strength distribution. The experimental parity is indicated by blue for negative and red for positive parity. Experimental spin-parity, J^π , values that are tentative are shown by open circles, and those with multiple of no J^π assignments are shown by the black points. The Gamow-Teller strength distributions are obtained with the FSU Hamiltonian with pure Δ configurations. The parities of the Gamow-Teller strength distributions are $\Delta = 0$ (green) and $\Delta = 2$ (red) and negative for $\Delta = 1$ (blue).

1. Phys. Rev. C 100, 034308 (2019)
 2. Phys. Rev. Research 2, 043342 (2020)

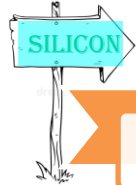
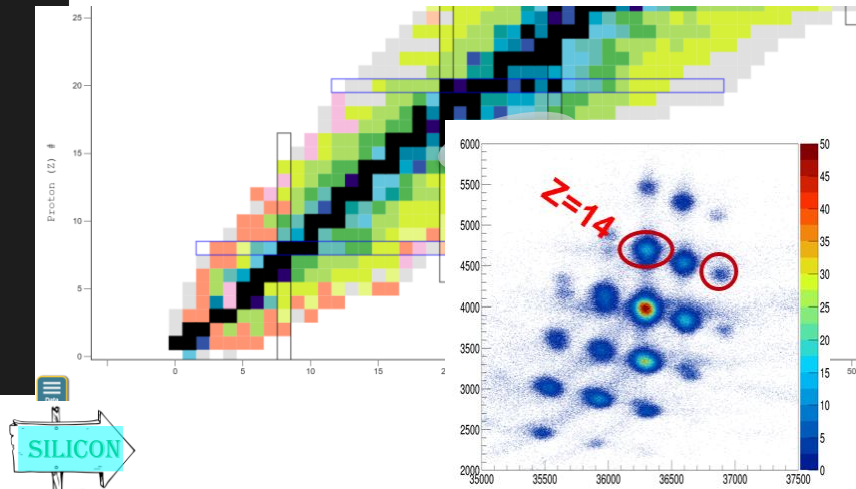
β^- decay of neutron-rich nuclei

- ❑ Large Q_{β^-} values (~ 15 MeV)
- ❑ Small $t_{1/2}$ (could be less than 10ms)
- ❑ Lower S_n values in daughter
- ❑ Higher probability of delayed neutron emission
- ❑ Neutron and proton Fermi levels in different shells
- ❑ Parent and daughter ground states likely have different parities
- ❑ First Forbidden transitions likely

→ Need to benchmark the beta-decay properties



Let's visit an exotic neighborhood !



^{37}Si

^{38}Si

^{39}Si

^{40}Si

$^{41}\text{Si}^*$

$^{42}\text{Si}^*$

^{37}Al



^{43}S

^{44}S

^{45}S

^{46}S

^{42}P

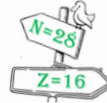
^{43}P

^{44}P

^{45}Cl

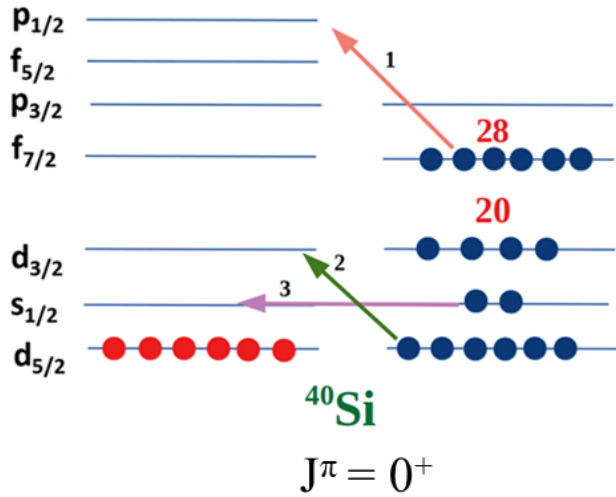
^{46}Cl

^{47}Cl

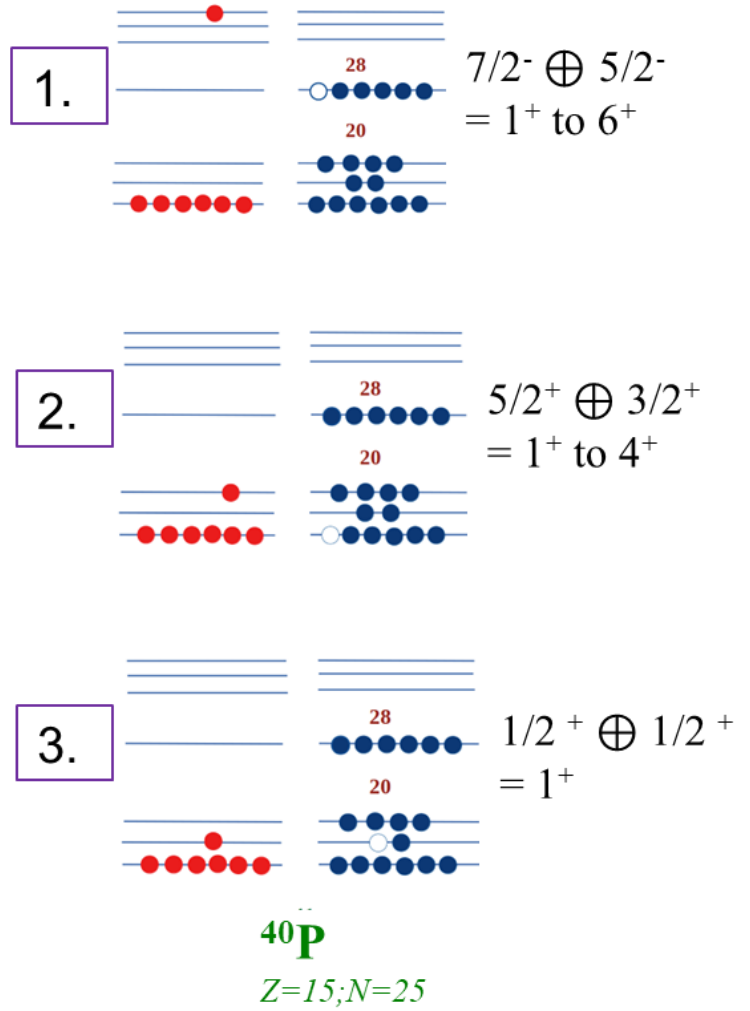


Even-even

³⁸Si, ⁴⁰Si decay



GT : 0⁺ → 1⁺



Even-even ^{38}Si , ^{40}Si decay

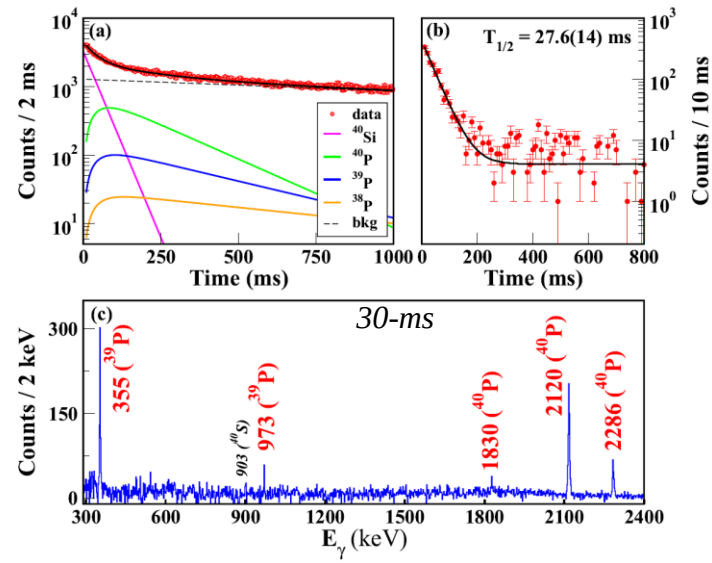


FIG. 1. (a) Decay curve derived for ^{40}Si from β -correlated implants within the same pixel for 1000 ms along with the fit used to extract half-life and the initial activity. The components of the fit are (i) exponential decay of parent, ^{40}Si , (ii) exponential growth and decay of daughter nuclei, ^{40}P (β), ^{39}P (β -n), ^{38}P (β -2n), and (iii) exponential background. Known half-lives were used for the daughter nuclides [18]. (b) Decay curve from (a) in coincidence with γ transitions in the daughter ^{40}P . The data are fitted to an exponential decay function with a constant background. (c) Partial β -delayed γ spectrum observed for 30 ms after a ^{40}Si implant, with the new transitions in ^{40}P marked by energy, as well as those from ^{39}P populated in β -delayed one-neutron emission.

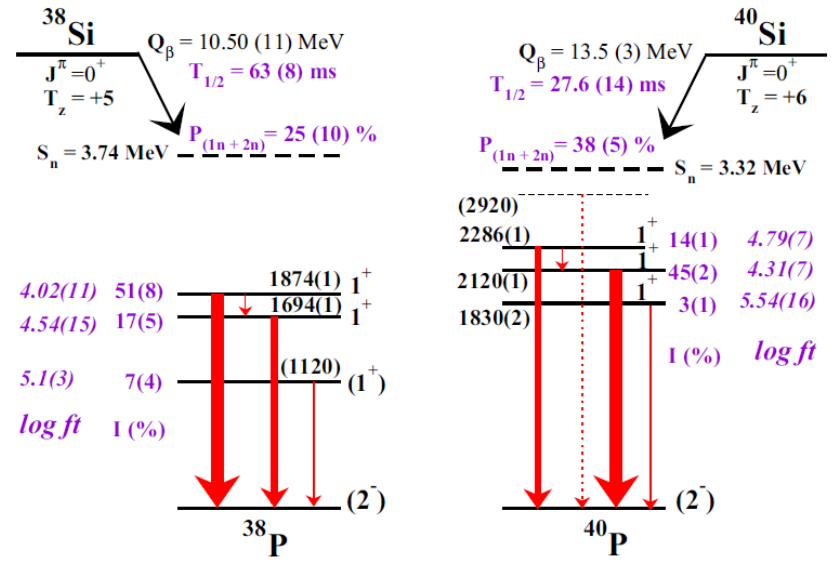


FIG. 13. Partial level scheme of $^{38,40}\text{P}$ as established in the β^- decay of $^{38,40}\text{Si}$ from Ref. [5]. A tentative 2940-keV state has been added not shown in Ref. [5].

Even-even ^{38}Si , ^{40}Si decay

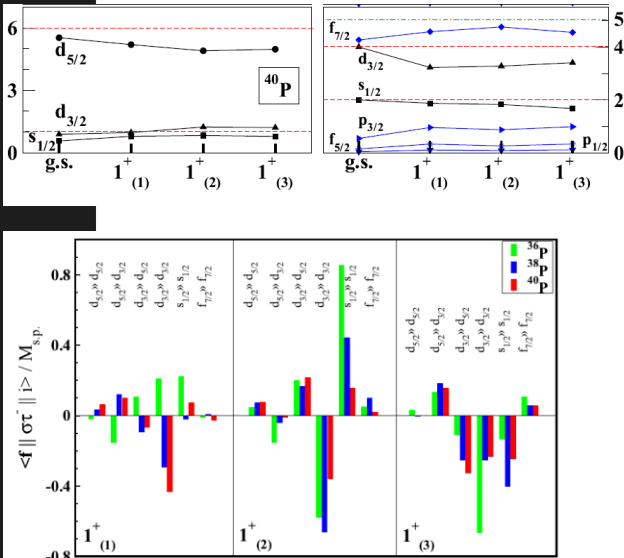


FIG. 6. Gamow-Teller matrix elements (M_{fi}) for the 1^+ states in $^{36,38,40}\text{P}$ decomposed into orbital components. The matrix elements have been normalized to the single-particle estimates ignoring the phase ($s_{1/2} \rightarrow s_{1/2} = 1.414$; $d_{5/2} \rightarrow d_{5/2} = 1.67$; $d_{5/2} \rightarrow d_{3/2} = 1.79$; $d_{3/2} \rightarrow d_{5/2} = 1.79$; $d_{3/2} \rightarrow d_{3/2} = 0.89$; $f_{7/2} \rightarrow f_{7/2} = 1.85$).

^{34}Si

^{36}Si

^{38}Si

^{40}Si

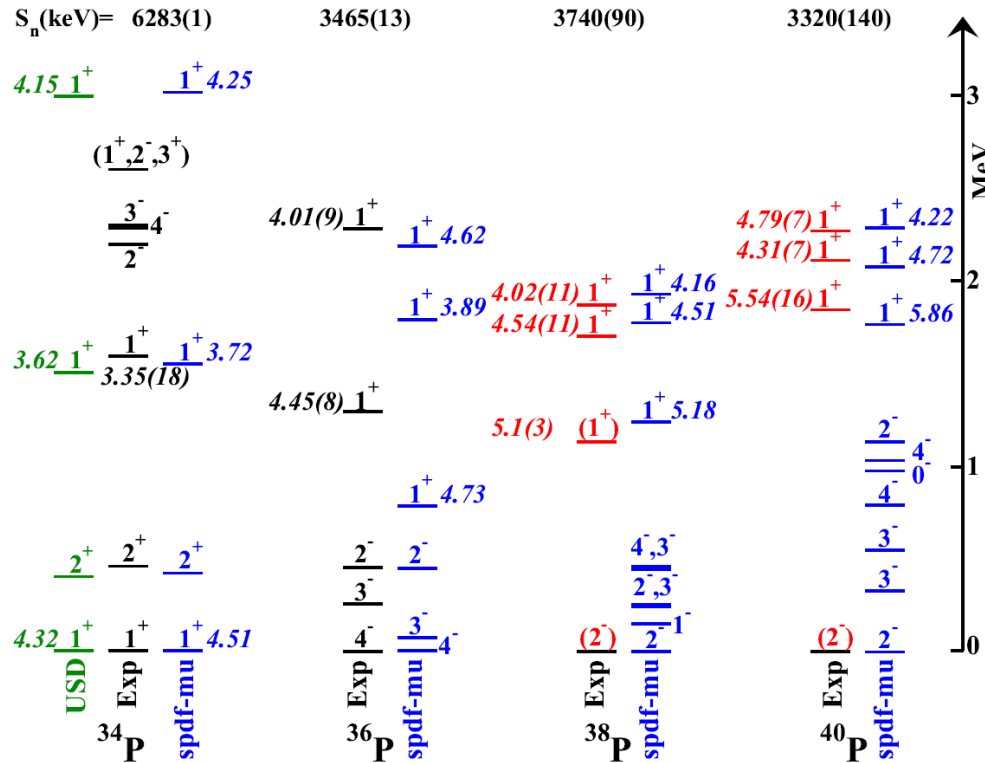


FIG. 4. Partial level schemes of $^{34,36,38,40}\text{P}$ ($N = 19, 21, 23, 25$) as obtained in the β decay of the corresponding Si isotopes. New information from this experiment is depicted in red. Data for $^{34,36}\text{P}$ are from Refs. [22, 25]. Results of shell model calculations using the SDPF-MU interaction



Even-even ^{44}S , ^{46}S decay

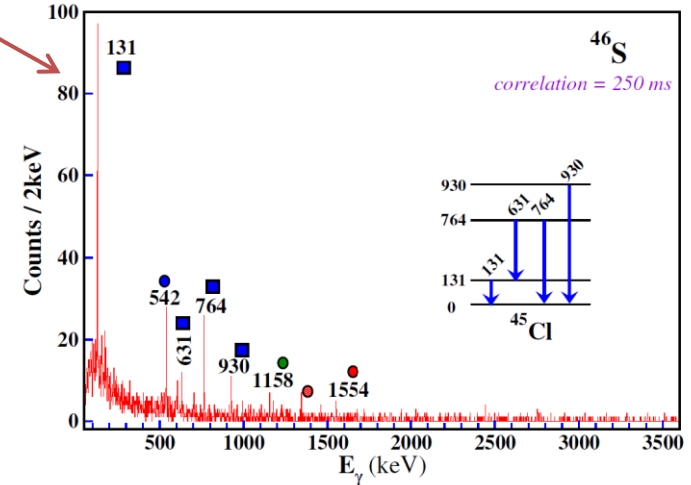
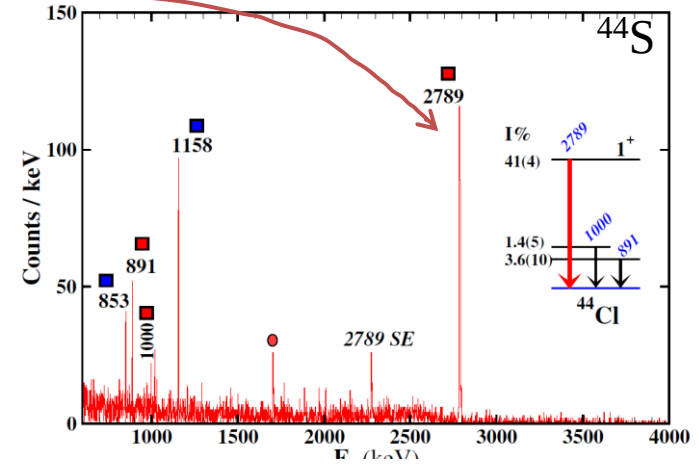
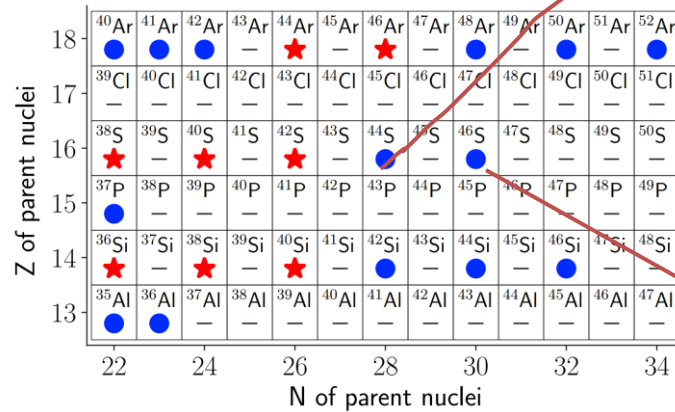


Fig. 8 from Yoshida et al., PRC 97 054321 (2018):
 → The red stars indicate strong low lying GT transitions (predicted and observed).
 → Blue circles are predicted isotopes with $B(\text{GT}) > 0.1$

The absence of the bound 1^+ state in ^{46}Cl may be points to weaker pn interaction in neutron-rich nuclei



Even-even ^{44}S , ^{46}S decay

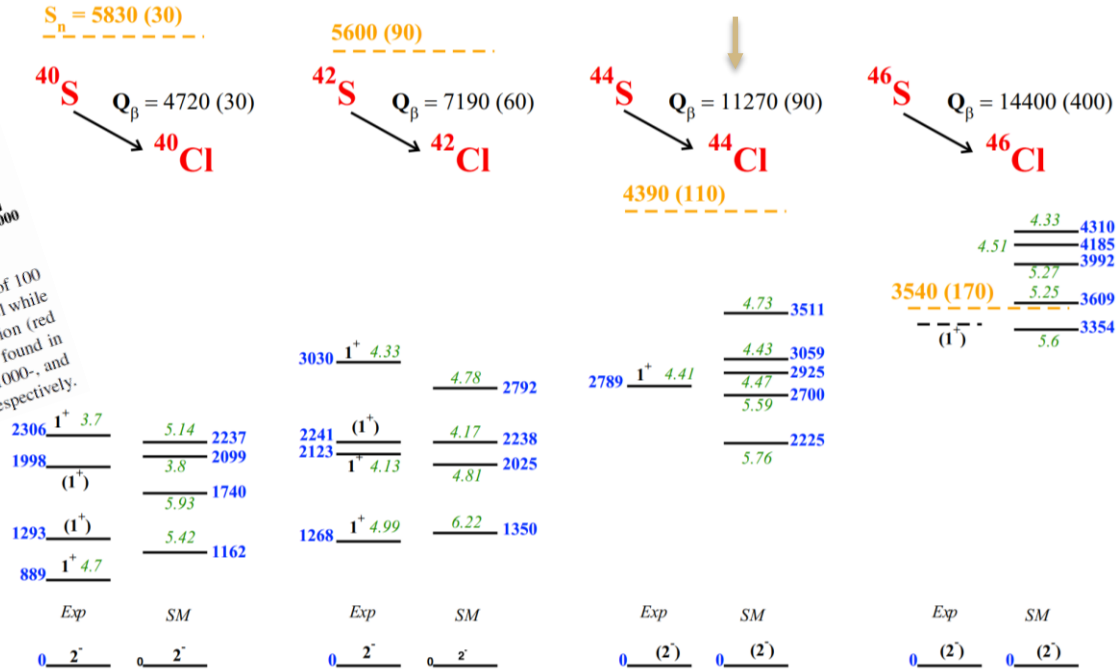
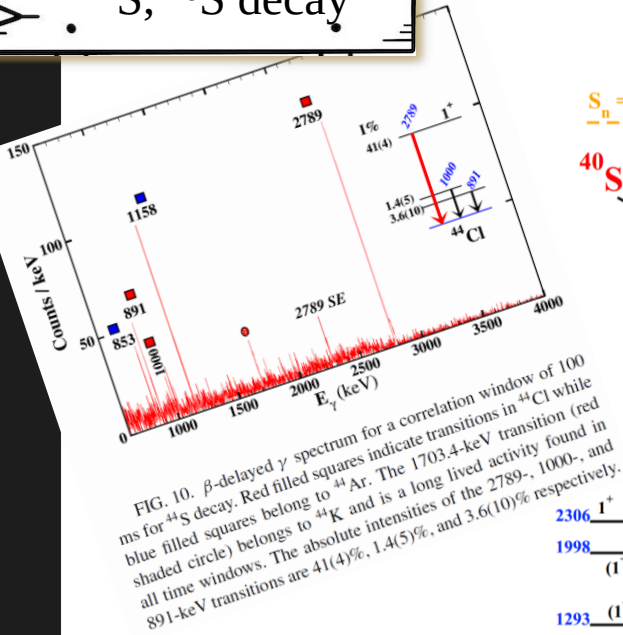


FIG. 17. β decay of even-even S isotopes from $A = 40$ to 46 . Data for $^{40,42}\text{S}$ are from NNDC [31]. Only the 1^+ states expected to be populated via allowed GT transitions along with SM prediction are shown. As mentioned in the text we could not isolate the weakly populated bound 1^+ state in ^{46}Cl . The focus is to illustrate that with increasing neutron number the GT strength imbibed by the 1^+ states moves to higher energies eventually residing in the neutron unbound states for ^{46}S .



Even-Odd ^{37}Si , ^{39}Si decay

The allowed GT transitions from the $5/2^-$ ground state of these isotopes do not favor any single state in the daughter nuclei, rather the strength is fragmented. This would imply a very small overlap between the ground state of the Si isotopes and the negative parity $(1p1h)$ states in $^{37,39}\text{P}$.

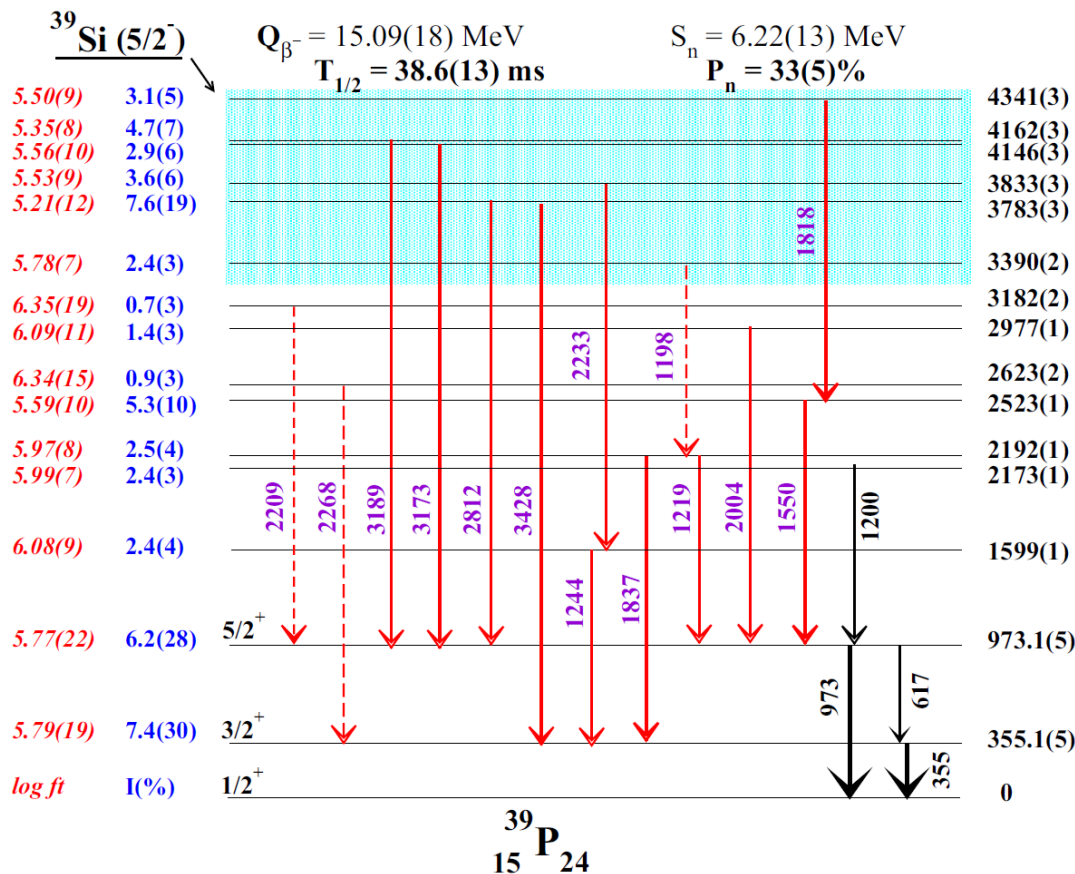


FIG. 10. Partial level scheme of ^{39}P as established in the present β^- decay of ^{39}Si . The measured absolute branching, half-life, and Q_{β^-} [17] were used to calculate the $\log ft$ values [19]. The shaded box indicates the states which are presumed to be directly populated in the β^- decay of ^{39}Si and are candidates for intruders states with negative parity.

Even-Odd ^{43}S , ^{45}S decay.

^{45}S

$J^\pi = (3/2^-)$
 $T_z = +13/2$

$Q_\beta = 14.92(33) \text{ MeV}$

$T_{1/2} = 69(1) \text{ ms}$

$P_n = 60(10) \%$

$S_n = 5850(160) \text{ keV}$

E_β (keV)	$\log ft$	$I(\%)$	E_γ (keV)	$I(\%)$
6.051(10)	0.9(2)		5361(2)	
5.598(10)	2.7(5)		5249(2)	
5.872(10)	1.5(3)		5160(3)	
5.881(10)	1.8(4)		4728(2)	

$\log ft$ $I(\%)$

E_β (keV)	J^π	E_γ (keV)	$I(\%)$
1.8(3)	$(7/2^+)$	2700(1)	
2.6(5)	$(7/2^+)$	2391(1)	
{1.8(4)*}	$(1/2^+)$	1949(1)	
2.6(8)	$(5/2^+)$	1619(1)	
3.0(13)	$(5/2^+)$	929(1)	
10.8(12)	$(3/2^+)$	765(1)	
16(4)	$1/2^+$	132(1)	
~ 0	$3/2^+$	0	

^{45}Cl

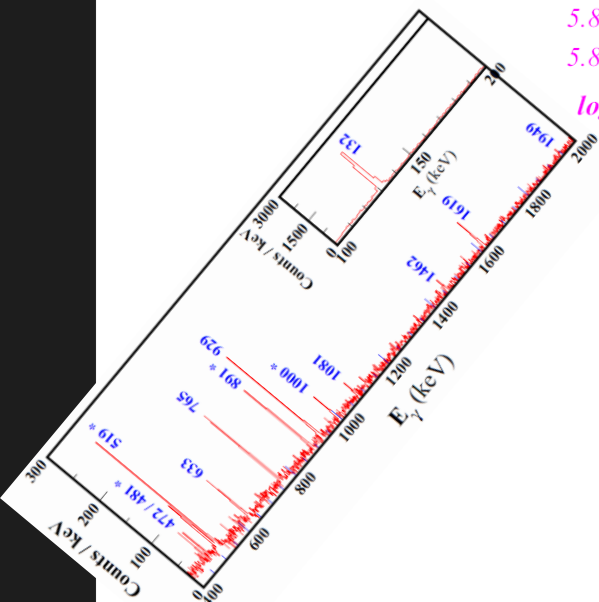
$1/2^-$ $3/2^-$ $5/2^-$

E_γ (keV)	J^π
3416	$7/2^+$
3296	$7/2^+$
2860	$7/2^+$
2693	$7/2^+$
2601	$7/2^+$
2347	$7/2^+$
2132	$7/2^+$

E_γ (keV)	J^π
1364	$5/2^+$
978	$5/2^+$

E_γ (keV)	J^π
671	$3/2^+$
174	$1/2^+$

SDPFSDG-MU



Even Z vs Odd Z decay

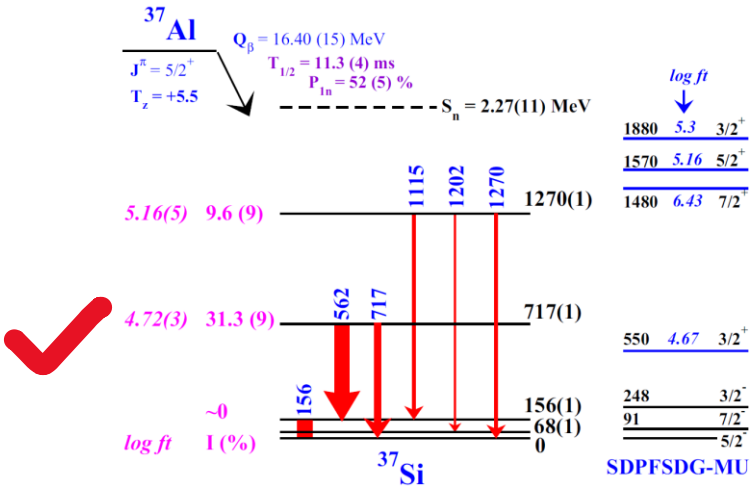
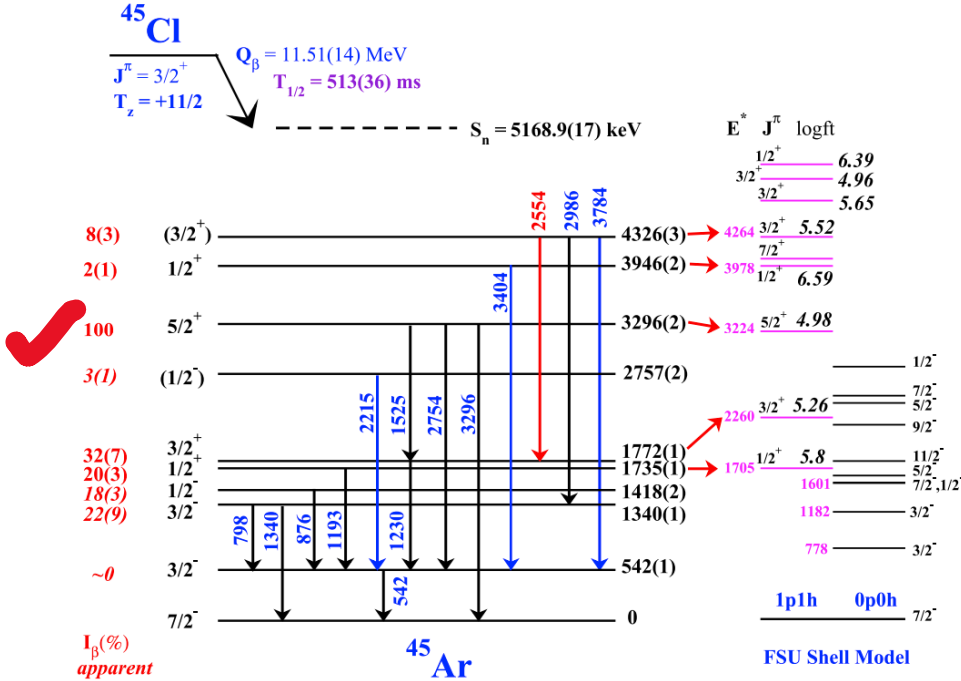


FIG. 3. Partial level scheme of ^{37}Si as established in the present β^- decay of ^{37}Al , similar to the most recent work [7]. The measured half-life and P_{1n} value are also shown. The measured absolute branching, half-life, and Q_{β^-} [17] were used to calculate the $\log ft$ values [19] of the excited states at 717 and 1270 keV. Shell-model calculations (see the text for details) employing the SDPFSDG-MU interaction [10,11] are also shown alongside.



S. Bhattacharya *et. al.*, PRC 108, 024312 (2023)



B. Abromeit *et. al.*, PRC 100, 014323 (2019)

I. Cox *et al.*, Phys. Rev. Lett. 132, 152503 (2024)

Even Z vs Odd Z decay

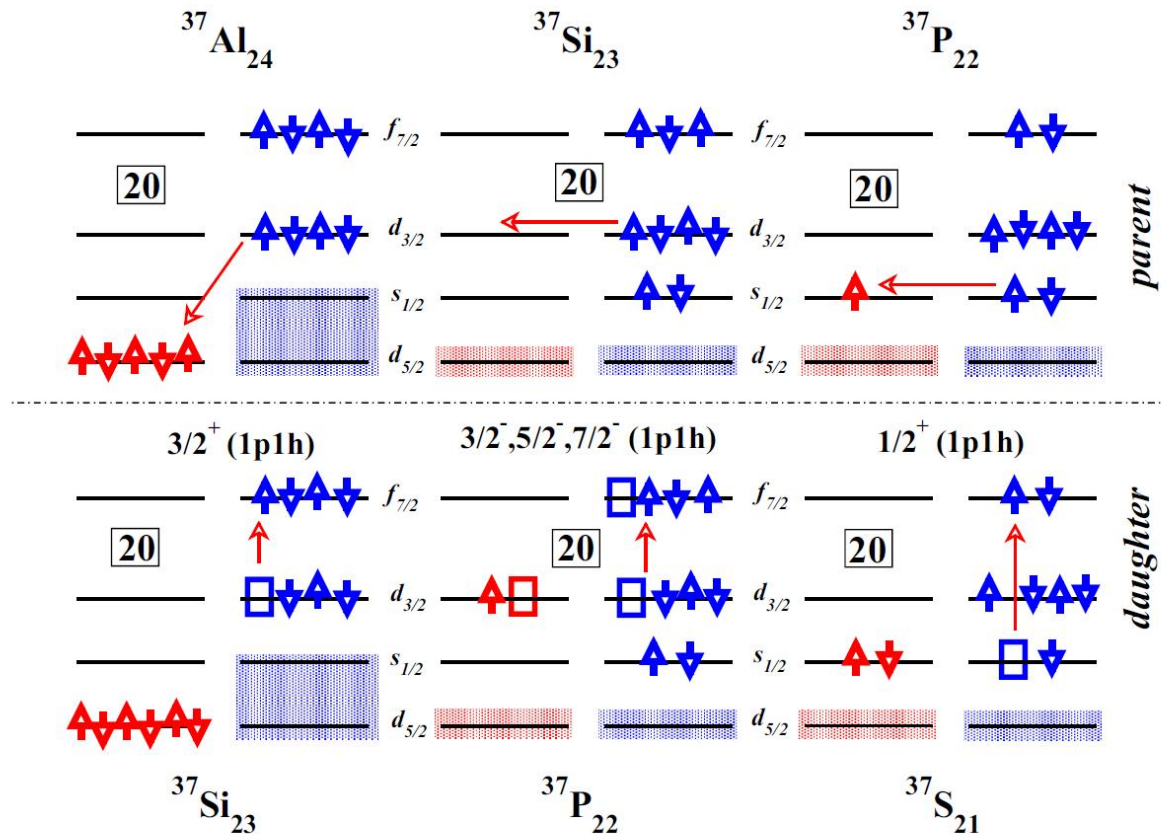
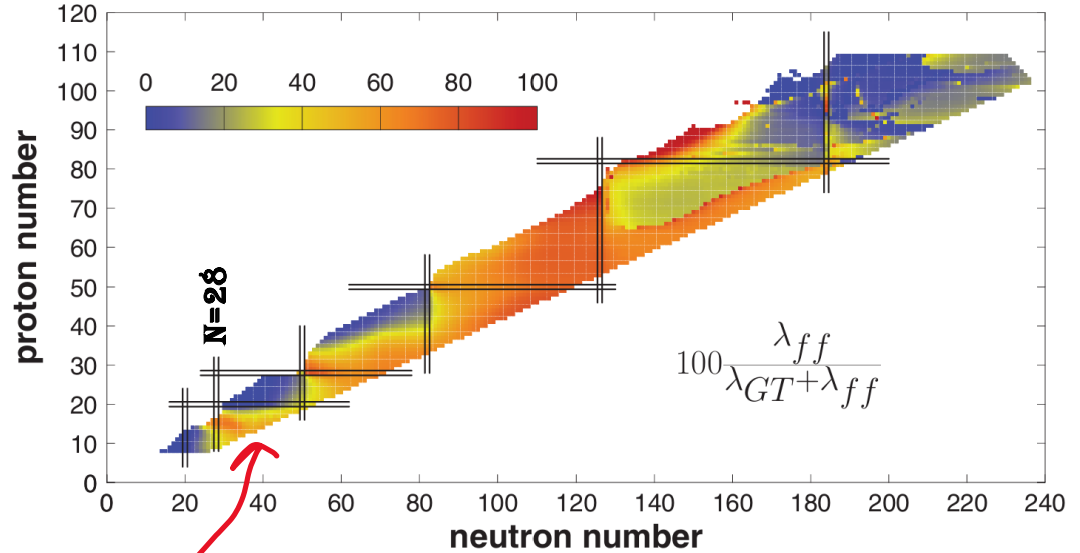
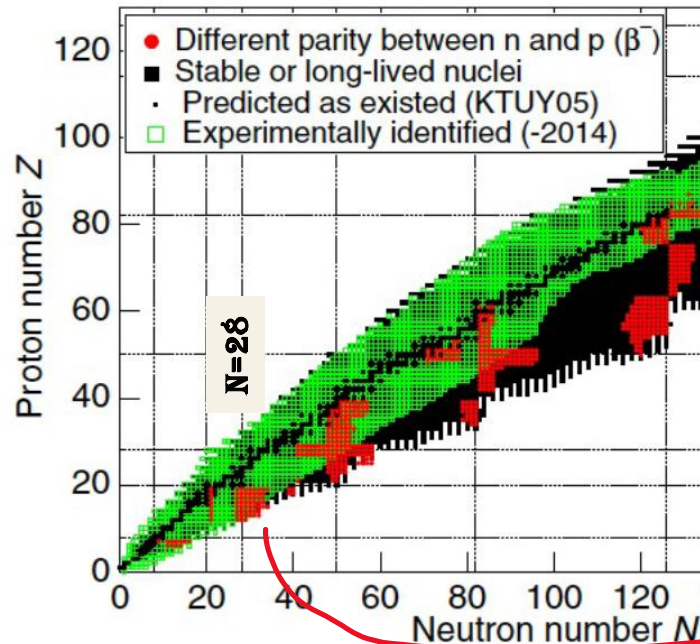


FIG. 14. Simplistic visualization of the β^- decay of ^{37}Al , ^{37}Si , and ^{37}P to show the dominant configuration of the parent ground state and the corresponding state that is created in the daughter nuclei. The shaded boxes represent filled orbitals. The solid boxes show the hole created in the β decay.



First Forbidden
Parity change

T. Marketin, L. Huther, G. Martinez-Pinedo, PRC93, 025805 (2016)*



The contribution of the first-forbidden transitions in the total decay rate for nuclei with predicted half-lives shorter than 1 s.

*A fully self-consistent theoretical framework was employed based on the relativistic nuclear energy density functional



Role of FF transitions

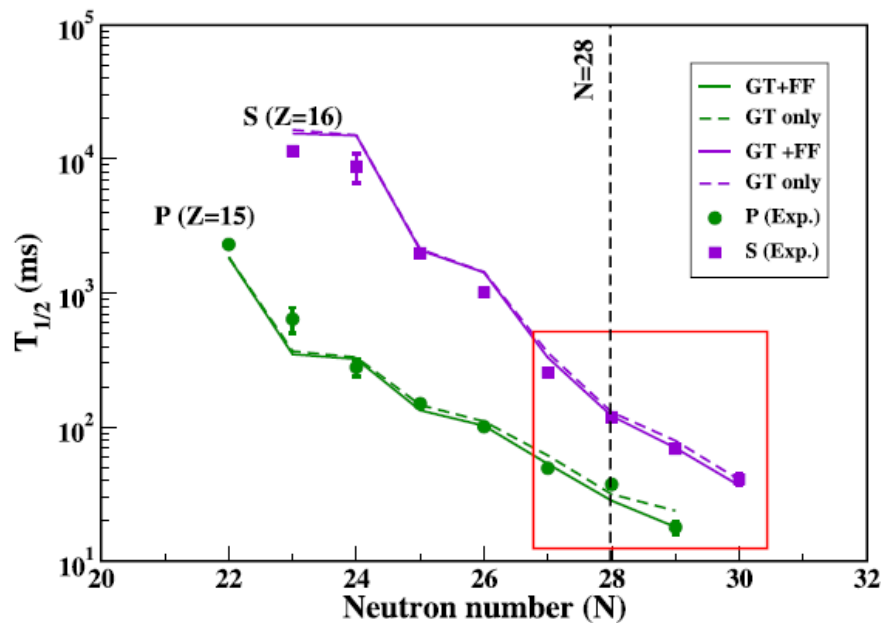
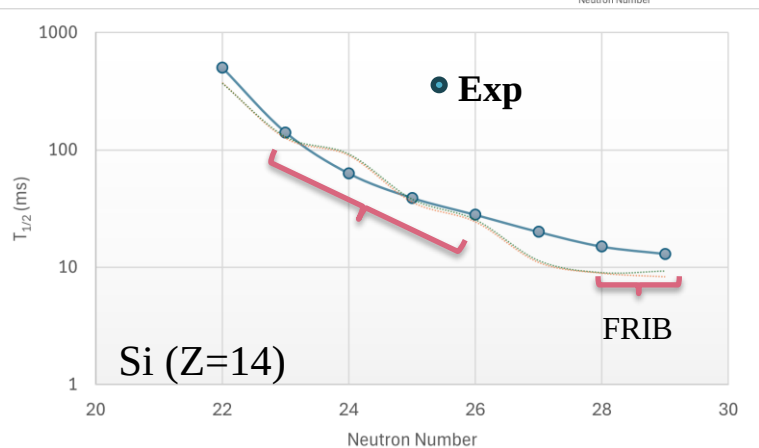
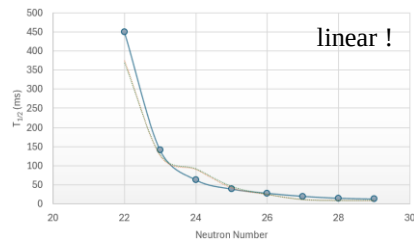


FIG. 14. Comparison of measured $T_{1/2}$ values for P and S isotopes from $N = 22$ to $N = 30$ with shell-model calculations using the SDPFSDG-MU interaction [13]. The numbers in the red box are from the current data set while others are the evaluated values from NNDC [31].

^{41}Si : PLB, 252 (2004)

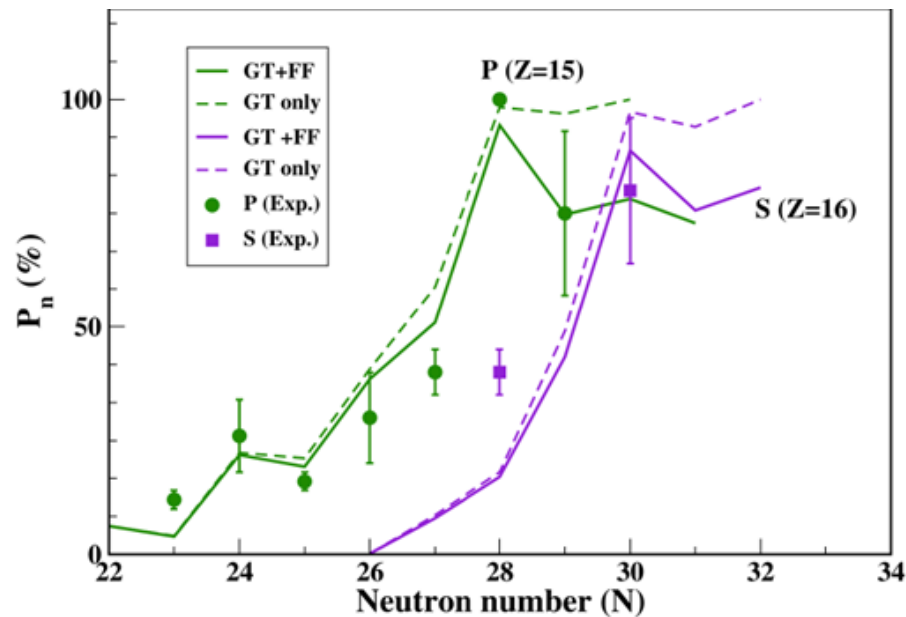
FRIB: Crawford et al, Phys. Rev. Lett. 129, 212501 (2022)

[13] S. Yoshida et al., PRC 97 054321 (2018); Erratum

Role of FF transitions

TABLE II. Comparison of the measured half-lives ($T_{1/2}$) and SM predictions discussed in the text [15] for the P and S isotopes studied in this work

Nuclide	Expt.		J^π (E^*)	SM	
	$T_{1/2}$ (ms) (no γ)	$T_{1/2}$ (ms) γ -gated		$T_{1/2}$ (ms) GT+FF	$T_{1/2}$ (ms) GT only
^{42}P	47.1(20)	49.5(25)	0^- (0 MeV)	36.982	55.969
			1^- (0.13 MeV)	44.198	56.085
			2^- (0.19 MeV)	53.294	61.616
			3^- (0.29 MeV)	60.898	64.127
			4^- (0.41 MeV)	66.198	68.429
^{43}P	37.5(22)	—	$1/2^+$ (0 MeV)	28.337	31.709
^{44}P	18(1)	—	0^- (0 MeV)	16.643	21.597
			1^- (0.27 MeV)	18.026	23.872
			2^- (0.35 MeV)	24.700	29.081
^{44}S	125.5(25)	119(6)	0^+ (0 MeV)	121.273	129.352
^{46}S	41(4)	—	0^+ (0 MeV)	36.808	40.536



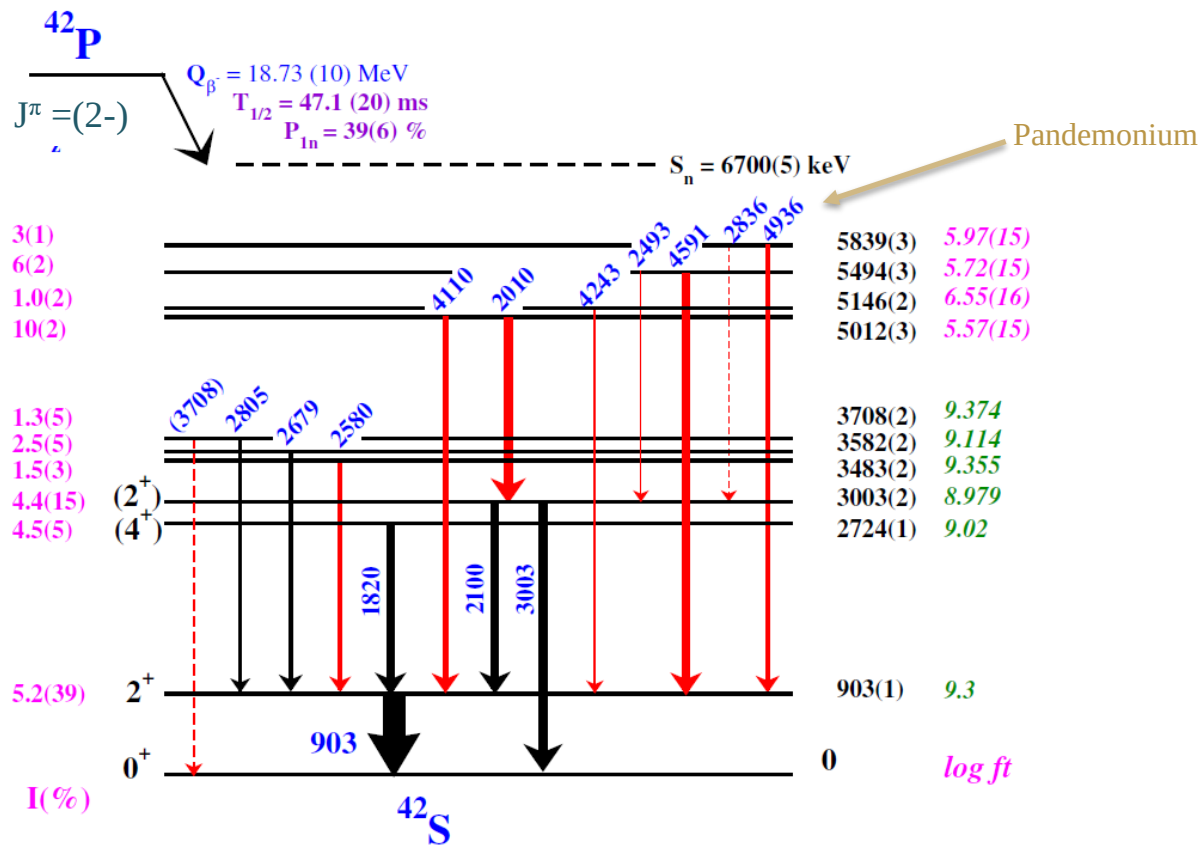
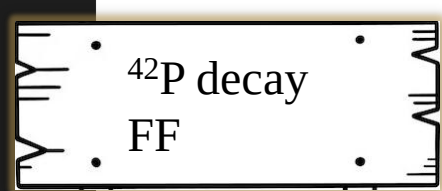
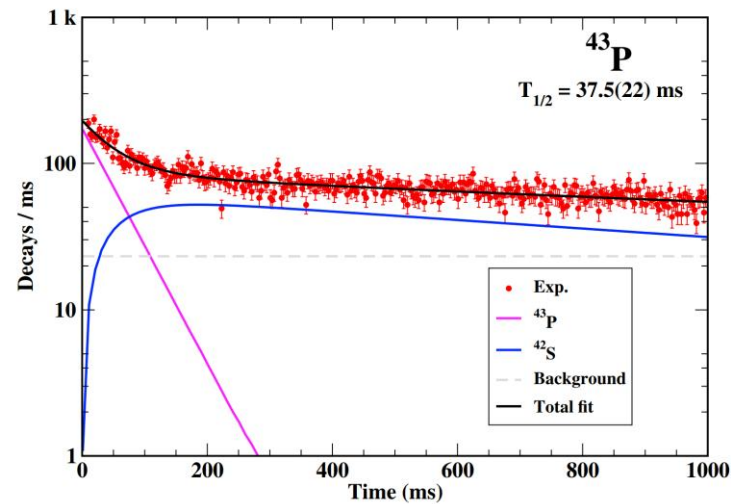
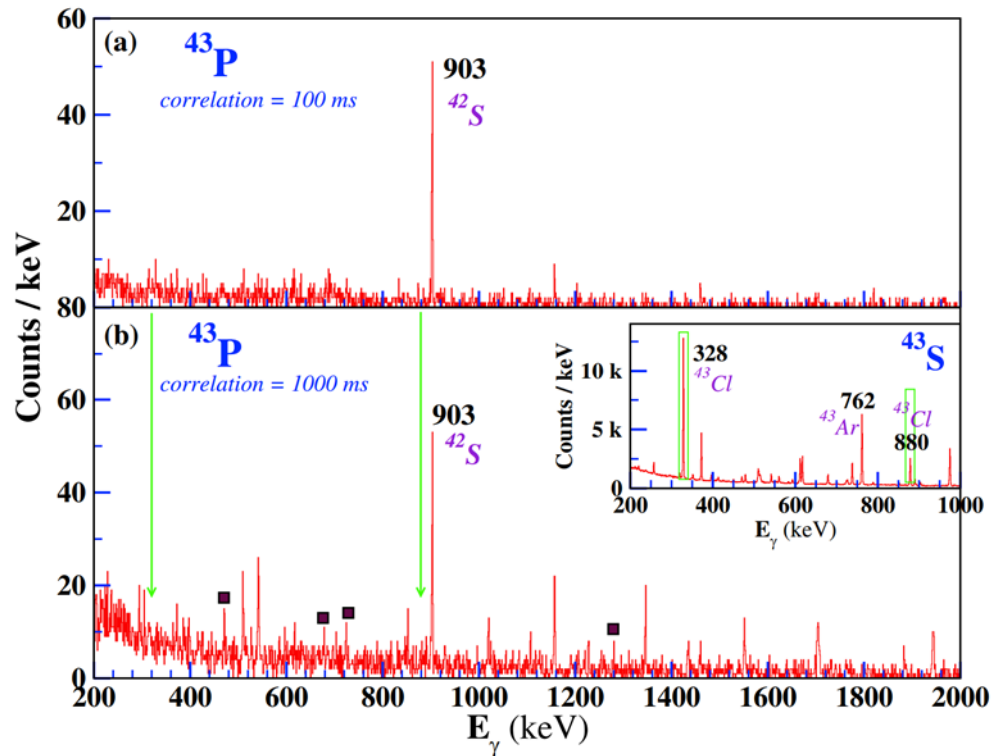
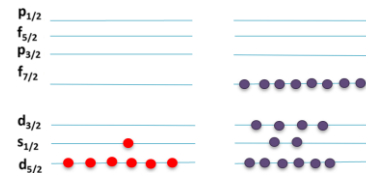


FIG. 4. Partial level scheme of ^{42}S following β decay of ^{42}P with a $T_{1/2} = 47.1(20) \text{ ms}$ and $Q_{\beta^-} = 18.73(10) \text{ MeV}$. The transitions marked black were known before, whereas red indicates the new transitions. The absolute branching for each level was calculated using the measured yield in the gamma transition, total number of implants from the decay curve, and the γ detection. The width of the arrows are approximately proportional to the absolute intensity. The $\log ft$ values were calculating using the $\log ft$ calculator [31]. For levels above 5 MeV, they represent GT transitions while below indicate FF.

^{43}P decay $P_n = 100\%$ (no FF)

$^{43}\text{P} \rightarrow ^{43}\text{S}$
($Z=15; N=28$) ($Z=16; N=27$)

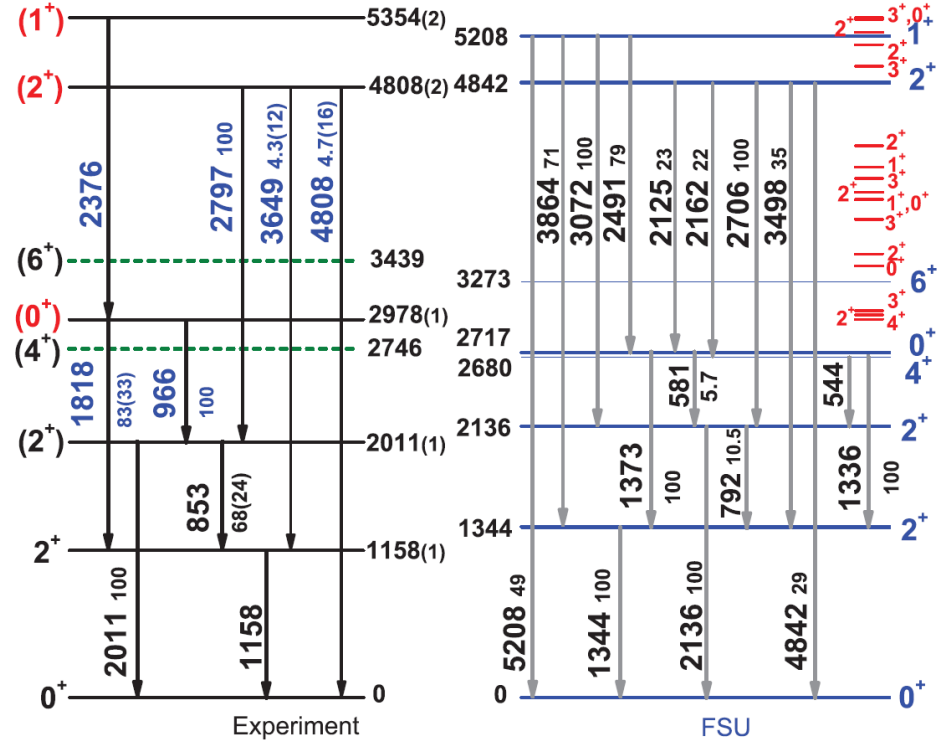


Why FF not important?

TABLE VI. Measured and calculated delayed neutron emission probabilities in percent. $Q_{x\beta}$ values for ^{46}Cl and ^{47}Cl are also noted [40].

Isotope	$Q_{\beta_{xn}}(\text{MeV})$	J^π	$P_n(\text{Exp.})$ %	$P_n(V_{\text{MU}})$ GT+FF, Q_{exp}	$P_n(V_{\text{MU}})$ GT, Q_{exp}
^{46}Cl	16.04(10) $_{0n}$	0 ⁻	75(15)	34.90	43.34
	7.960(100) $_{1n}$	1 ⁻		23.83	26.01
	2.80(14) $_{2n}$	2 ⁻		23.17	27.57
		3 ⁻		32.28	38.28
^{47}Cl	15.79(20) $_{0n}$	1/2 ⁺	98(12)	86.13	96.22
	12.12(20) $_{1n}$	3/2 ⁺		77.56	87.04
	4.0(3) $_{2n}$				

Delayed neutron
daughter

 ^{45}Cl
 $J^\pi = 3/2^+$
 $T_z = +11/2$
 $Q_\beta = 11.51(14) \text{ MeV}$
 $T_{1/2} = 513(36) \text{ ms}$
 βn  ^{44}Ar 

Delayed neutron daughter

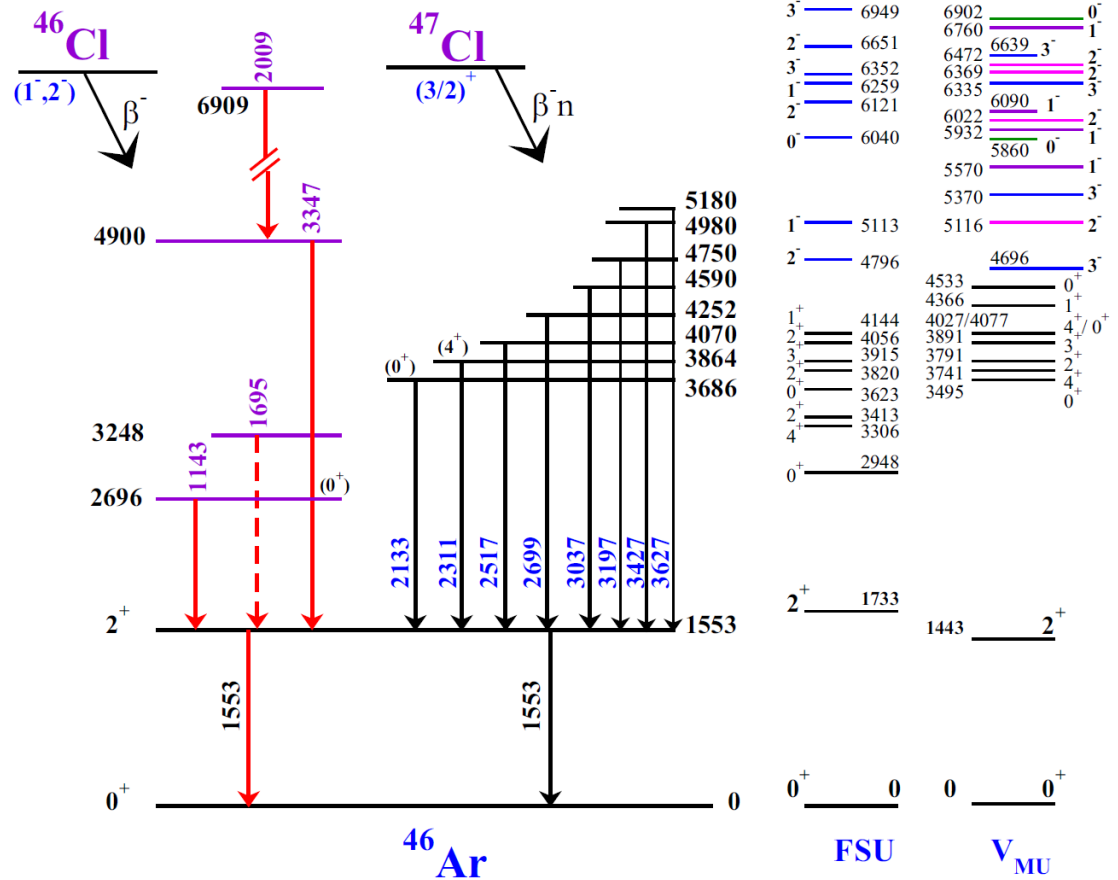


FIG. 8. A partial level scheme of ^{46}Ar from this work following the βn -decay of ^{46}Cl is shown on the left. The level scheme deduced from βn decay of ^{47}Cl is shown on the right. Alongside are predictions from shell model calculations using the FSU [25] and V_{MU} interactions [26]. The positive-parity states are $0p0h$ states while the negative-parity states are $1p1h$ states with excitations across the $N = 20$ shell gap. The first ten positive-parity states are shown for both, while negative parity states (0^- , 1^- , 2^- , and 3^- only) are shown up to 7.0 MeV. The neutron separation energy S_n is 8071.8(24) MeV for ^{46}Ar [40].

$\beta 1n$ & $\beta 2n$

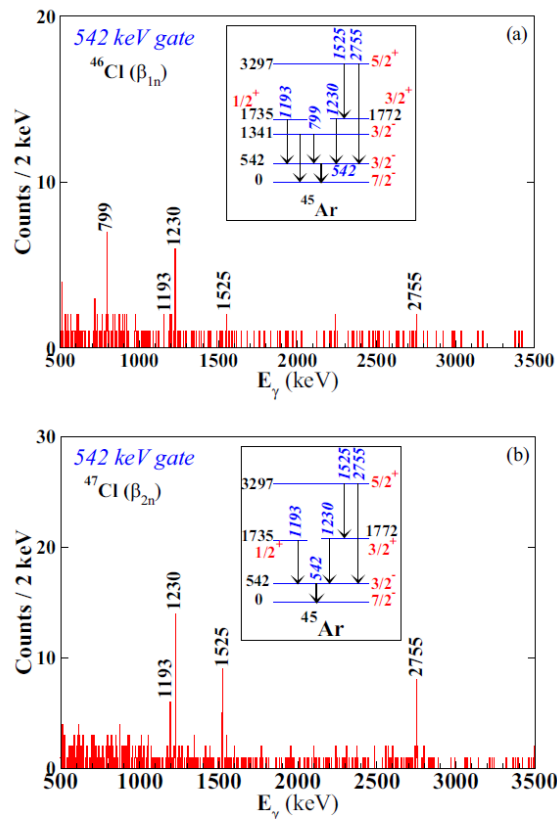
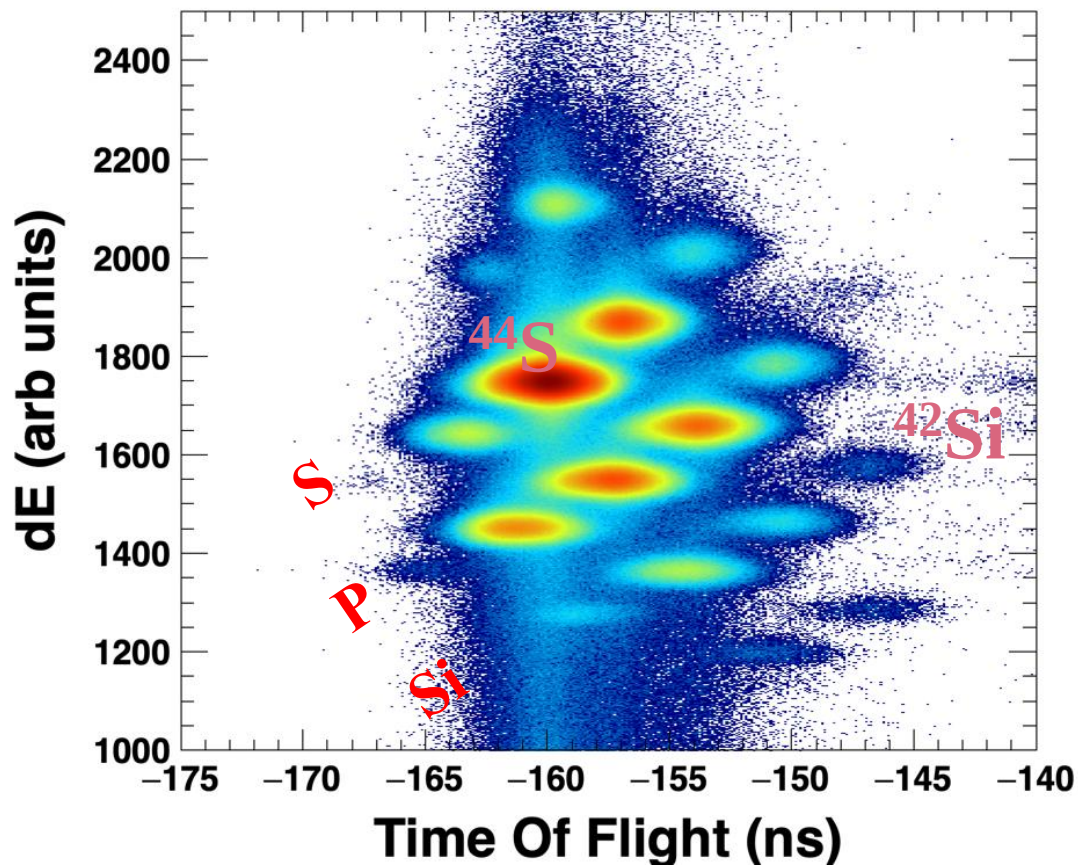


FIG. 7. (a) γ -ray transitions observed in coincidence with the 542-keV transition in ^{45}Ar from the $\beta 1n$ channel of ^{46}Cl decay. (b) γ -ray transitions observed in coincidence with the 542-keV transition in ^{45}Ar from the $\beta 2n$ decay of ^{47}Cl . Two-neutron emission from the unbound states in ^{47}Ar feeds only positive-parity states in ^{45}Ar while a negative-parity state is strongly populated in ^{46}Cl $\beta 1n$ decay. The ^{46}Cl ground state likely has $J^\pi = 1^-$ or 2^- , see Sec. III A while for ^{47}Cl , $J^\pi = 3/2^+$ is favored.

At FRIB





Summary & Outlook :

- ❑ β^- decay of Si, P, S and Cl near $N=28$ was carried out at NSCL using a Ge/Si DSSD as an implant detector surrounded by SEGA/16 Clover detectors for delayed gamma spectroscopy.
- ❑ Work to be extended at FRIB
- ❑ The trends of half lives and beta delayed neutron emission probability, P_n , were compared with SM calculation using the SDPF-MU interaction/FSU interaction
- ❑ As we approach $N=28$, the decrease of S_n values and the transfer of GT strength to higher energies leads to large P_n approaching 100%.
- ❑ Influence of First Forbidden transitions in the beta decay was observed: reducing $t_{1/2}$ and P_n



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