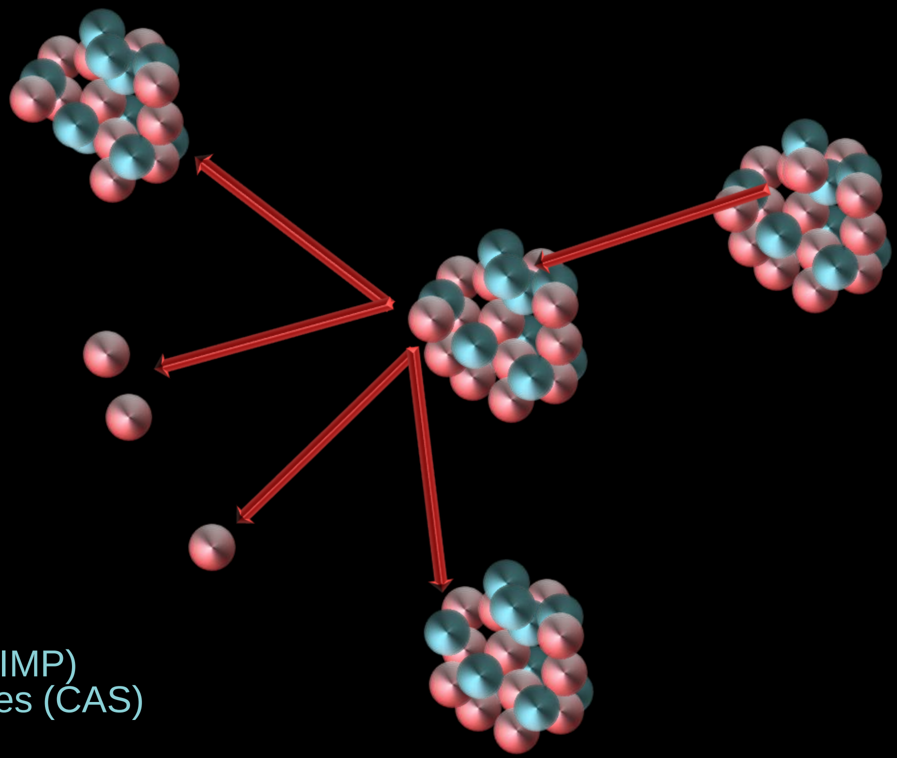
Theoretical Description of *β*-delayed Proton Emission of Proton Rich *sd*- and *pf*- shell nuclei

Yi Hua LAM (藍乙華), Nadezda A. Smirnova



中国科学院近代物理研究所
Institute of Modern Physics (IMP)
Chinese Academy of Sciences (CAS)

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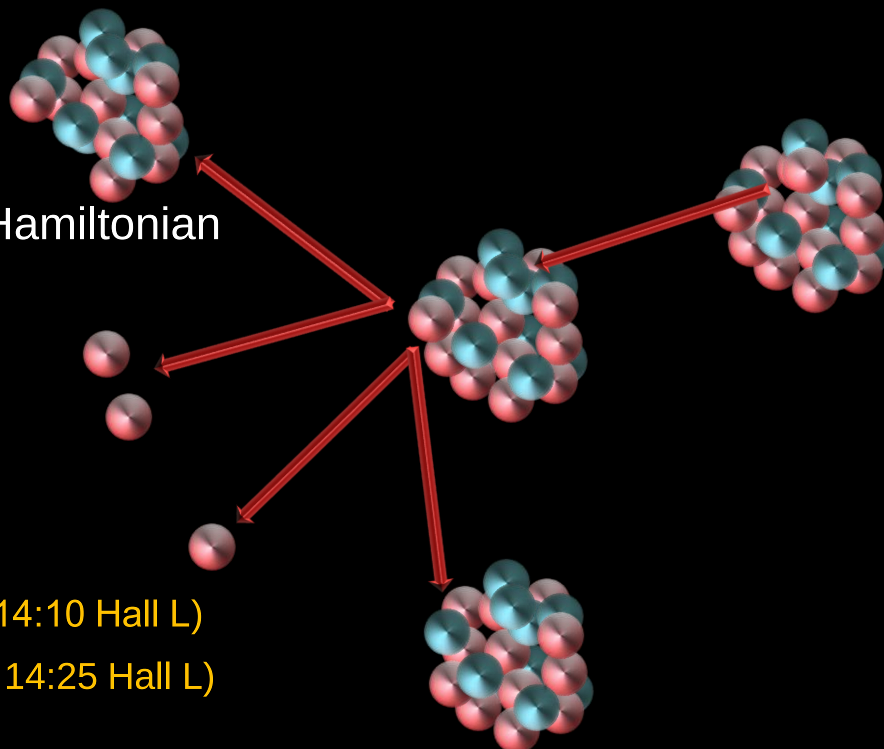
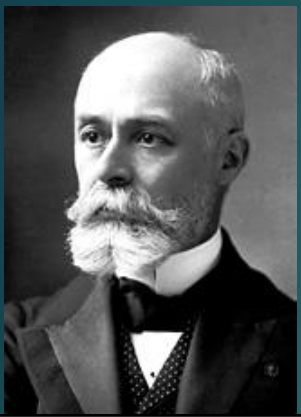


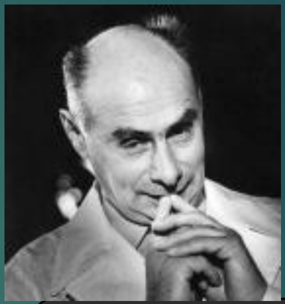
- Background
  - Physics motivation
- Shell-model isospin non-conserving (INC) Hamiltonian
  - Construction of INC Hamiltonian
- *β*-delayed proton emission
  - *sd*-shell: ^{22}Si, ^{23}Si, ^{24}Si, ^{25}Si,
  - *pf*-shell:
    - ^{53}Ni,
    - ^{56}Zn (see W. Richter's talk, on Thursday 14:10 Hall L)
    - ^{52}Ni (see Y. H. Zhang's talk, on Thursday 14:25 Hall L)
- Summary and Perspectives

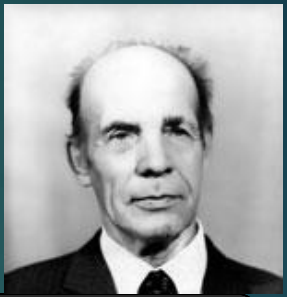
Physics motivation
Discovery of radioactivity



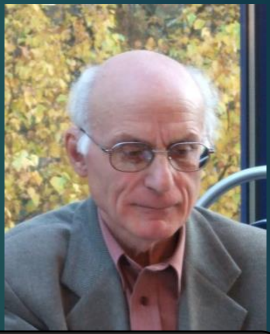
Henri Becquerel
3 groups of radioactivity: negative, positive, and electrically neutral

F. Jouliot and I. Curie
β^{+}





G.N. Flerov and K.A. Petrzhak
spontaneous fission

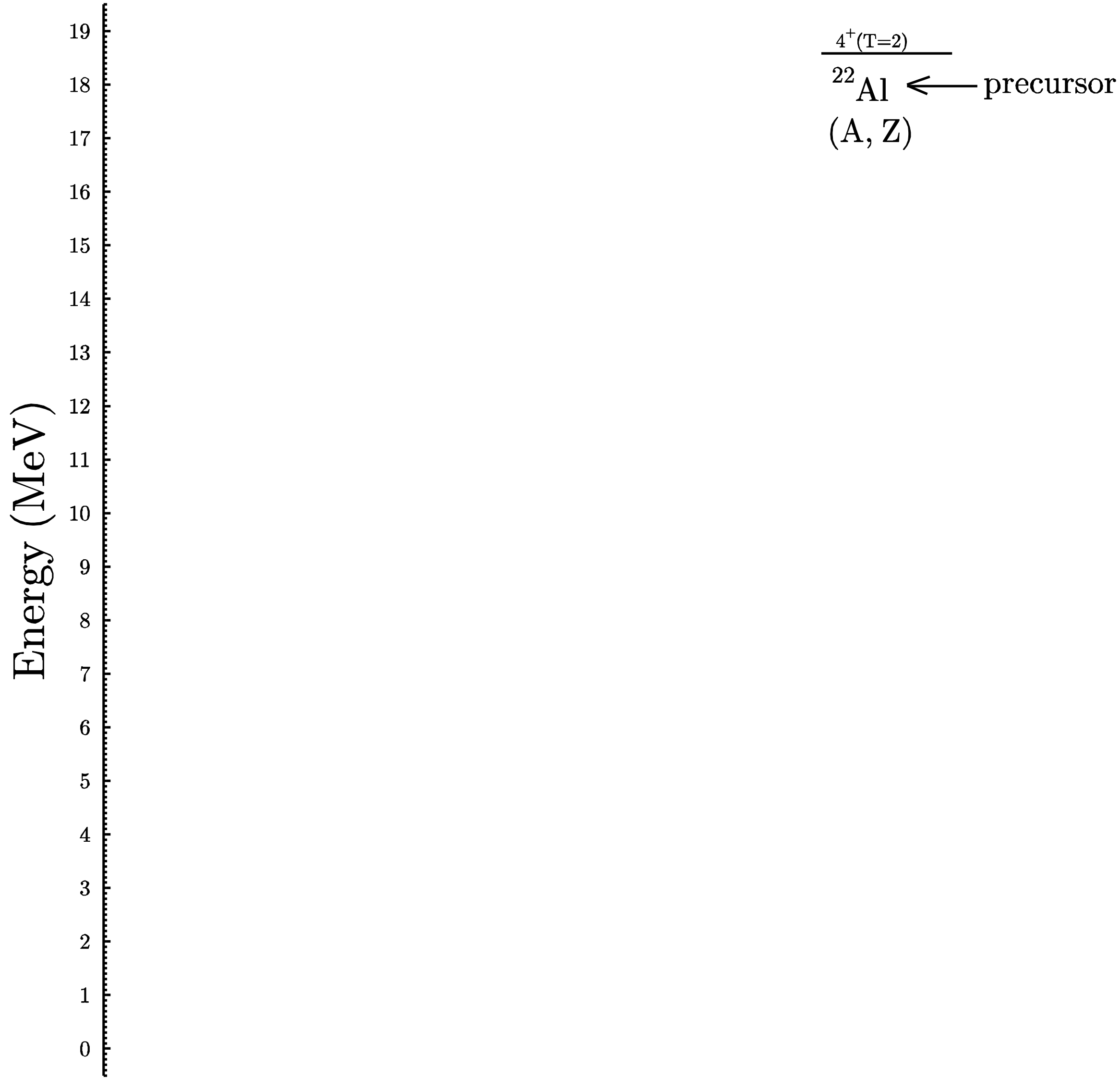


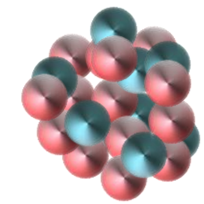
V. A. Karnaukhov and G. M. Ter-Akopian
β-delayed proton emission

M. Pfutzner:
$2p$

S. Hofmann:
p

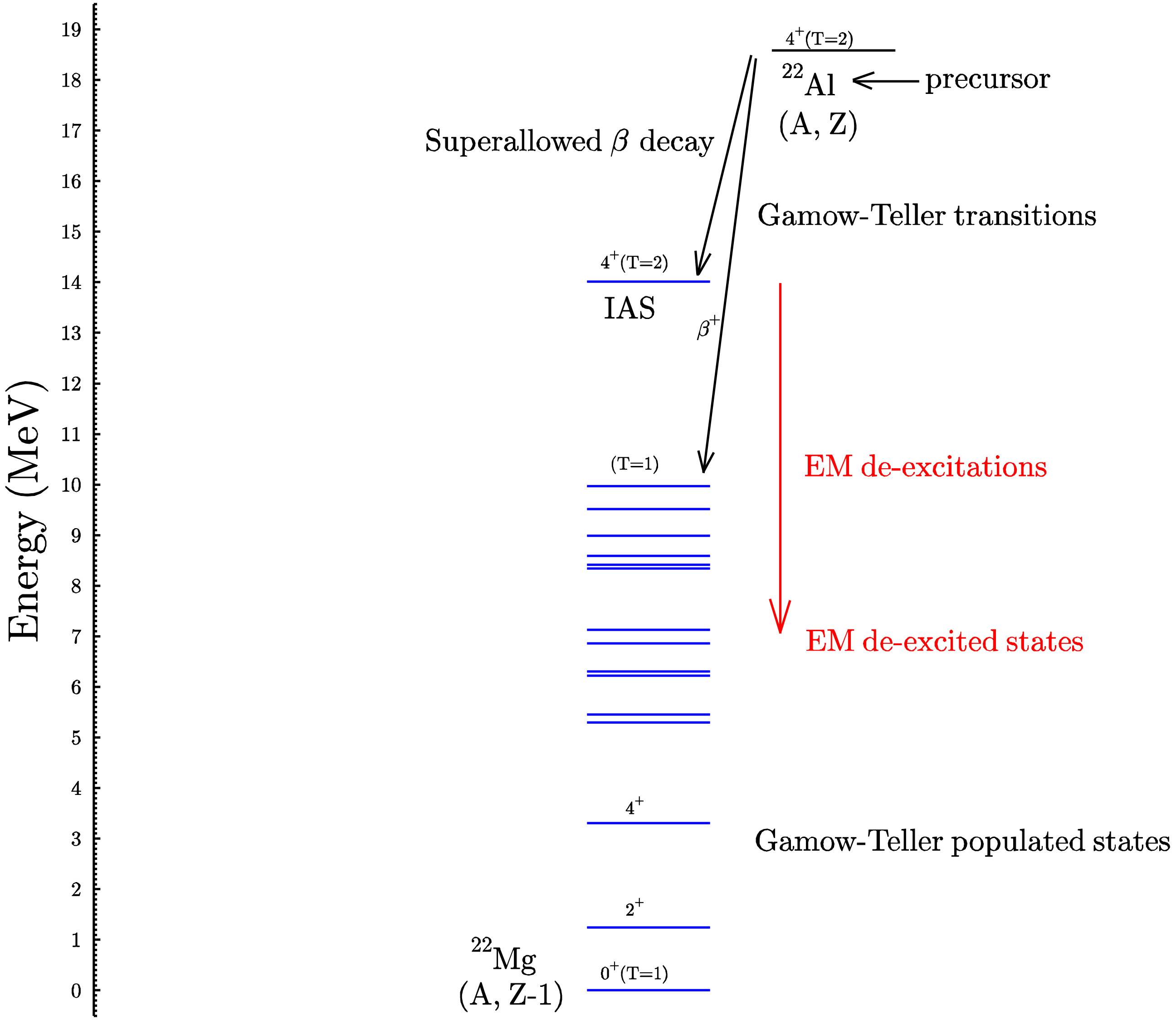
Physics motivation
β-delayed proton emissions

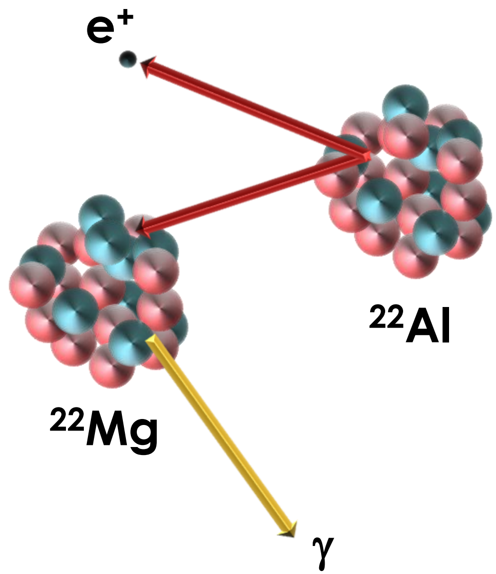




^{22}Al

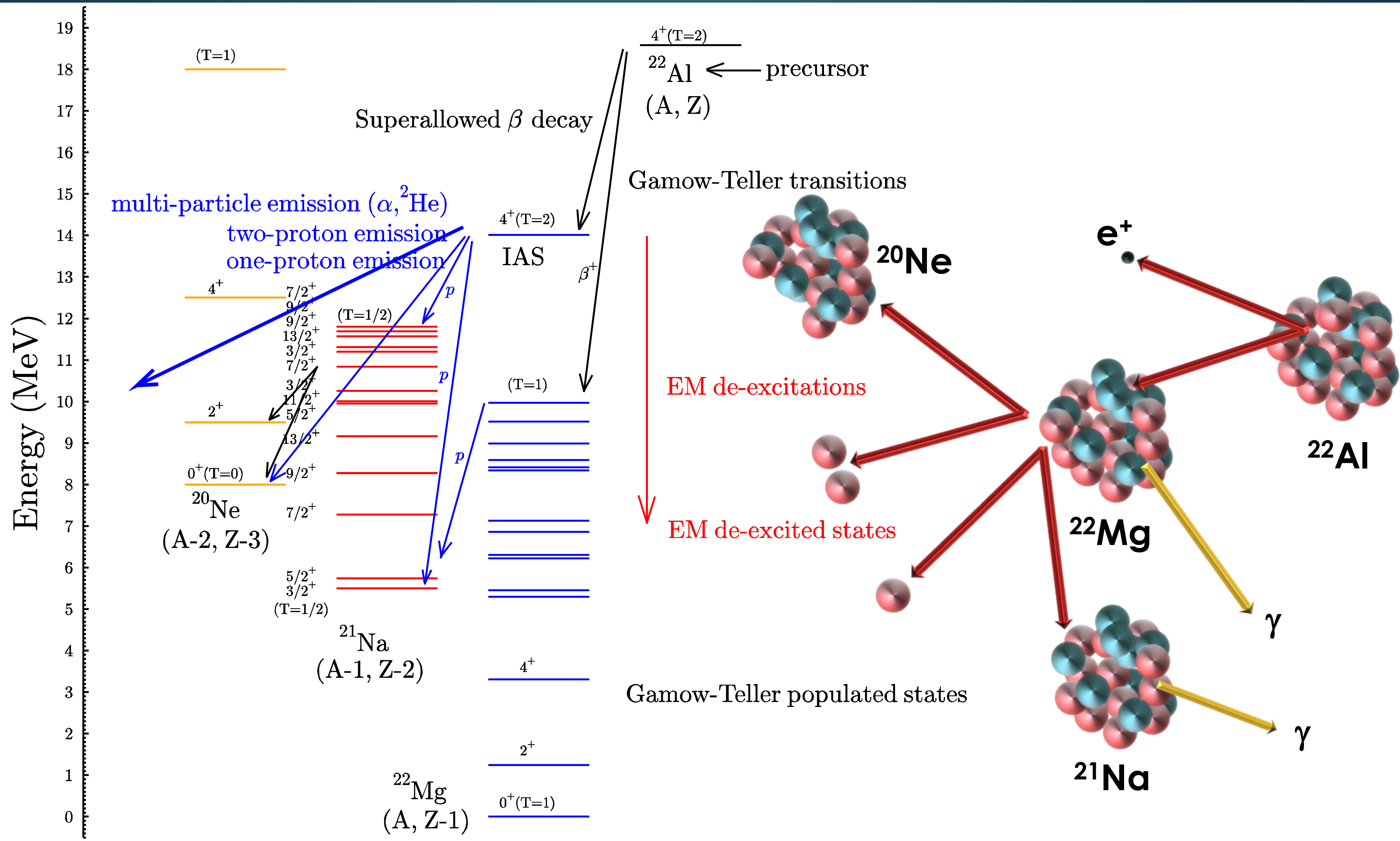
Physics motivation
β-delayed proton emissions



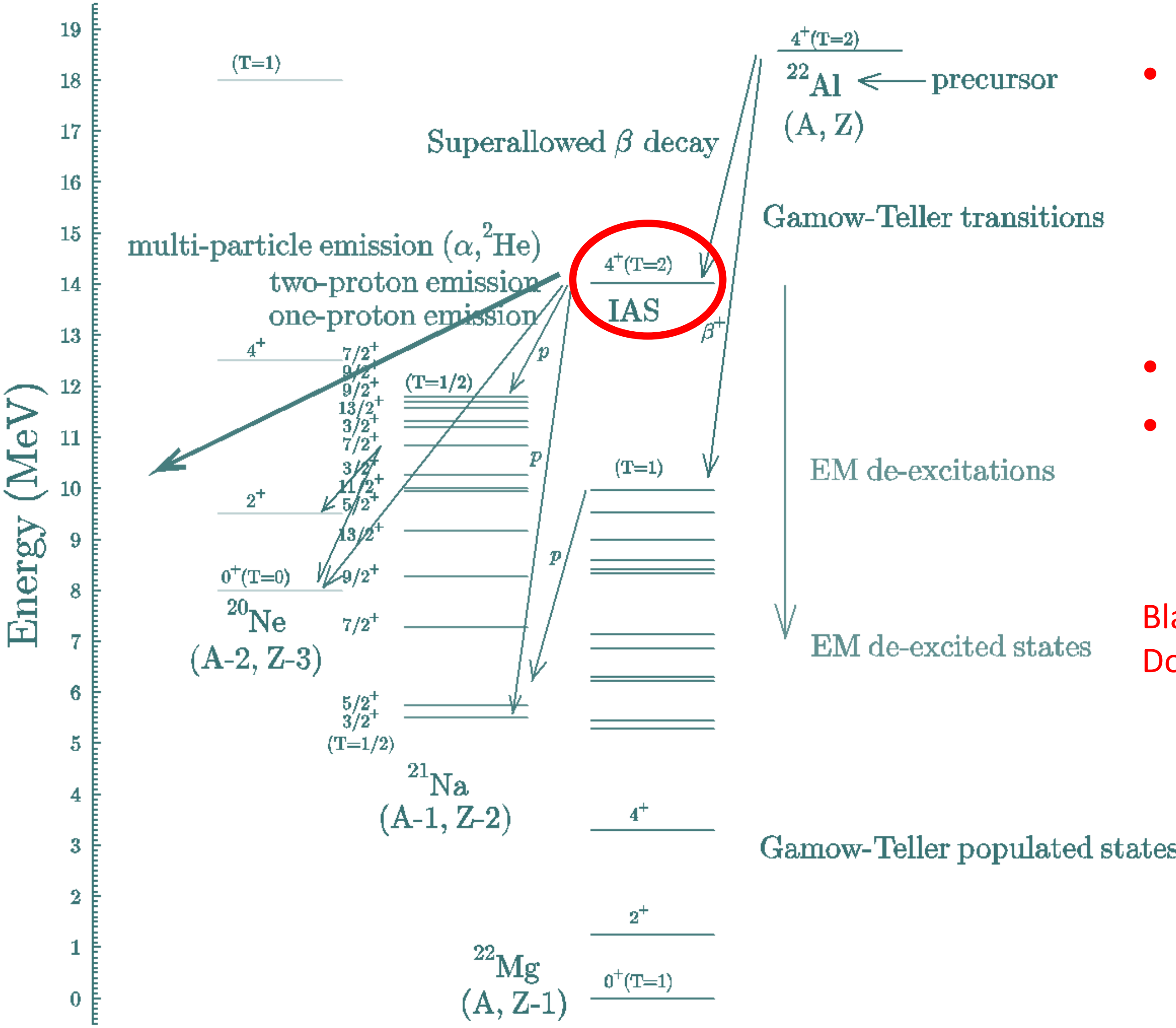


Physics motivation

β-delayed proton emissions



Physics motivation
β-delayed proton emissions

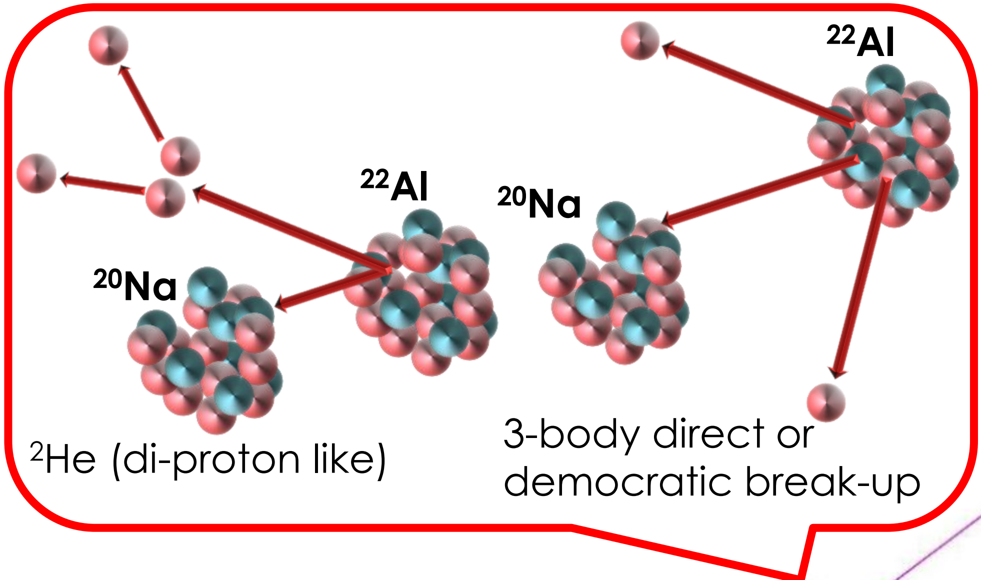


- Determining the **IAS**, and *isovector* and *isotensor* coefficients of **isobaric multiplet mass equation (IMME)**
- Breaking down of IMME?
- Estimating/extrapolating masses of proton-rich nuclei

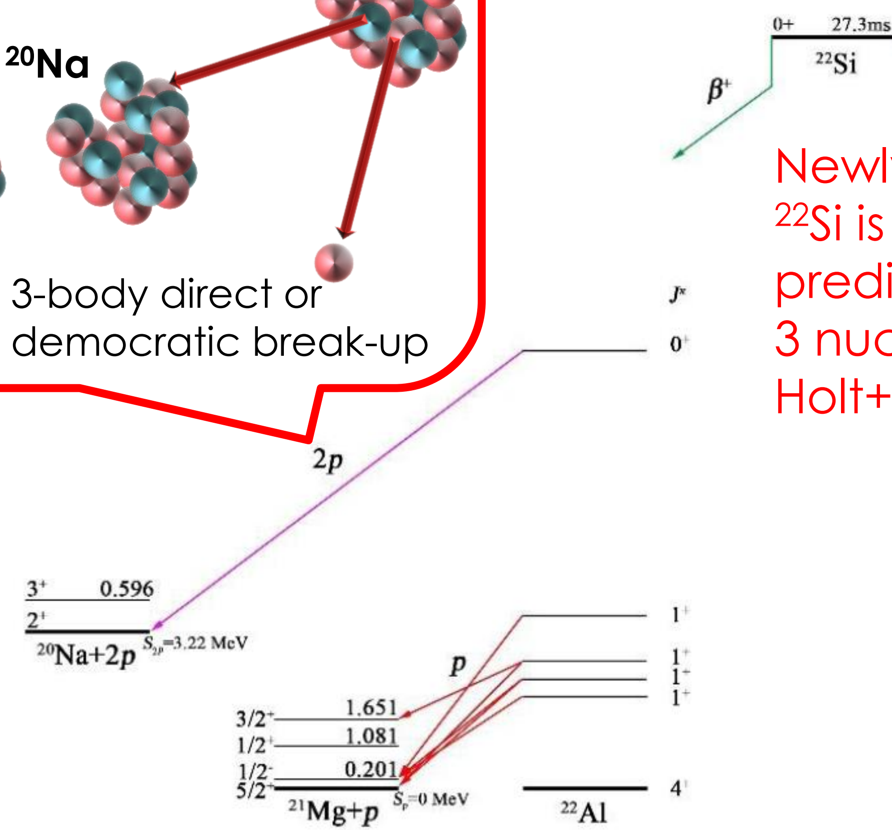
Blank & Borge (PPNP 60, 403)
Dossat+ (NPA 792, 18)

β-delayed proton emissions

$^{22}Si \rightarrow {}^{22}Al \rightarrow {}^{21}Mg$



$$M(^{22}Si) = M(^{22}Al, IAS) + \Delta E_{C(g.s.)} - \Delta_{nH}$$

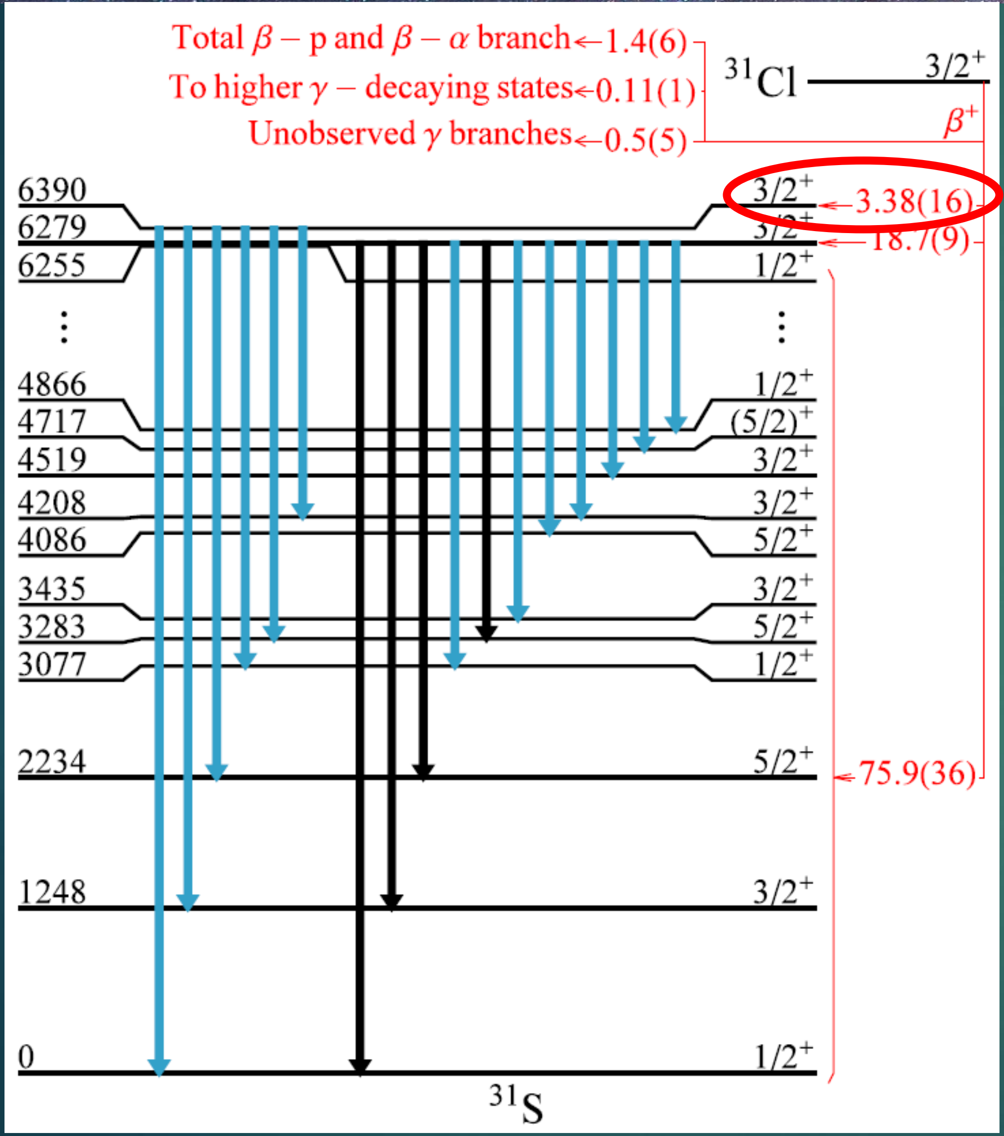


Newly measured mass of ^{22}Si is very close to the prediction of 3 nucleon forces Holt+ (PRL 110 022502)

Xin Xing XU, Chen Jian LIN, Li Jie SUN+ (Preliminary)

YHL & N. A. Smirnova calculated for Xin Xing XU+ (in preparation)

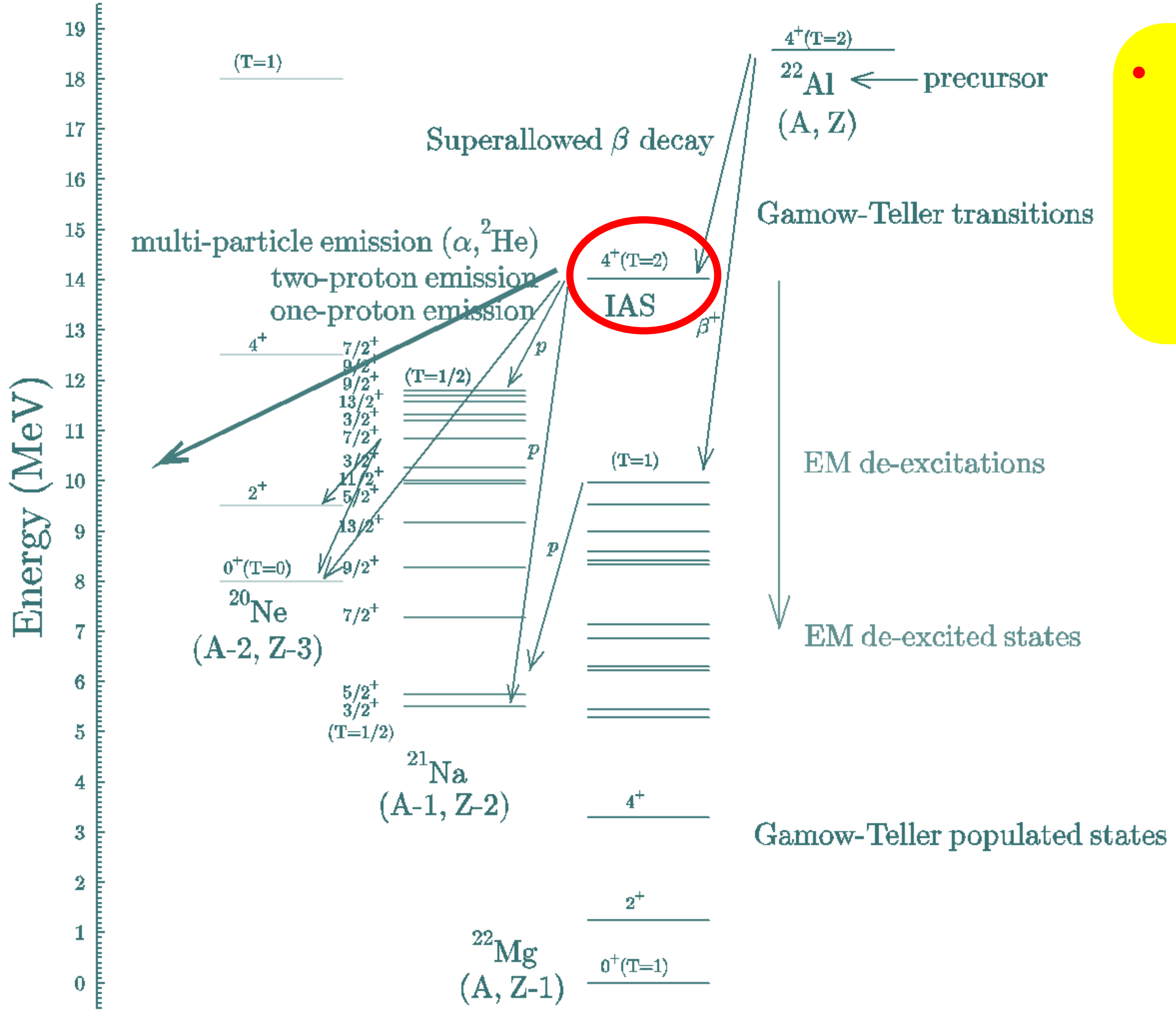
Physics motivation
Determining structure of proton-rich nuclei



Obtaining the pivotal level of ^{31}S which determining ^{30}P(p,γ)^{31}S reaction rates that influences nova nucleosynthesis

Bennett+ (PRL 116, 102502)

Physics motivation
β-delayed proton emissions



- Only uses **one set of Hamiltonian** to describe all physical phenomena of a given partial decay scheme.

Construction of INC Hamiltonian

Isospin Conserving Nucl. Hamiltonian

$$\hat{H}\psi_{TT_Z} \equiv \left(\hat{H}_0 + \hat{V}\right)\psi_{TT_Z} = E_T\psi_{TT_Z}, \quad \psi_{TT_Z} = \sum_k a_{T_k}\phi_{TT_Z}$$

Solve eigenvalue prob.

Nucl. wave function, ψ_{TT_Z}

YHL & N. A. Smirnova & E. Caurier (PRC 87, 054304)

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Solve eigenvalue prob.

Nucl. wave function, ψ_{TT_Z}

Isospin-symmetry breaking terms,

$$\hat{V}_{INC} = \lambda_{Coul}\hat{V}_{Coul} + \lambda_\pi\hat{V}_\pi + \lambda_\rho\hat{V}_\rho + \lambda_0\hat{V}_0^{T=1} + \hat{H}_0^{IV}$$

Assume $v_{pp} \neq v_{nn} \neq v_{pn}$

Isospin-symmetry breaking terms

$$V_{Coul}, V_0\left(V_\pi, V_\rho\right)$$

Nolen-Schiffer anomaly

Short range correlation:

1. Unitarity Correlation Operator Method (UCOM)

2. Jastrow-type SRC:

```
a. Miller-Spencer
b. CD-Bonn
c. Argonne V18
```

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```

Within perturbation theory, evaluate

$$\left\langle \psi_{TT_Z} \middle| \hat{V}_{INC} \middle| \psi_{TT_Z} \right\rangle = E^{(0)}(\alpha,T) + E^{(1)}(\alpha,T)T_Z + E^{(2)}(\alpha,T)\left(3T_Z^2 - T(T+1)\right)$$

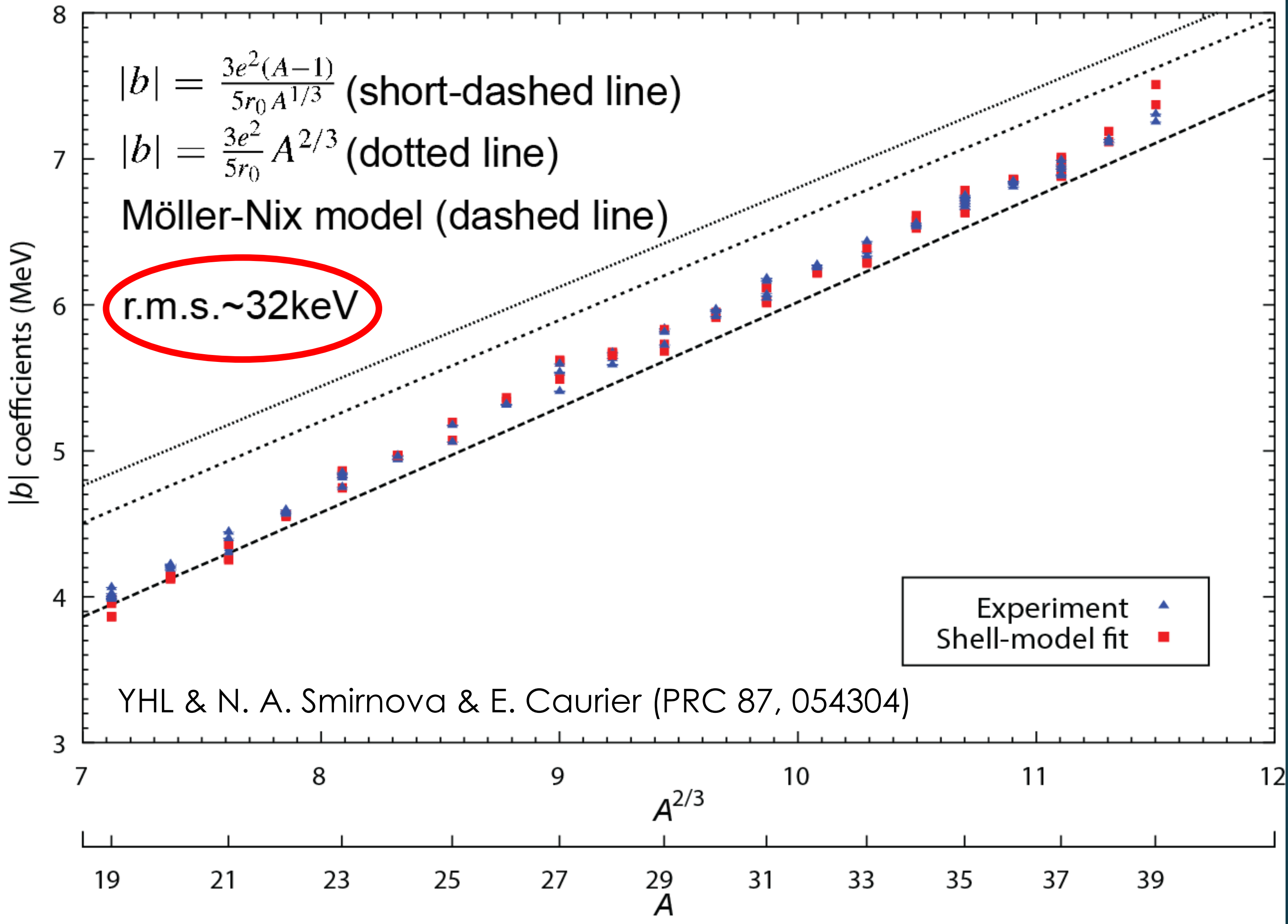
Fit Strength Parameters $\lambda_{Coul}, \lambda_\pi, \lambda_\rho, \lambda_0, \hat{H}_0^{IV}$

to reproduce exp. isobaric multiplet mass equation (IMME) *b* & *c* coef.

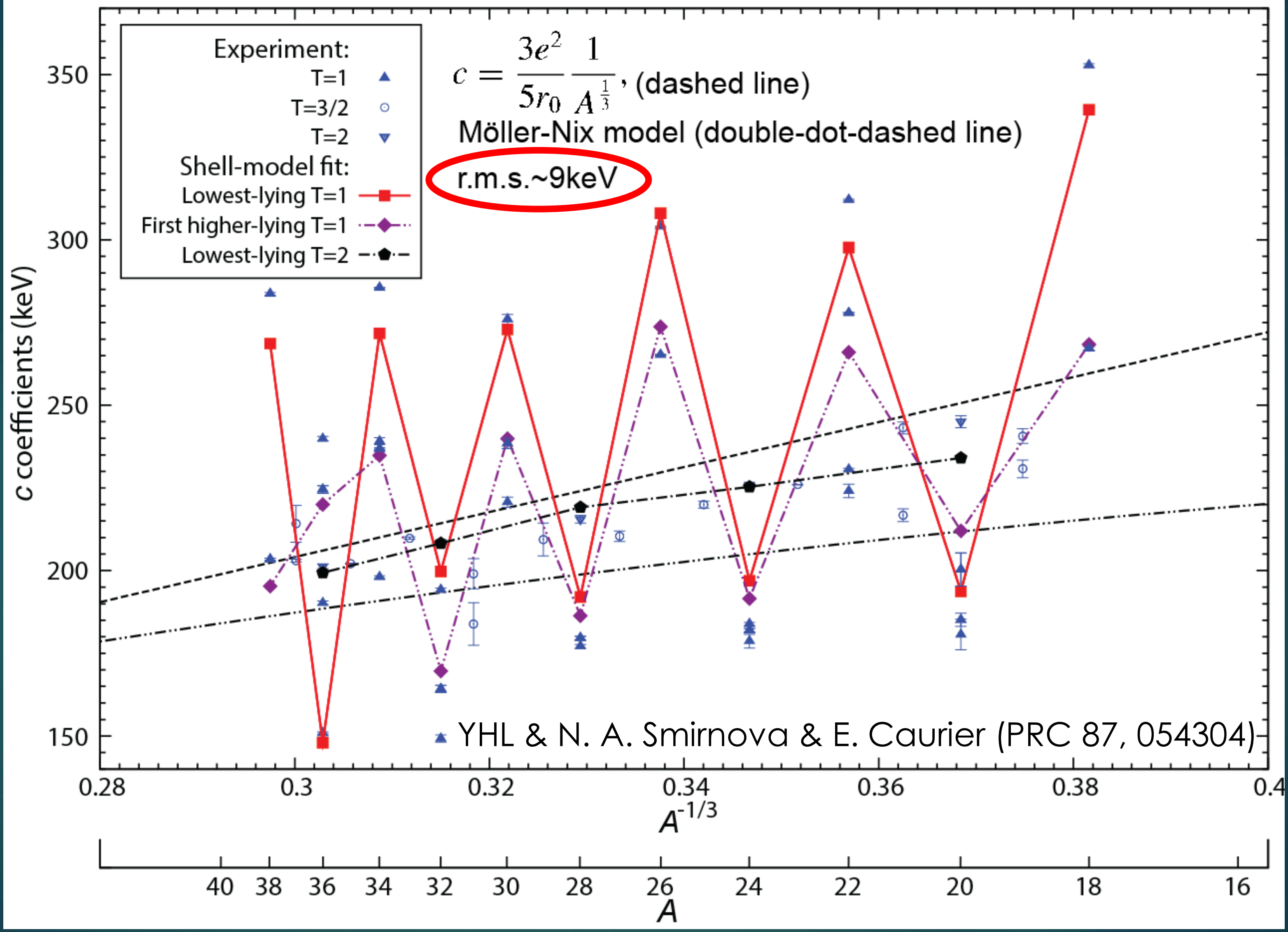
$$M(\alpha,T,T_Z) = a(\alpha,T) + b(\alpha,T)T_Z + c(\alpha,T)T_Z^2$$

YHL & N. A. Smirnova & E. Caurier (PRC 87, 054304)

Construction of INC Hamiltonian



Construction of INC Hamiltonian



Construction of INC Hamiltonian

Isospin Conserving Nucl. Hamiltonian

$$\hat{H}\psi_{TT_Z} \equiv \left(\hat{H}_0 + \hat{V}\right)\psi_{TT_Z} = E_T\psi_{TT_Z}, \quad \psi_{TT_Z} = \sum_k a_{T_k}\phi_{TT_Z}$$

Solve eigenvalue prob.

Nucl. wave function, ψ_{TT_Z}

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Isospin-symmetry breaking terms,

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$$V_{Coul}, V_0\left(V_\pi, V_\rho\right)$$

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Within perturbation theory, evaluate

$$\left\langle \psi_{TT_Z}\middle|\hat{V}_{INC}\middle|\psi_{TT_Z}\right\rangle = E^{(0)}(\alpha,T) + E^{(1)}(\alpha,T)T_Z + E^{(2)}(\alpha,T)\left(3T_Z^2 - T(T+1)\right)$$

Fit Strength Parameters $\lambda_{Coul}, \lambda_\pi, \lambda_\rho, \lambda_0, \hat{H}_0^{IV}$
to reproduce exp. isobaric multiplet mass equation (IMME) *b* & *c* coef.

$$M(\alpha,T,T_Z) = a(\alpha,T) + b(\alpha,T)T_Z + c(\alpha,T)T_Z^2$$

Solve the eigenproblem for an INC Hamiltonian

$$\hat{H}_{INC}\psi(\alpha_p,\alpha_n) \equiv \left(\hat{H}_0 + V + \hat{V}_{INC}\right)\psi(\alpha_p,\alpha_n) = E\,\psi(\alpha_p,\alpha_n)$$

YHL & N. A. Smirnova & E. Caurier (PRC 87, 054304)

Isospin symmetry & Isospin admixed states

Isospin symmetry states,

$$\left|\psi_m^A(JT=3/2)\right\rangle = \sum_i \alpha_i \left|\phi_{n,l,j,T=3/2}\right\rangle_i$$

Isospin admixed states,

$$\left|\psi_m^A(JT=3/2)\right\rangle = \sum_i \alpha_i \left|\phi_{n,l,j,T=3/2}\right\rangle_i + \sum_j \beta_j \left|\phi_{n,l,j,T=1/2}\right\rangle_j + \sum_k \chi_k \left|\phi_{n,l,j,T=5/2}\right\rangle_k + \ldots$$

Isobaric analogue state of ^{53}Co with isospin symmetry,

$$\left|7/2^-,\mathrm{IAS}_{T=3/2}\right\rangle = \sum_i \alpha_i \left|7/2^-,T=3/2\right\rangle_i$$

Isobaric analogue state of ^{53}Co with admixed isospin,

$$\left|7/2^-,\mathrm{IAS}_{T=3/2}\right\rangle = \sum_i \alpha_i \left|7/2^-,T=3/2\right\rangle_i + \sum_j \beta_j \left|7/2^-,T=1/2\right\rangle_j + \sum_k \chi_k \left|7/2^-,T=5/2\right\rangle_k + \ldots$$

Isospin non-conserving Hamiltonian

***sd*-shell nuclei**

$$\text{cd-USDB} = \text{USDB} + V_{Coul}(\text{UCOM}) + V_0(\text{USDB}, T = 1) + \text{isovector SPE}$$

***pf*-shell nuclei (unoptimized INC)**

$$\text{cd-KB3G} = \text{KB3G} + V_{Coul} + \text{isovector SPE}$$
$$\text{cd-GXPF1a} = \text{GXPF1a} + V_{Coul} + \text{isovector SPE}$$

YHL & N. A. Smirnova & E. Caurier (PRC 87, 054304); Ormand & Brown (NPA 491, 1)

β-delayed proton emissions

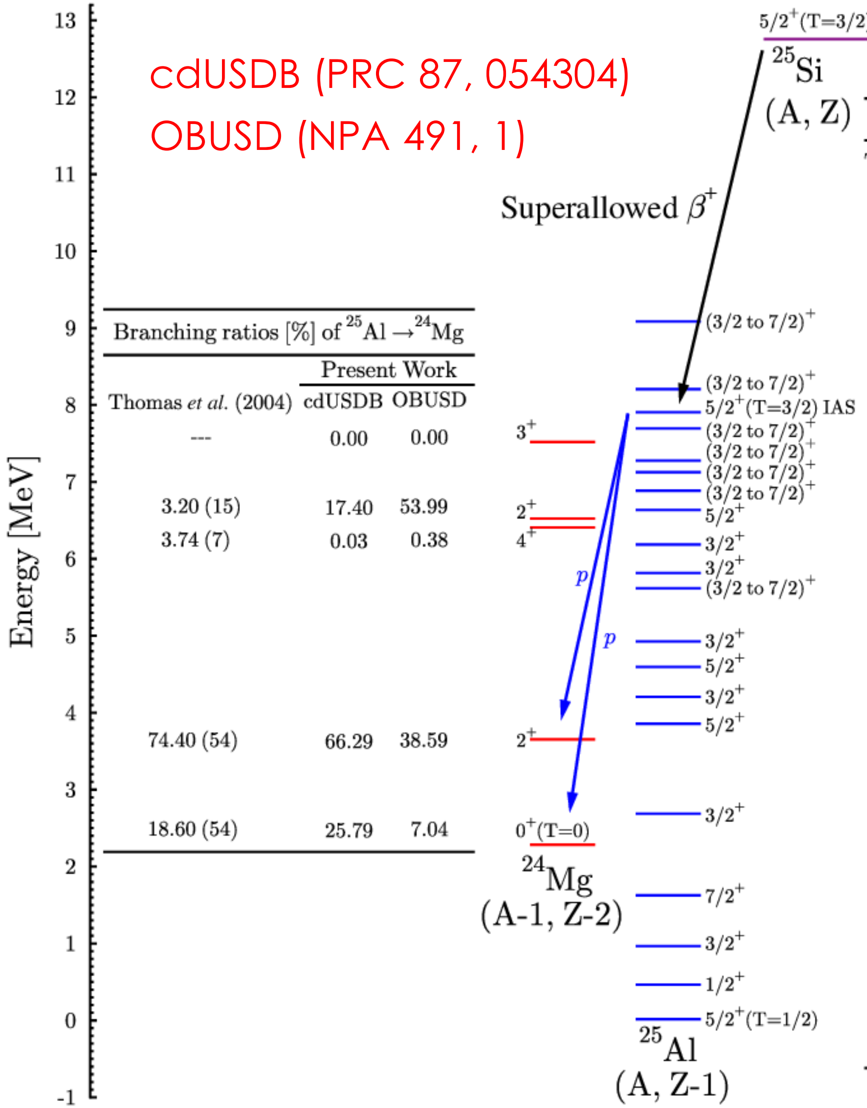
$^{25}Si \rightarrow {}^{25}Al \rightarrow {}^{24}Mg$

cdUSDB (PRC 87, 054304)

OBUSD (NPA 491, 1)

Branching ratios [%] of ^{25}Al → ^{24}Mg

Level	Thomas *et al.* (2004)	Present Work cdUSDB	Present Work OBUSD
3^+	---	0.00	0.00
2^+	3.20 (15)	17.40	53.99
4^+	3.74 (7)	0.03	0.38
2^+	74.40 (54)	66.29	38.59
0^+(T=0)	18.60 (54)	25.79	7.04



Half lives, branching ratios [%] and log *ft* of ^{25}Si → ^{25}Al

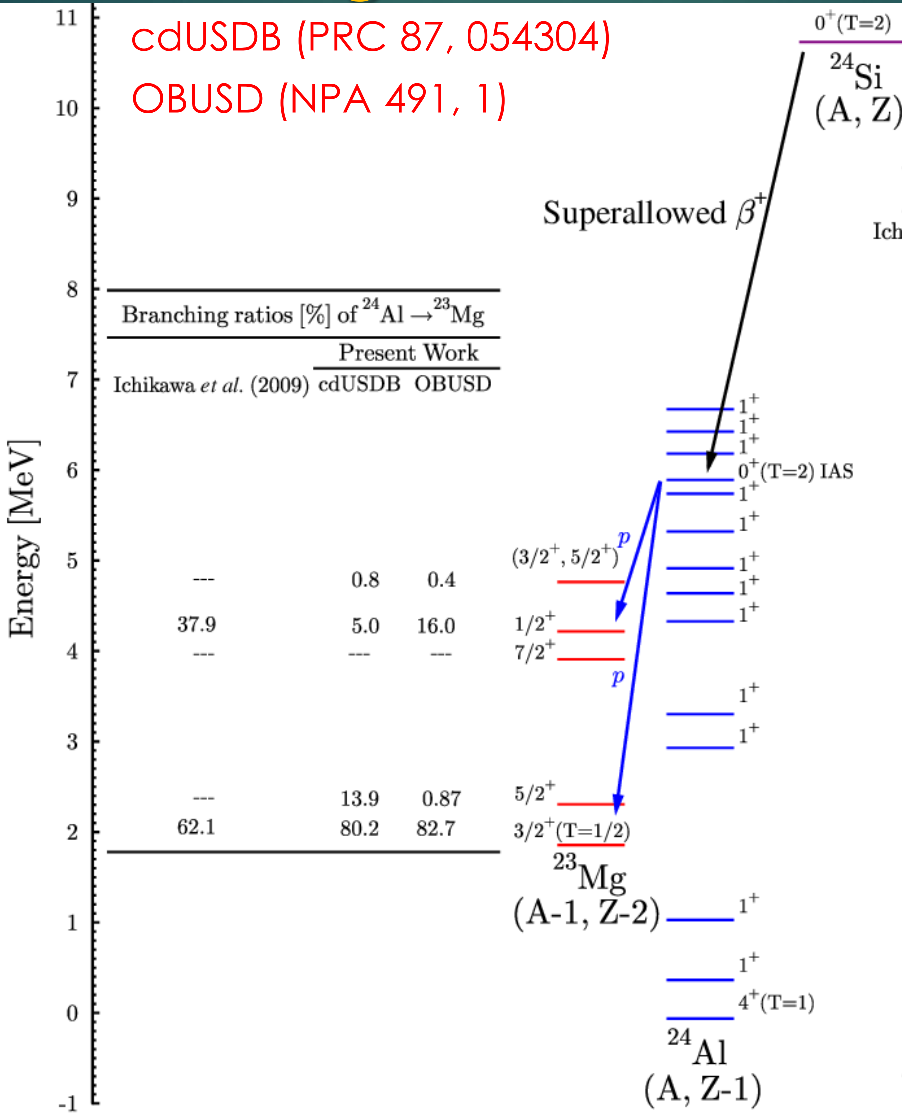
	Thomas *et al.* (2004)		cdUSDB		OBUSD	
$T_{1/2}$ [ms]	220 (3)		241.0		246.1	
Level	BR(%)	log *ft*	BR(%)	log *ft*	BR(%)	log *ft*
(3/2 to 7/2)$^+$	0.21 (4)	4.32 (10)			0.18	4.28
(3/2 to 7/2)$^+$	1.2 (2)	4.12 (9)			0.63	4.41
5/2$^+$(T=3/2) IAS	12.8 (8)	3.25 (3)	16.60	3.30	13.52	3.29
(3/2 to 7/2)$^+$	0.34 (6)	4.94 (9)			0.16	5.29
(3/2 to 7/2)$^+$	1.0 (6)	4.65 (13)			0.13	5.61
(3/2 to 7/2)$^+$	3.7 (2)	4.17 (3)			1.32	4.63
(3/2 to 7/2)$^+$	0.5 (1)	5.13 (11)				
5/2$^+$	0.16 (7)	5.73 (34)	0.42	5.34	0.56	5.24
3/2$^+$	0.32 (6)	5.60 (10)	0.03	6.50	0.16	5.83
3/2$^+$	1.7 (2)	5.00 (6)	0.34	5.51	0.11	6.05
(3/2 to 7/2)$^+$	0.6 (1)	5.56 (11)	0.21	5.93	0.66	5.48
3/2$^+$	0.6 (2)	5.76 (18)	0.78	5.38	0.27	6.02
5/2$^+$	3.2 (3)	5.11 (4)	2.79	5.15	3.03	5.05
3/2$^+$	2.9 (3)	5.26 (5)	1.54	5.52	1.78	5.40
5/2$^+$	0.4 (1)	6.21 (18)	0.05	7.14	0.16	6.61
3/2$^+$	4.8 (3)	5.43 (3)	8.40	5.17	7.64	5.16
7/2$^+$	15 (3)	5.17 (12)	13.56	5.22	14.38	5.15
3/2$^+$	26 (4)	5.05 (8)	20.17	5.16	20.5	5.10
1/2$^+$						
5/2$^+$(T=1/2)	25 (7)	5.25 (17)	22.34	5.34	21.40	5.31

β-delayed proton emissions

$^{24}Si \rightarrow {}^{24}Al \rightarrow {}^{23}Mg$

cdUSDB (PRC 87, 054304)

OBUSD (NPA 491, 1)



Branching ratios [%] of ^{24}Al $\rightarrow$ ^{23}Mg

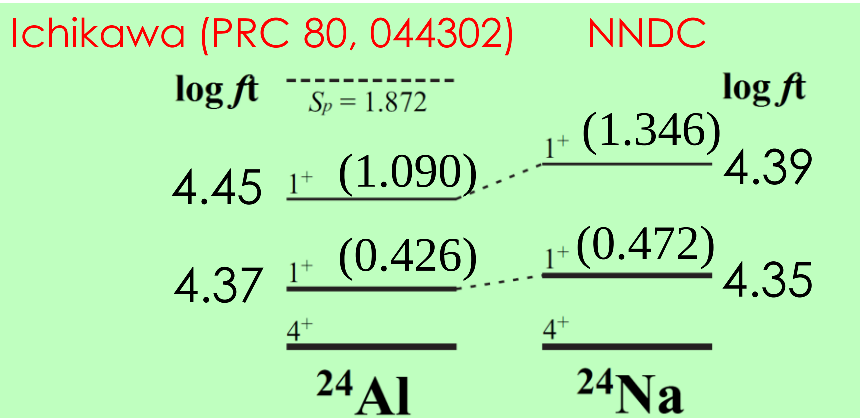
Ichikawa *et al.* (2009)	Present Work: cdUSDB	Present Work: OBUSD
---	0.8	0.4
37.9	5.0	16.0
---	---	---
---	13.9	0.87
62.1	80.2	82.7

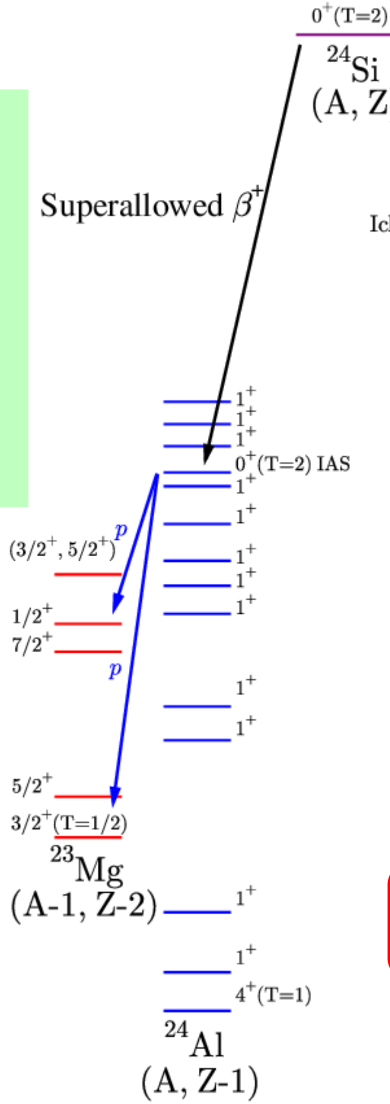
Branching ratios [%] and log *ft* of ^{24}Si $\rightarrow$ ^{24}Al

Ichikawa *et al.* (2011) $T_{1/2}$ [ms] 140±8		cdUSDB $T_{1/2}$ [ms] 171		OBUSD $T_{1/2}$ [ms] 161	
Br[%]	log *ft*	Br[%]	log *ft*	Br[%]	log *ft*
0.07 (2)	4.90 (10)	0.1	4.79	0.3	4.22
0.26 (4)	4.47 (7)	1.9	3.55	0.1	5.22
2.2 (2)	3.68 (4)	0.5	4.23	4.4	3.51
9.9 (9)	3.18 (4)	14.3	3.20	11.7	3.21
1.0 (3)	4.25 (12)	1.4	4.01	0.2	4.93
0.68 (10)	4.62 (6)	0.0	7.84	1.0	4.46
0.8 (1)	4.72 (6)	2.0	4.35	1.7	4.41
1.1 (1)	4.70 (5)	0.6	5.05	1.1	4.68
0.49 (7)	5.17 (6)	2.2	4.63	1.4	4.73
11 (1)	4.16 (5)	6.0	4.45	9.8	4.20
5.8 (7)	4.56 (5)	15.2	4.13	12.7	4.21
23.9 (15)	4.45 (3)	19.4	4.58	26.5	4.46
41.0 (44)	4.37 (4)	36.1	4.51	29.1	4.57

β-delayed proton emissions

$^{24}Si \rightarrow {}^{24}Al \rightarrow {}^{23}Mg$





Branching ratios [%] and log ft of ^{24}Si $\rightarrow$ ^{24}Al

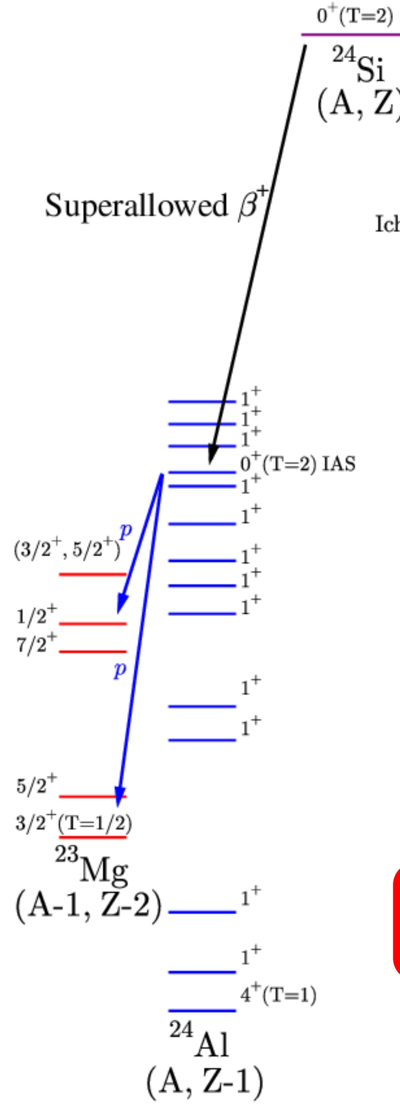
Ichikawa *et al.* (2011)		cdUSDB		OBUSD	
$T_{1/2}$ [ms] 140±8		$T_{1/2}$ [ms] 171		$T_{1/2}$ [ms] 161	
Br[%]	log ft	Br[%]	log ft	Br[%]	log ft
0.07 (2)	4.90 (10)	0.1	4.79	0.3	4.22
0.26 (4)	4.47 (7)	1.9	3.55	0.1	5.22
2.2 (2)	3.68 (4)	0.5	4.23	4.4	3.51
9.9 (9)	3.18 (4)	14.3	3.20	11.7	3.21
1.0 (3)	4.25 (12)	1.4	4.01	0.2	4.93
0.68 (10)	4.62 (6)	0.0	7.84	1.0	4.46
0.8 (1)	4.72 (6)	2.0	4.35	1.7	4.41
1.1 (1)	4.70 (5)	0.6	5.05	1.1	4.68
0.49 (7)	5.17 (6)	2.2	4.63	1.4	4.73
11 (1)	4.16 (5)	6.0	4.45	9.8	4.20
5.8 (7)	4.56 (5)	15.2	4.13	12.7	4.21
23.9 (15)	4.45 (3)	19.4	4.58	26.5	4.46
41.0 (44)	4.37 (4)	36.1	4.51	29.1	4.57

β-delayed proton emissions

$^{24}Si \rightarrow {}^{24}Al \rightarrow {}^{23}Mg$

TBME $\langle ij\|V\|kl\rangle_{JT}^{pp}$	**USDB:USD**
$\left\langle (1s_{1/2})^2 \middle\| V \middle\| (1s_{1/2})^2 \right\rangle_{01}^{pp}$	**+20%**
$\langle 1s_{1/2}0d_{5/2}\|V\|1s_{1/2}0d_{5/2}\rangle_{31}^{pp}$	**-10%**
$\langle 1s_{1/2}0d_{5/2}\|V\|1s_{1/2}0d_{5/2}\rangle_{21}^{pp}$	**-15%**
$\left\langle (0d_{5/2})^2 \middle\| V \middle\| (1s_{1/2})^2 \right\rangle_{01}^{pp}$	**-18%**
$\left\langle 1s_{1/2}0d_{5/2} \middle\| V \middle\| (0d_{5/2})^2 \right\rangle_{21}^{pp}$	**-8%**

TBME $\langle ij\|V\|kl\rangle_{JT}^{pn}$	
$\langle 1s_{1/2}0d_{5/2}\|V\|1s_{1/2}0d_{5/2}\rangle_{31}^{pn}$	**-10%**
$\langle 1s_{1/2}0d_{5/2}\|V\|1s_{1/2}0d_{5/2}\rangle_{21}^{pn}$	**-15%**
$\left\langle 1s_{1/2}0d_{5/2} \middle\| V \middle\| (0d_{5/2})^2 \right\rangle_{21}^{pn}$	**-8%**
$\langle 1s_{1/2}0d_{5/2}\|V\|1s_{1/2}0d_{5/2}\rangle_{30}^{pn}$	**-8%**
$\langle 1s_{1/2}0d_{5/2}\|V\|1s_{1/2}0d_{5/2}\rangle_{20}^{pn}$	**+78%**
$\left\langle 1s_{1/2}0d_{5/2} \middle\| V \middle\| (0d_{5/2})^2 \right\rangle_{30}^{pn}$	**+2%**



Branching ratios [%] and log ft of $^{24}Si \rightarrow {}^{24}Al$

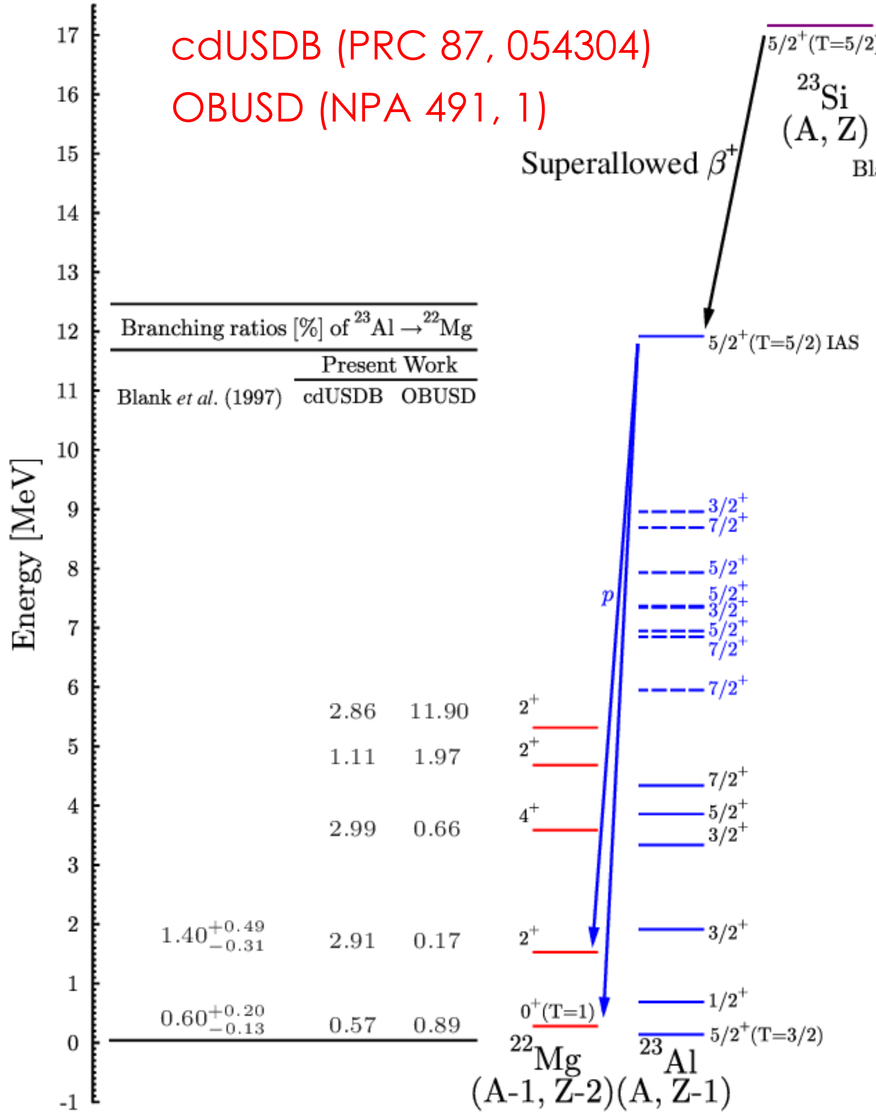
Ichikawa *et al.* (2011) $T_{1/2}$ [ms] 140±8		cdUSDB $T_{1/2}$ [ms] 171		OBUSD $T_{1/2}$ [ms] 161	
Br[%]	log ft	Br[%]	log ft	Br[%]	log ft
0.07 (2)	4.90 (10)	0.1	4.79	0.3	4.22
0.26 (4)	4.47 (7)	1.9	3.55	0.1	5.22
2.2 (2)	3.68 (4)	0.5	4.23	4.4	3.51
9.9 (9)	3.18 (4)	14.3	3.20	11.7	3.21
1.0 (3)	4.25 (12)	1.4	4.01	0.2	4.93
0.68 (10)	4.62 (6)	0.0	7.84	1.0	4.46
0.8 (1)	4.72 (6)	2.0	4.35	1.7	4.41
1.1 (1)	4.70 (5)	0.6	5.05	1.1	4.68
0.49 (7)	5.17 (6)	2.2	4.63	1.4	4.73
11 (1)	4.16 (5)	6.0	4.45	9.8	4.20
5.8 (7)	4.56 (5)	15.2	4.13	12.7	4.21
23.9 (15)	4.45 (3)	19.4	4.58	26.5	4.46
41.0 (44)	4.37 (4)	36.1	4.51	29.1	4.57

β-delayed proton emissions

$^{23}Si \rightarrow {}^{23}Al \rightarrow {}^{22}Mg$

cdUSDB (PRC 87, 054304)

OBUSD (NPA 491, 1)



Branching ratios [%] of $^{23}Al \rightarrow {}^{22}Mg$

Level (^{22}Mg)	Blank *et al.* (1997)	Present Work cdUSDB	Present Work OBUSD
2^+		2.86	11.90
2^+		1.11	1.97
4^+		2.99	0.66
2^+	$1.40^{+0.49}_{-0.31}$	2.91	0.17
0^+(T=1)	$0.60^{+0.20}_{-0.13}$	0.57	0.89

Branching ratios [%] and log ft of $^{23}Si \rightarrow {}^{23}Al$

Level (^{23}Al)	Blank *et al.* (1997) Br[%]	Blank *et al.* (1997) log ft	cdUSDB Br[%]	cdUSDB log ft	OBUSD Br[%]	OBUSD log ft
	$T_{1/2}$ [ms] 40.7±0.4		$T_{1/2}$ [ms] 39.5		$T_{1/2}$ [ms] 38.8	
$5/2^+$(T=5/2) IAS	> 3.7	< 3.25	6.8	3.09	3.3	3.39
$3/2^+$			1.4	4.74		
$7/2^+$			1.0	4.96		
$5/2^+$			1.2	5.09		
$5/2^+$			1.0	5.29		
$3/2^+$			3.2	4.79		
$5/2^+$			1.2	5.30		
$7/2^+$			2.7	4.99		
$7/2^+$			1.3	5.49		
$7/2^+$	13.6	4.80	14.2	4.73	7.9	4.98
$5/2^+$	39.4	4.40	24.7	4.60	25.6	4.57
$3/2^+$	7.8	5.21	11.9	4.98	12.6	4.97
$3/2^+$	10.1	5.36	2.1	5.95	0.3	6.90
$1/2^+$						
$5/2^+$(T=3/2)			7.7	5.66	6.3	5.75

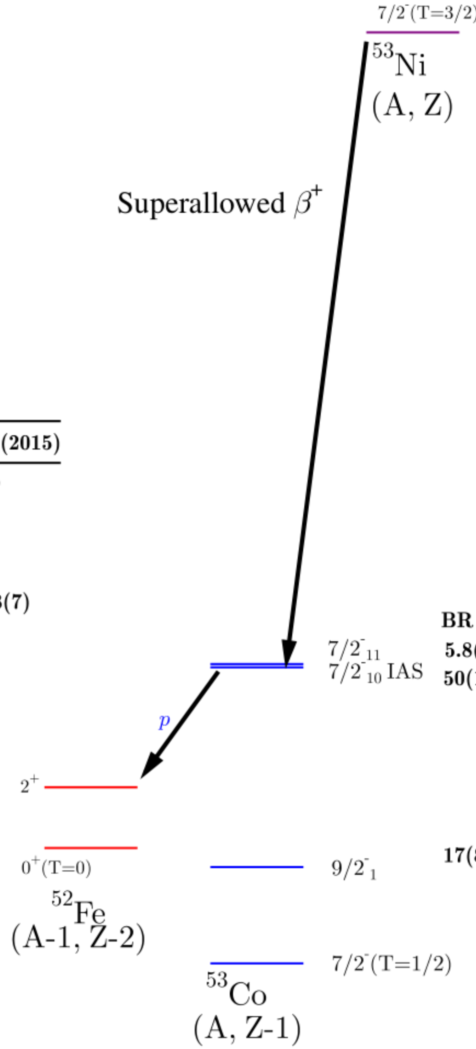
β-delayed proton emissions

$^{53}Ni \rightarrow {}^{53}Co \rightarrow {}^{52}Fe$

	cd-GXPF1a	cd-KB3G	Su+ (2015)
B(F)	2.98	2.99	2.6(7)
Iso. mix. [%]	0.5	0.3	
Γ_γ [eV]	0.36	0.30	
Γ_p [eV]	0.03	0.25	
Γ_p/Γ_γ	0.08	0.83	0.018(7)

$^{53}Co^i \rightarrow {}^{52}Fe$

Su+ (2015) I_p(%)	cd-GXPF1a Branching ratios (%)
1.8	9
--	0.8



	Su+ (2015) BR (%)	Su+ (2015) log ft	cd-GXPF1a BR (%)	cd-GXPF1a log ft
$7/2^-_{11}$	5.8(7)	4.28(6)	1.4	4.95
$7/2^-_{10}$ IAS	50(11)	3.36(10)	65.8	3.30
$9/2^-_1$	17(8)	4.51(21)	2.5	5.35

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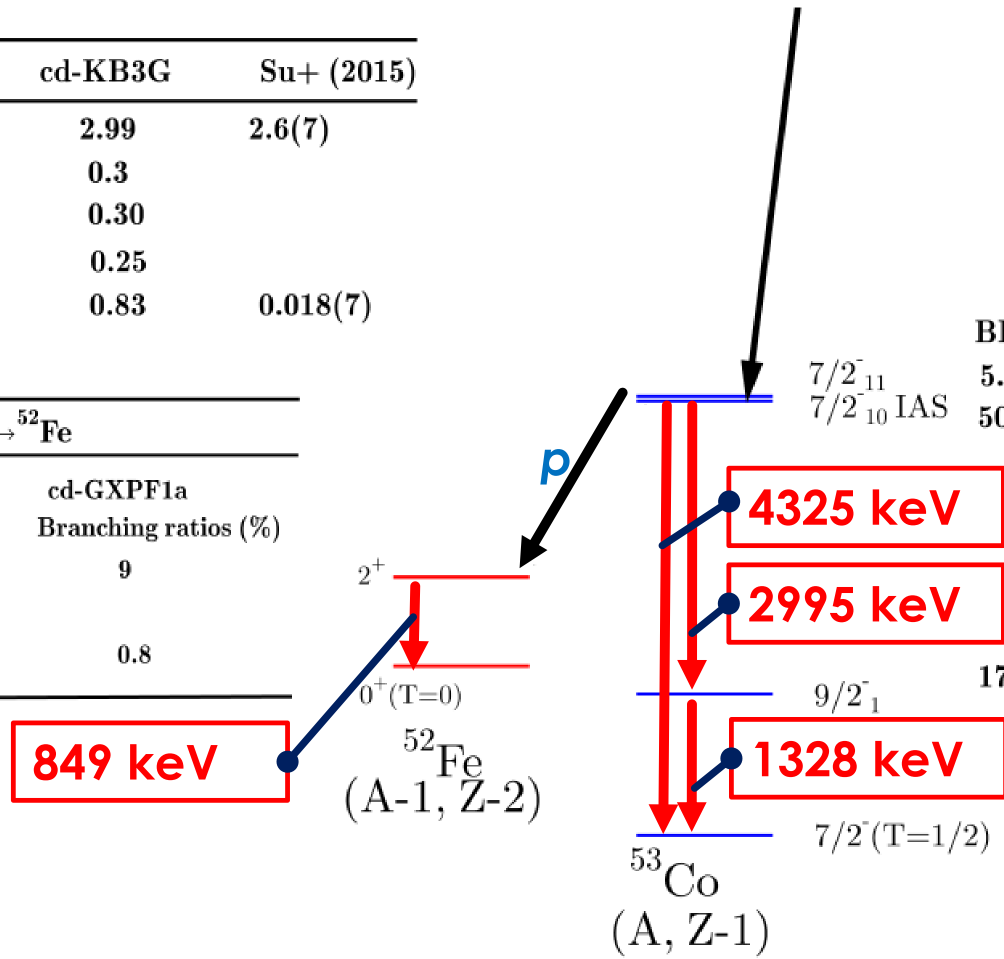
β-delayed proton emissions

$^{53}Ni \rightarrow {}^{53}Co \rightarrow {}^{52}Fe$

	cd-GXPF1a	cd-KB3G	Su+ (2015)
B(F)	2.98	2.99	2.6(7)
Iso. mix. [%]	0.5	0.3	
Γ_γ [eV]	0.36	0.30	
Γ_p [eV]	0.03	0.25	
Γ_p/Γ_γ	0.08	0.83	0.018(7)

$^{53}Co^{i} \rightarrow {}^{52}Fe$	
Su+ (2015) I_p(%)	cd-GXPF1a Branching ratios (%)
1.8	9
--	0.8

	Su+ (2015)		cd-GXPF1a	
	BR (%)	log ft	BR (%)	log ft
$7/2^-_{11}$	5.8(7)	4.28(6)	1.4	4.95
$7/2^-_{10}$ IAS	50(11)	3.36(10)	65.8	3.30
$9/2^-_1$	17(8)	4.51(21)	2.5	5.35



YHL & N. A. Smirnova calculated for J. Su+ (PLB 756, 323)

Summary & Perspective

- Most of the partial decay scheme of *sd*-shell precursors can be described with the newly constructed isospin non-conserving Hamiltonian.
- Without nuclear-origin isospin symmetry breaking force, we can still describe some partial decay scheme of *pf*-shell precursors. Will inclusion of nuclear-origin isospin symmetry breaking force improve the calculation?
- USD/USDB is widely used in the study of neutron-rich nuclei. Thomas-Ehrman shift may cause the change of configuration in wave functions, but is not considered in USD/USDB, (and maybe also GXPF1).
- Evolution of the SPE of 1s1/2, and of TBME involving 1s1/2, and 1s1/2-0d5/2 orbits are not considered for the proton-rich side.

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Thank you…