The Isospin-Forbidden Proton Emission of Proton-Rich *sd*- and *pf*-Shell Nuclei

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- **Background**

  Physics motivation

- **Shell-model isospin non-conserving (INC) Hamiltonian**

  Construction of INC Hamiltonian

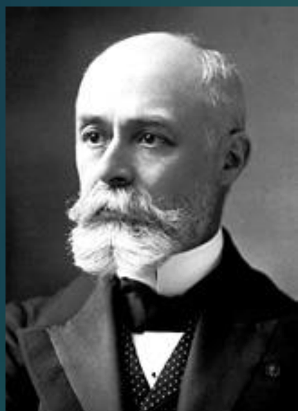
- **β-delayed isospin-forbidden proton emission**

  sd-shell nuclei: $^{25}\mathrm{Si}$, $^{33}\mathrm{Ar}$, $^{37}\mathrm{Ca}$,

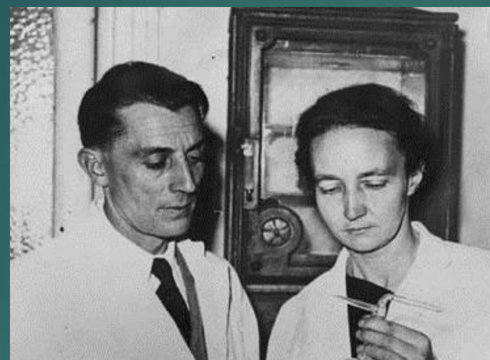
  pf-shell nuclei: $^{53}\mathrm{Ni}$, $^{56}\mathrm{Zn}$

- **Summary and Perspectives**

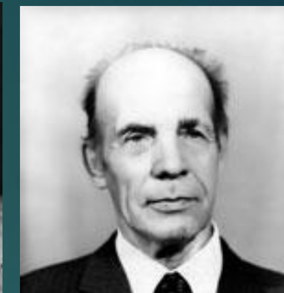
Physics motivation
Discovery of radioactivity



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



F. Jouliot and I. Curie
β^{+}



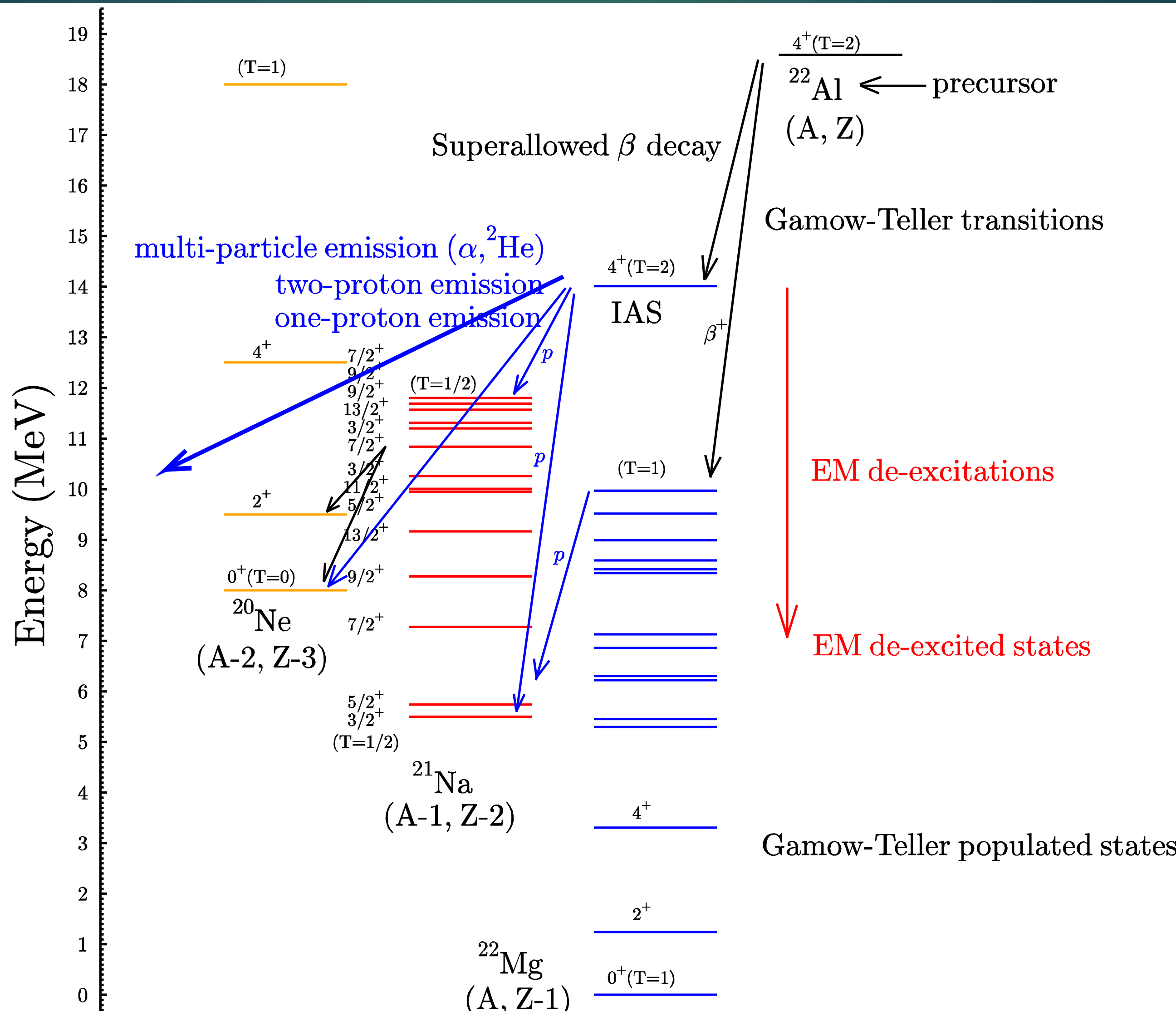
G.N. Flerov and K.A. Petrzhak
spontaneous fission

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

M. Pfutzner:
$2p$

S. Hofmann:
p

Physics motivation
β-delayed proton emissions



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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Solve eigenvalue prob.

Nucl. wave function, ψ_{TT}

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:

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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.

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

Construction of INC Hamiltonian

Isospin Conserving Nucl. Hamiltonian

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

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2. Jastrow-type SRC:
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   - b. CD-Bonn
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$$\left\langle \psi_{TT_Z}\middle|\hat{V}_{INC}\middle|\psi_{TT_Z}\right\rangle = E^{(0)}(\alpha,T) + E^{(1)}(\alpha,T)T_Z + E^{(2)}(\alpha,T)\left(3T_Z^2 - T(T+1)\right)$$

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

Solve the eigenproblem for an INC Hamiltonian

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

Isospin non-conserving Hamiltonian

***sd*-shell nuclei**

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

***pf*-shell nuclei**

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

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

Isospin symmetry & Isospin admixed states

Isospin symmetry states,

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

Isospin admixed states,

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

Isobaric analogue state of 53Co with isospin symmetry,

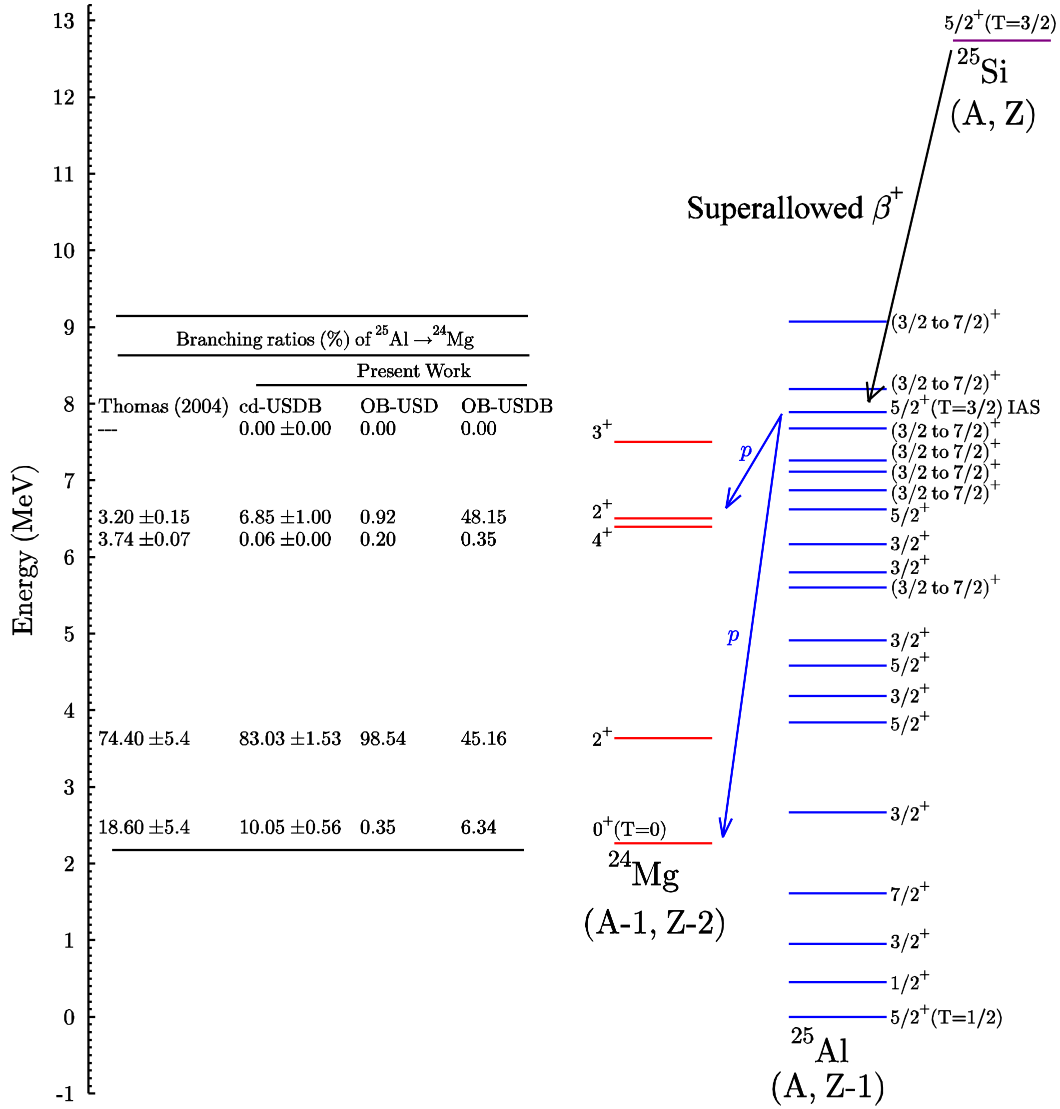
$$\left|7/2^-, \mathrm{IAS}_{T=3/2}\right\rangle = \sum_i \alpha_i \left|7/2^-, T=3/2\right\rangle$$

Isobaric analogue state of 53Co with admixed isospin,

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

β-delayed proton emissions

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



Branching ratios (%) of $^{25}Al \rightarrow {}^{24}Mg$

Thomas (2004)	Present Work: cd-USDB	OB-USD	OB-USDB
---	0.00 ±0.00	0.00	0.00
3.20 ±0.15	6.85 ±1.00	0.92	48.15
3.74 ±0.07	0.06 ±0.00	0.20	0.35
74.40 ±5.4	83.03 ±1.53	98.54	45.16
18.60 ±5.4	10.05 ±0.56	0.35	6.34

Branching ratios (%) and log(ft) of $^{25}Si \rightarrow {}^{25}Al$

	Exp. [Thomas (2004)] Br(%)	log(ft)	Theo. [cd-USDB] Br(%)	log(ft)
$(3/2\ to\ 7/2)^+$	0.21 ±0.04	4.32 ±0.10		
$(3/2\ to\ 7/2)^+$	1.2 ±0.2	4.12 ±0.09		
$5/2^+$(T=3/2) IAS	12.8 ±0.8	3.25 ±0.03	16.60	3.30
$(3/2\ to\ 7/2)^+$	0.34 ±0.06	4.94 ±0.09		
$(3/2\ to\ 7/2)^+$	0.5 ±0.1	5.13 ±0.13		
$(3/2\ to\ 7/2)^+$	3.7 ±0.2	4.17 ±0.03		
$(3/2\ to\ 7/2)^+$	0.6 ±0.1	5.56 ±0.11		
$5/2^+$	0.16 ±0.07	5.73 ±0.34	0.42	5.34
$3/2^+$	0.32 ±0.06	5.60 ±0.10	0.03	6.50
$3/2^+$	1.7 ±0.2	5.00 ±0.06	0.34	5.51
$(3/2\ to\ 7/2)^+$	1.0 ±0.6	4.65 ±0.71	0.21	5.93
$3/2^+$	0.6 ±0.2	5.76 ±0.18	0.78	5.38
$5/2^+$	3.2 ±0.3	5.11 ±0.04	2.79	5.15
$3/2^+$	2.9 ±0.3	5.26 ±0.05	1.54	5.52
$5/2^+$	0.4 ±0.1	6.21 ±0.18	0.05	7.14
$3/2^+$	4.8 ±0.3	5.43 ±0.03	8.40	5.17
$7/2^+$	15 ±3	5.17 ±0.12	13.56	5.22
$3/2^+$	26 ±4	5.05 ±0.08	20.17	5.16
$1/2^+$				
$5/2^+$(T=1/2)	25 ±7	5.25 ±0.17	22.34	5.34

β-delayed proton emissions of sd-shell nuclei

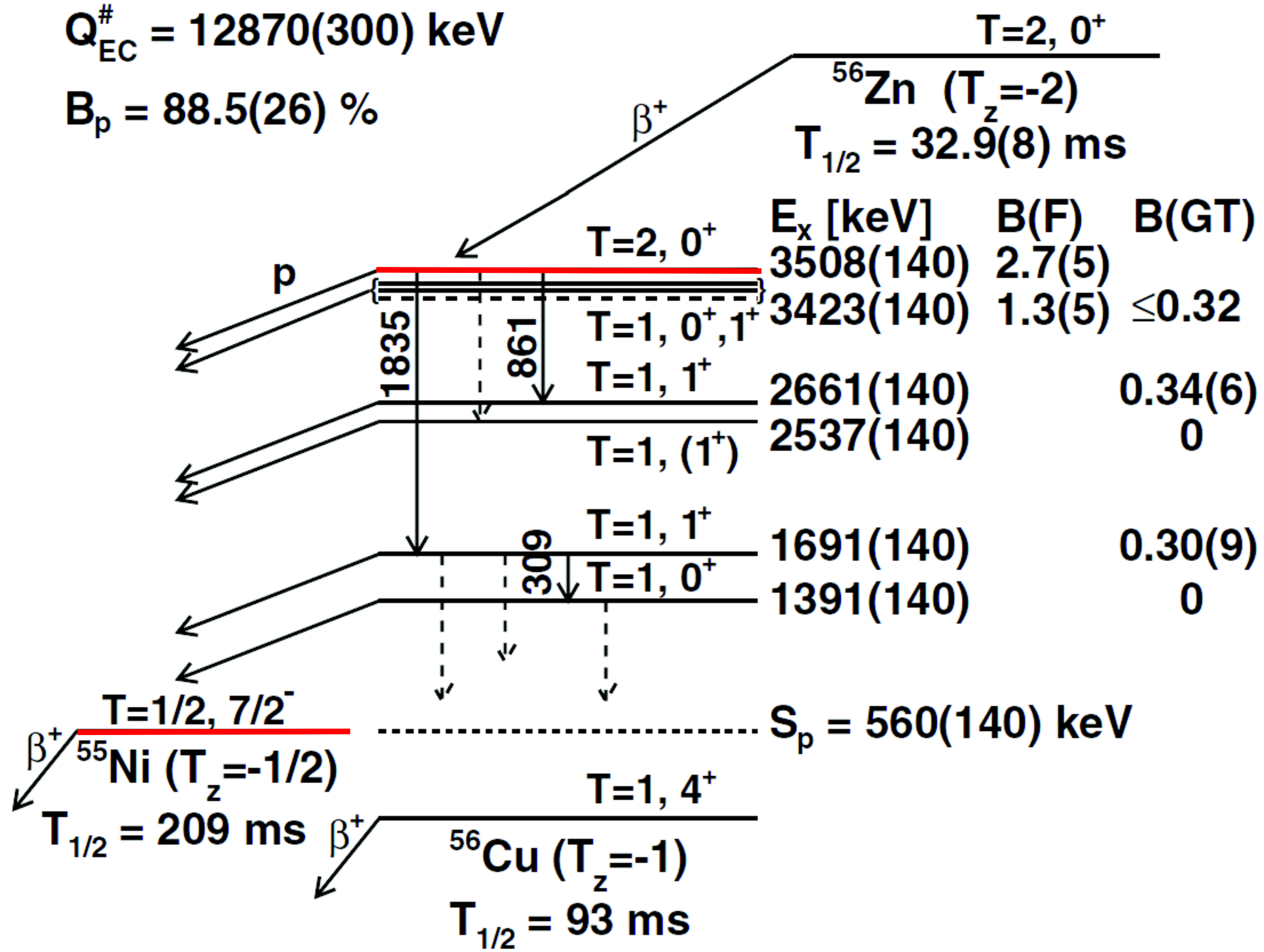
$${}^{A}_{Z}D \rightarrow {}^{A}_{Z-1}E \rightarrow {}^{A-1}_{Z-2}F$$

J^{π}	E_{exc} (MeV) E_{exp}	E_{theo}	$E_{c.m.}$ (MeV)	Γ_p (keV)	Branching ratios (%) Present work	Exp.
^{24}Mg						Thomas (2004)
0^+	0.000	0.000 (0)	5.624 (3)	11.28 (71)	10.05 (56)	18.60
2_1^+	1.369	1.495 (1)	4.252 (2)	94.19 (1178)	83.03 (153)	74.40
4_1^+	4.123	4.347 (4)	1.489 (7)	0.07 (1)	0.06 (0)	3.74
2_2^+	4.238	4.116 (5)	1.377 (6)	7.58 (61)	6.85 (100)	3.20
3_1^+	5.235	5.060 (5)	0.389 (5)	0.00 (0)	0.00 (0)	—
^{28}Si						Vieira (1979)
0^+	0.000	0.000	5.893	1.874×10^{-3}	1.113	86.4 (28)
2_1^+	1.779030 (11)	1.962	4.114	1.659×10^{-1}	98.509	12.7 (7)
4_1^+	4.61786 (4)	4.611	1.275	6.369×10^{-4}	0.378	0.9 (3)
0_2^+	4.97992 (8)	4.807	0.913	5.003×10^{-8}	0.000	—
^{32}S						Borge (1987)
0^+	0.000	0.000	3.272	1.210×10^{-3}	99.593	observed
2_1^+	2.23057 (15)	2.139	1.041	4.939×10^{-6}	0.407	very low intensity
^{36}Ar						Sextro (1974)
0^+	0.000	0.000	3.192	6.410×10^{-4}	96.035	observed
2_1^+	2.23057 (15)	1.797	1.222	2.647×10^{-5}	3.965	—

[1]Present calculations use INC Hamiltonian composed of USDB, V_{coul}(UCOM), and V_0(USDB).
[2]The error bars are provided from the standard deviation based on different SRC schemes.
[3]The E_{exp} of 3_1^+ is quoted from NNDC online.
[4]Level scheme of each first column belongs to the respective secondary daughter nucleus.

β-delayed proton emissions

$^{56}Zn \rightarrow {}^{56}Cu \rightarrow {}^{55}Ni$



Orrigo+, PRL 112, 222501

β-delayed proton emissions

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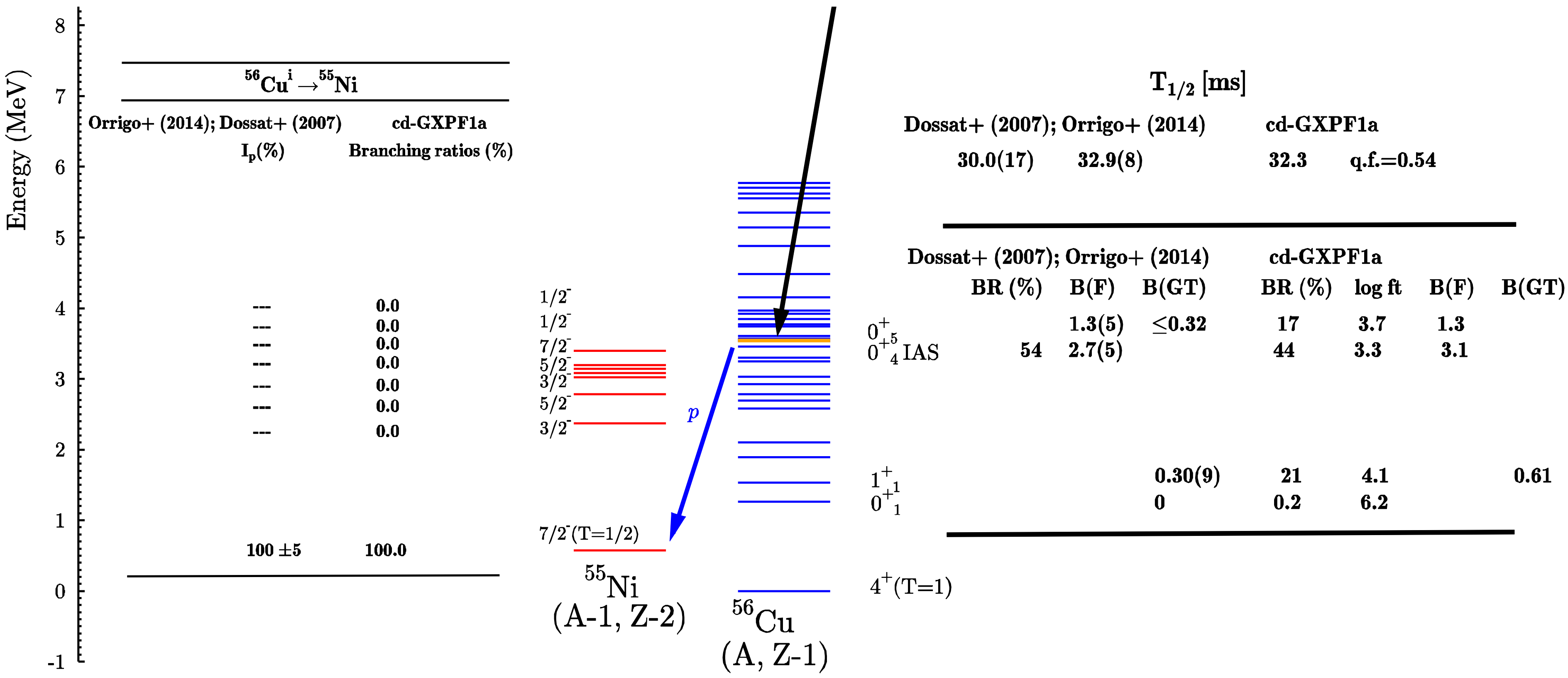
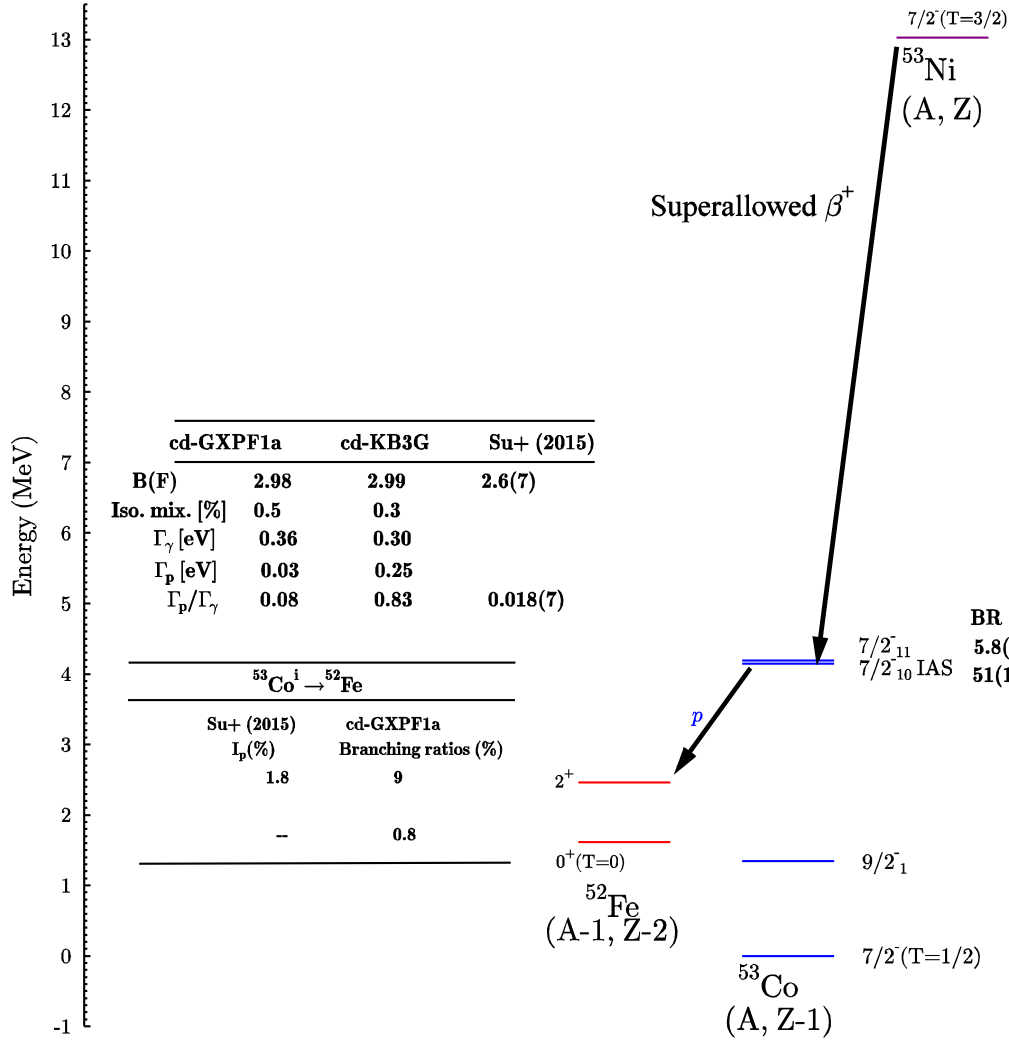


YHL, Smirnova (preliminary results)

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	1.4	4.95
$7/2^-_{10}$ IAS	51(11)	3.35	65.8	3.30

YHL, Smirnova (calculated for Jun SU *et al.*, submitted to PRL)

Summary & Perspective

- Partial decay scheme of isospin-forbidden proton emission can be a sensitive probe to isospin non-conserving microscopic approaches.
- We have obtained a set of theoretical partial decay schemes with branching ratios comparable with experimental data, e.g. $^{25}\mathrm{Si}$, $^{33}\mathrm{Ar}$, $^{37}\mathrm{Ca}$, $^{53}\mathrm{Ni}$, $^{56}\mathrm{Zn}$. However, some precursors are not well described.
- We need more fine tune on isospin non-conserving Hamiltonian with more accurate nuclear origin isospin symmetry breaking $\hat{V}_0^{T=1}$, e.g. χ-EFT potential (excluding Coulomb), etc.
- Construction/Fine tuning of INC Hamiltonians of *psd*, *sdpf*, *pf*-shell nuclei is in progress.
- Other β–delayed precursors of *sd* and *pf*- shell, and applications of INC Hamiltonian will be calculated.

Thank you…