Microscopic description of the two-proton radioactivity

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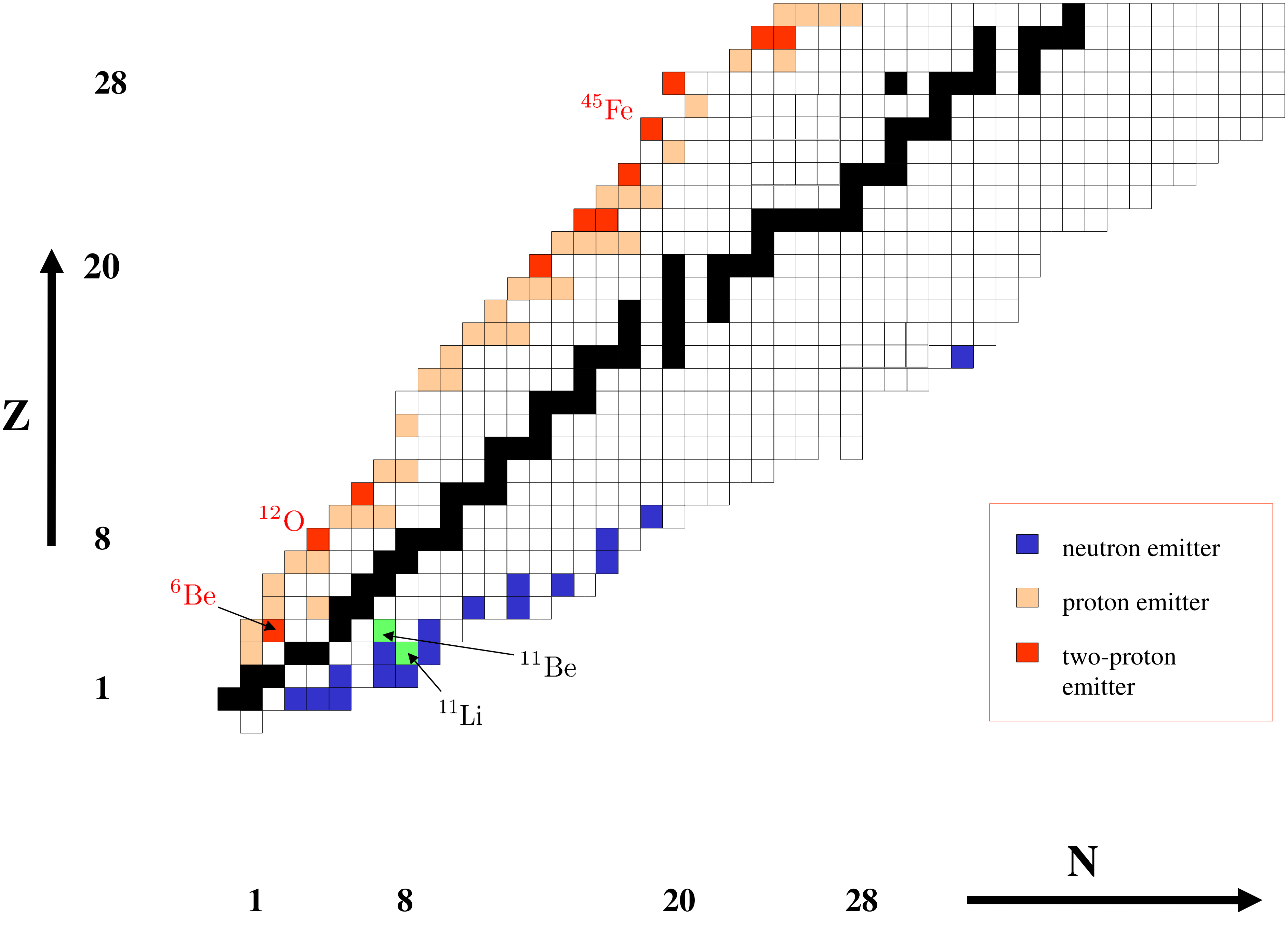


28
20
Z
8
1
^{45}Fe
^{12}O
^{6}Be
^{11}Be
^{11}Li
neutron emitter
proton emitter
two-proton emitter
1
8
20
28
N

Closed quantum system

Multiconfigurational Shell Model (1953)

✔ description of nuclei in the “valley of stability”

✔ all nucleons are in bound orbits

Open quantum system

Continuum Shell Model (CSM): (1976)

✔ shell model with the real energy continuum

✔ realistic applications with SMEC (1999)

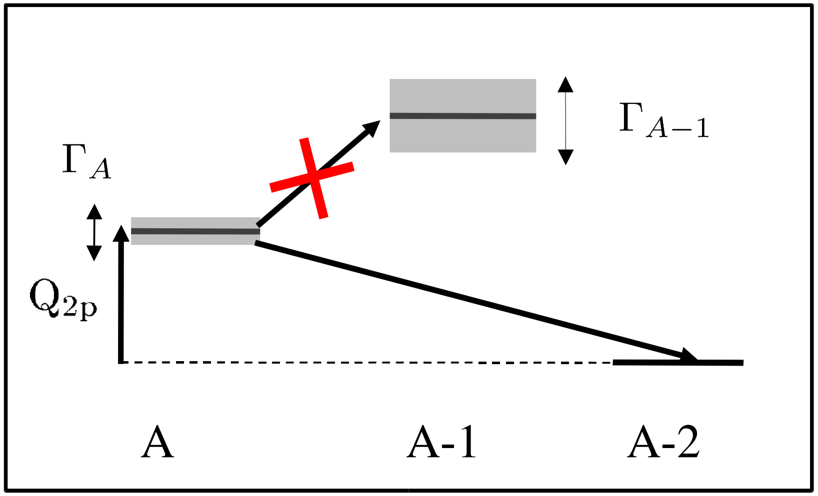
Gamow Shell Model (2002)

✔ shell model with the complex energy continuum

✔ no restriction on the number of nucleons in the continuum

Searching for two-proton radioactivity . . .

✔ theoretical prediction by Goldansky (1960)

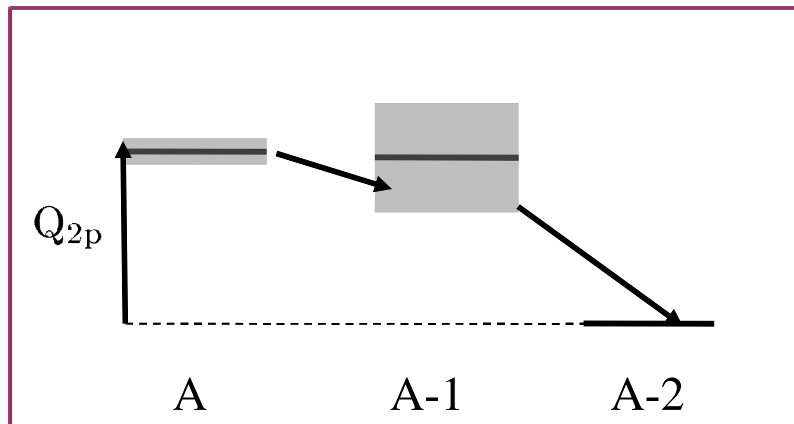


$$E_{A-1} - \frac{\Gamma_{A-1}}{2} > E_A + \frac{\Gamma_A}{2}$$

- emission of two protons with same energy ?
- « diproton » emission ?

✔ first experiments : ^{6}Be , ^{12}O decays . . .

interpretation of experimental results by **sequential / democratic emission**



✔ recent observation of two protons emission : ^{18}Ne (ORNL 2001) , ^{45}Fe , ^{54}Zn . . .

- ✗ Shell Model Embedded in the Continuum (SMEC)

- ✗ Limiting cases of two-proton decay :

  $\longrightarrow$ direct emission

  $\longrightarrow$ sequential emission

- ✗ Applications :

  $\longrightarrow$ decay from excited state : $^{18}\mathrm{Ne}$

  $\longrightarrow$ decay from ground state: $^{45}\mathrm{Fe}$, $^{48}\mathrm{Ni}$, $^{54}\mathrm{Zn}$

Shell Model Embedded in the Continuum (SMEC)

- division of Hilbert space in different subspaces:

"standard shell model" space → $\mathcal{Q} = [A]$

$\mathcal{P} = [A-1] \otimes [1]$

$\mathcal{T} = [A-2] \otimes [2]$

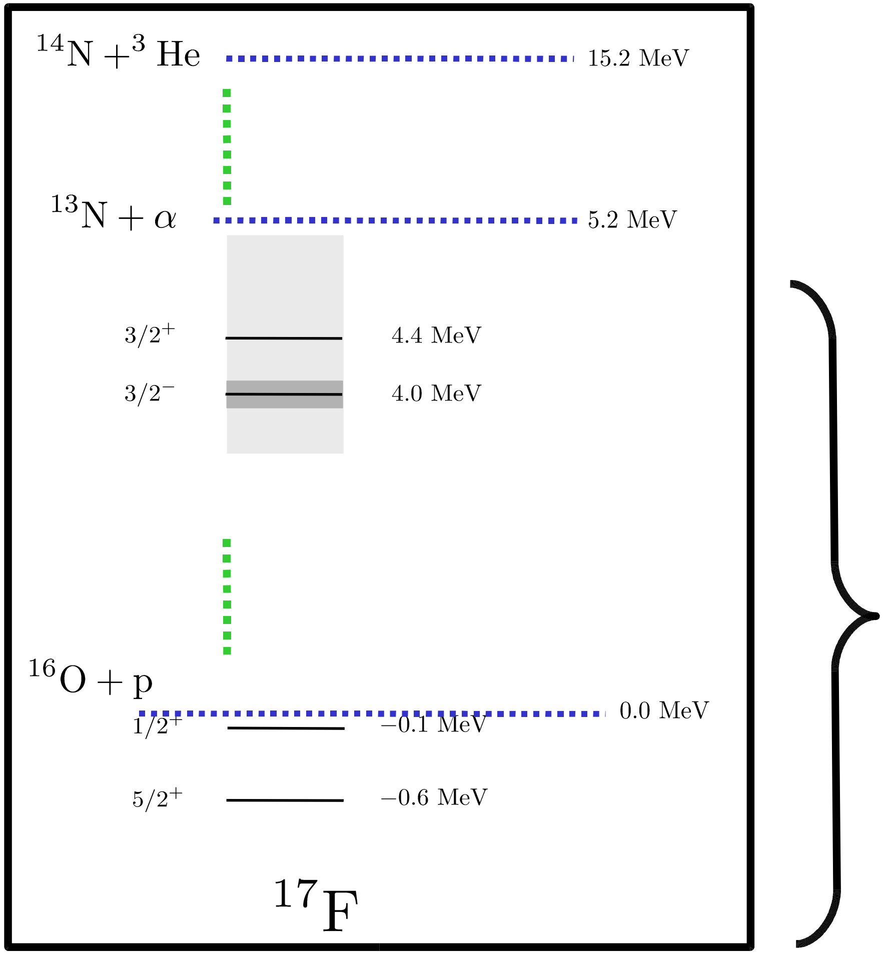
$\cdots$

nucleons in (quasi) bound states

nucleon(s) in continuum states

- completeness relation: $Q + P + T + \ldots = I_d$

$$\longrightarrow \quad |\Psi\rangle = |\Psi_Q\rangle + |\Psi_P\rangle + |\Psi_T\rangle + \ldots$$



$$Q + P = I_d$$

✗ two-proton decay study →

$$Q + P + T = I_d$$

$$H = H_{QQ} + H_{PP} + H_{TT} + H_{QP} + H_{QT} + H_{PQ} + \ldots$$

$\underbrace{H_{QQ} + H_{PP} + H_{TT}}$ unperturbed hamiltonian

$\underbrace{H_{QP} + H_{QT} + H_{PQ} + \ldots}$ coupling between subspaces

- $H_{QQ} \equiv H_{SM}$: " standard" shell model effective interaction

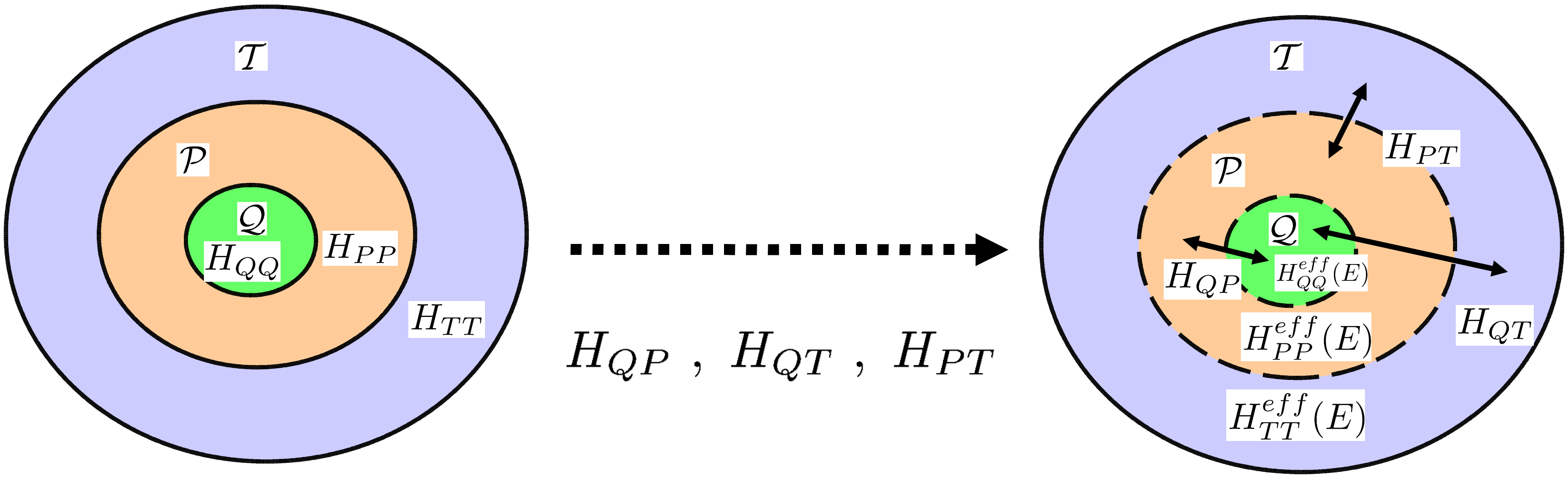
- $H_{PP} = P \left[\sum_i h_i + \sum_{i<j} V_{ij}^{res} \right] P$

- $H_{TT} = T \left[\sum_i h_i + \sum_{i<j} V_{ij}^{res} \right] T$

H_{PP}, H_{TT}: one-body potential + two-body residual interaction

- H_{QP} , H_{QT} , H_{PT} . . . $\longrightarrow \sum_{i<j} V_{ij}^{res}$

• effective hamiltonian $H_{QQ}^{eff}(E)$, $H_{PP}^{eff}(E)$, $H_{TT}^{eff}(E)$:



$$H_{QQ} \quad \longrightarrow \quad H_{QQ}^{eff}(E) = f(H_{QQ}, H_{PP}, H_{TT}, H_{QP}. \ldots)$$

$$H_{PP} \quad \longrightarrow \quad H_{PP}^{eff}(E) = g(H_{QQ}, H_{PP}, H_{TT}, H_{QP}. \ldots)$$

$$H_{QQ}|\Phi_{SM}^{i}\rangle = E_i|\Phi_{SM}^{i}\rangle \quad \longrightarrow \quad \begin{cases} H_{QQ}^{eff}(E)|\Psi_Q^k\rangle = E_k(E)|\Psi_Q^k\rangle \\ |\Psi_Q^k\rangle = \sum_i c_i|\Phi_{SM}^{i}\rangle \end{cases}$$

real energy

"mixing"

- scattering solution :

$(Q + P = I_d)$

$$|\Psi\rangle = |\xi\rangle + (Q + G_P^{(+)}(E)H_{PQ})\frac{1}{E - H_{QQ}^{eff}(E)}H_{QP}|\xi\rangle$$

non-resonant solution

resonant solution due to coupling

$$(E - H_{PP})|\xi\rangle = 0$$

- $H_{QQ}^{eff}(E)$ with full coupling :

Green functions

$$H_{QQ}^{eff}(E) = H_{QQ} + H_{QP}G_P^{(+)}(E)H_{PQ} + [H_{QT} + H_{QP}G_P^{(+)}(E)H_{PT}]\tilde{G}_T^{(+)}(E)[H_{TQ} + H_{TP}G_P^{(+)}(E)H_{PQ}]$$

coupling with one particle in the continuum

coupling with two particles in the continuum

• diagonalisation of $H_{QQ}^{eff}(E)$:

source terms in P and T

$$\langle\Phi_{SM}^{i}|H_{QQ}^{eff}(E)|\Phi_{SM}^{j}\rangle = E_{SM}^{i}\delta_{i,j} + \langle w_i|\omega_j^{(+)}\rangle + \langle w_i^{T}|\omega_j^{T,(+)}\rangle$$

continuation of SM state in P and T

$\mathcal{P}$ space

$$|w_i\rangle = H_{PQ}|\Phi_{SM}^{i}\rangle$$

$$|\omega_j^{+}\rangle = G_P^{+}(E)|w_j\rangle$$

$\mathcal{T}$ space

$$|w_i^{T,+}\rangle = (H_{TQ} + H_{TP}G_P^{+}(E)H_{PQ})|\Phi_{SM}^{i}\rangle$$

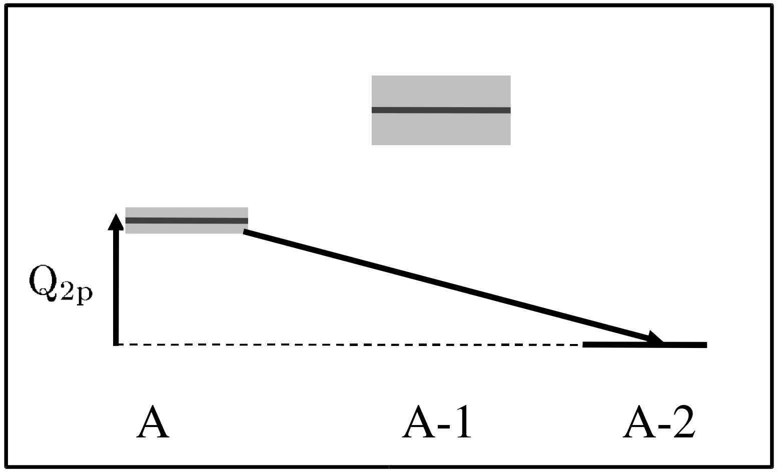
$$|\omega_j^{T,+}\rangle = \tilde{G}_T^{+}(E)|w_j^{T}\rangle$$

Two limiting cases of the two-proton emission

I. <u>Direct emission</u>:

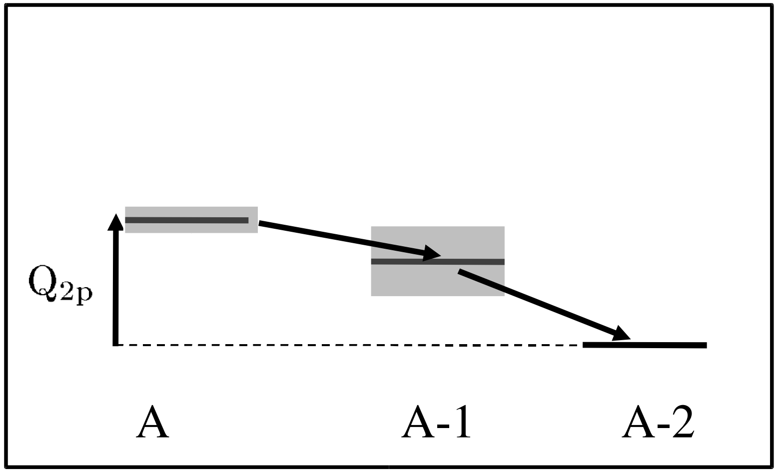
$$\{H_{QP}\ ,\ H_{PT} \to 0\}$$

$$H_{QQ}^{eff}(E) = H_{QQ} + H_{QT}G_T^+(E)H_{TQ}$$



I. <u>Indirect emission</u>:

$$\{H_{QT}\} \to 0$$



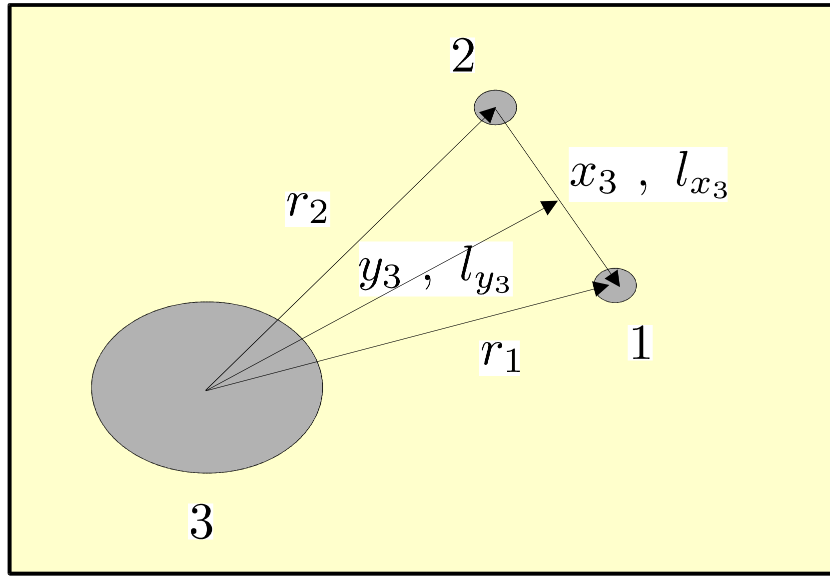
$$H_{QQ}^{eff}(E) = H_{QQ}+H_{QP}G_P^+(E)H_{PQ}+[H_{QP}G_P^+(E)H_{PT}]\tilde{G}_T^+(E)[H_{TP}G_P^+(E)H_{PQ}]$$

Direct emission

$$|w_i^T\rangle = H_{TQ}|\Phi^i_{SM}\rangle$$

$$|\omega_j^{T,+}\rangle = G_T^+(E)|w_j^T\rangle$$

expansion in the basis of the hyperspherical harmonics $\mathcal{Y}_{KL}^{l_{x_3},l_{y_3}}(\Omega_5)$



$$\sum_{c'}(E - H_{cc'}(\rho))\omega_{j,c'}^{T,(+)}(\rho) = w_{j,c}(\rho)$$

channel $c = (t, K, (l_{x_3}, l_{y_3})^L, S; J_{2p}, J)$

hypervariables
$$\rho = \sqrt{x_3^2 + y_3^2}$$
$$\alpha = \arctan\left(\frac{x_3}{y_3}\right)$$

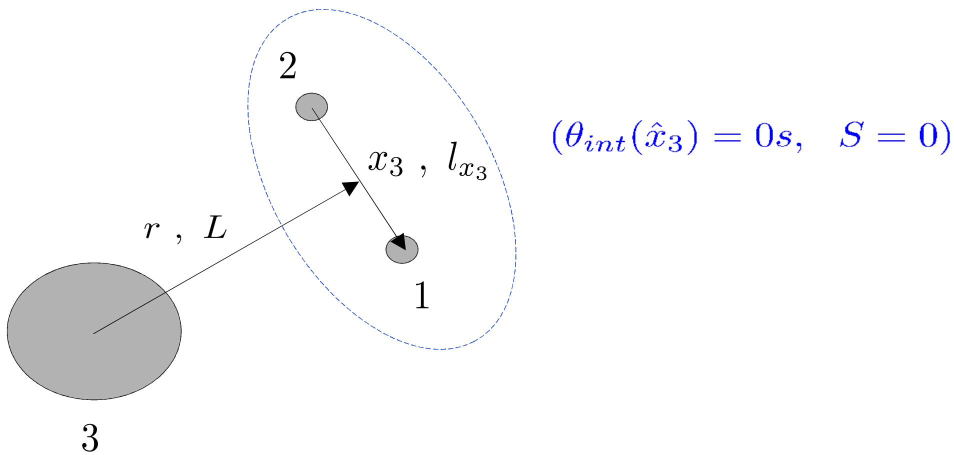
V_{ij}^{res} (zero range) $\longrightarrow$ $H_{cc'}(\rho) \sim -\dfrac{1}{\rho^3}$, $\rho \to 0$

V_{ij}^{res} (finite-range) $\longrightarrow$ $H_{cc'}(\rho)$ non-local

Simplified solution for the direct emission:

Two-step emission process:

1. emission of ^{2}He
2. disintegration of ^{2}He by the final state interaction



• expansion of the source term in the harmonic oscillator basis:

$$w^T_{i,c}(r) = \sum_n \left(\frac{A}{A-2}\right)^{(2n+L)/2} u_{n,L}(r)\langle t_{SM}, 0s, L, S=0, n|V_{res}|\Phi^i_{SM}\rangle$$

'recoil' of the daughter nucleus

harmonic oscillator function

• calculation of $|\omega_i^{T,(+)}\rangle$:

$$\left(E - U - T_{cl}\left[H_{int}^{A-2} + \frac{P^2}{2\mu} + V_0\right]T_{cl}\right)|\omega_{i,U}^{T,(+)}\rangle = |w_i^T\rangle$$

internal energy of the cluster

projection operator on the subspace containing the continuum states of $P^2/2\mu + V_0$

• disintegration of ^{2}He by the final state interaction:

→ final state interaction is taken into account by the density of state $\rho(U)$

$$\Gamma = \int_0^{Q_{2p}} \Gamma(U)\rho(U)dU$$

$$\Gamma(U) = -2Im[\langle\omega_{i,U}^{T,(+)}|w_i^T\rangle]$$

I. Indirect emission: sequential mechanism

✗ two successive and independent emissions

$$H_{PP} = H_{Q'Q'} + p h_{seq} p$$

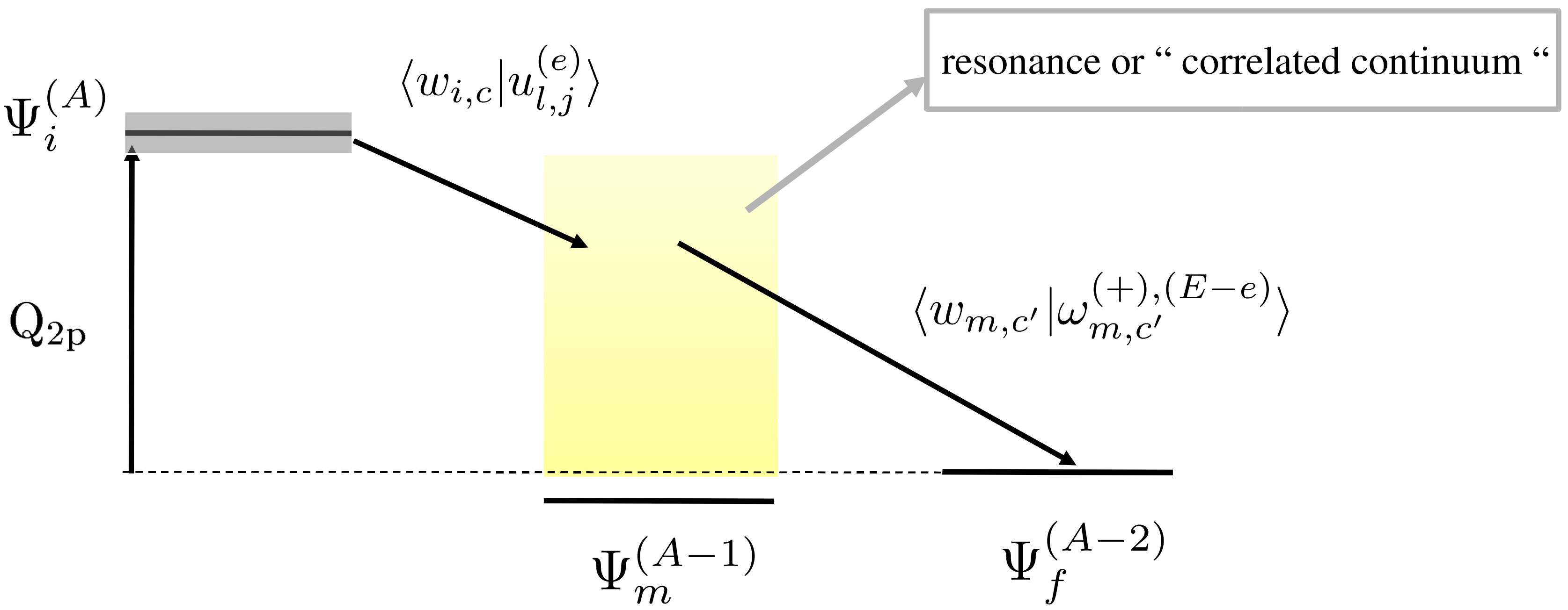
$$H_{TT} = H_{P'P'} + p h_{seq} p$$

$$H_{PT} = H_{Q'P'} \otimes I_d(A)$$

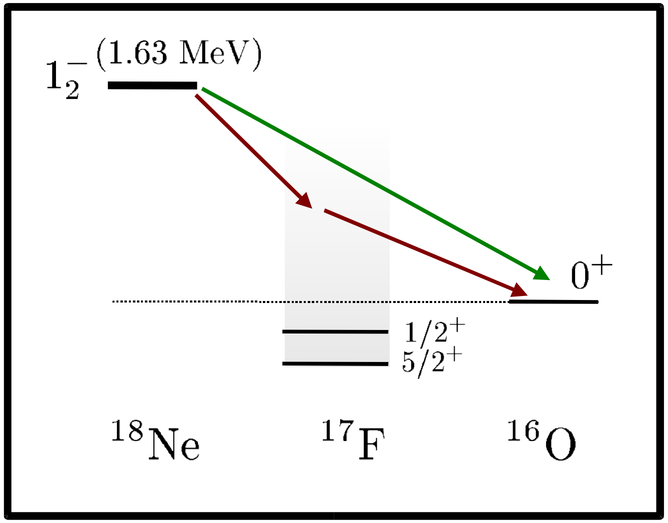
$\mathcal{Q}' = [A-1]$

$\mathcal{P}' = [A-2] \otimes [1]$

h_{seq} : one-body potential

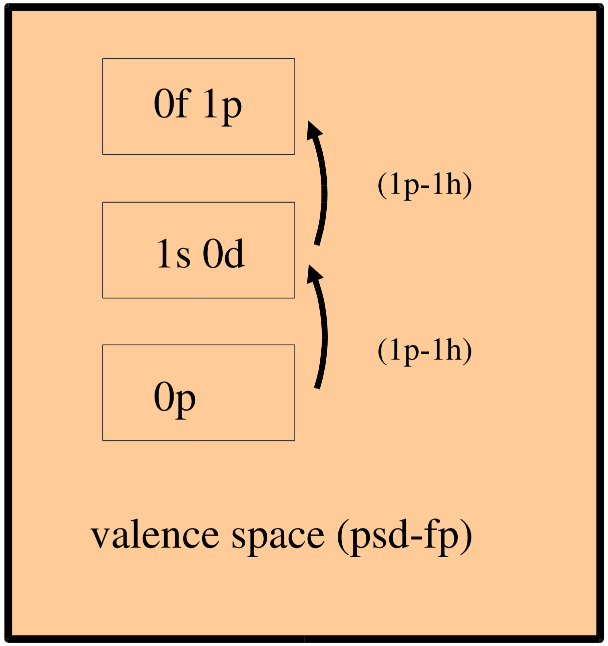


^{18}Ne decay



$$\Gamma_{dip}^{"exp"} = 21 \pm 3 \text{ eV}$$

$$\Gamma_{dem}^{"exp"} = 57 \pm 6 \text{ eV}$$

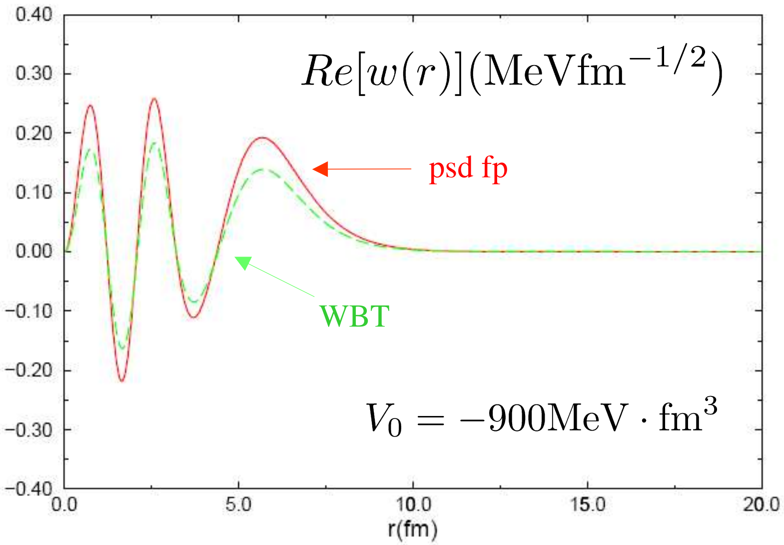


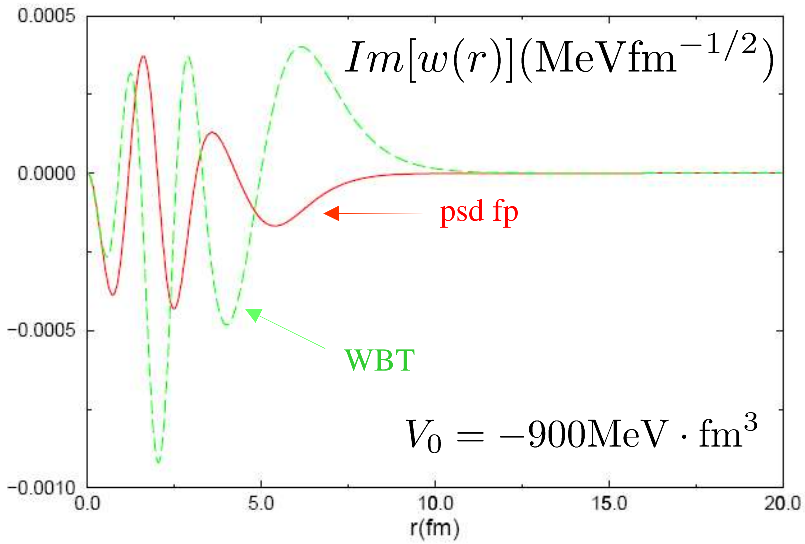
$H_{QQ} \equiv H^{SM}$: shell model interaction WBT , psd-fp

H_{QP} , H_{QT} ... : $V_{res} = V_0[\alpha + (1-\alpha)P^\sigma]\delta(\mathbf{r_1} - \mathbf{r_2})$ (Wigner Bartlett)

•1p proton decay channel opened: mixing of SM states ⟶ $|1^-_{2,mix}\rangle$

diproton decay





$$\Gamma_{dip}^{"exp"} = 21 \pm 3 \text{ eV}$$

	Γ (eV) (with mixing)	Γ (eV) (no mixing)
psd fp	1.89	0.80
WBT	1.01	1.17

sequential decay

	Γ (eV) (with mixing)	Γ (eV) (no mixing)
psd fp	88.8	13.1
WBT	13.6	38.0

$$\Gamma^{"exp"}_{dem} = 57 \pm 6 \text{ eV}$$

✗ sequential decay mainly via the $1/2^+$ correlated continuum :

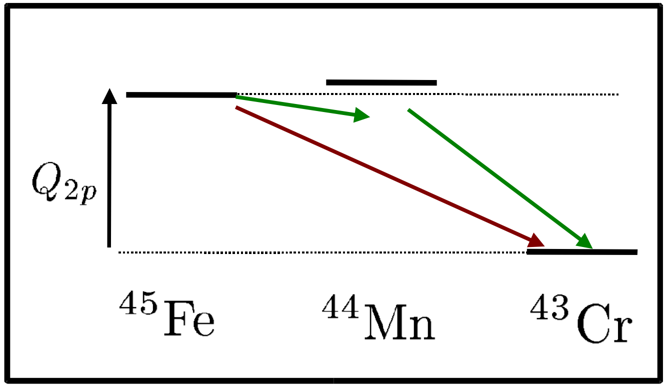
$$80.2\% \leq B^{1/2^+}_{\text{seq}} \leq 95.9\%$$

Structure of the $J^\pi = 1^-_2$ state

	(1s0d→0f1p)	(0p→1s0d)
psd fp	5.8%	8.5%
WBT	10.3%	21.2%

$$\Gamma_{dip}/\Gamma_{seq} < 8\%$$

^{45}Fe decay



- ✗ $Q_{2p} = 1.154(16)$ MeV
- ✗ $T^{exp}_{1/2} = 1.6^{+0.5}_{-0.3}$ ms
- ✗ uncertainty on the position of ^{44}Mn :

  $-24 \text{ keV} \leq Q_{1p} \leq +10 \text{ keV}$ (theory)

- IOKIN (shell model interaction) + Wigner Bartlett (V_{res})

Q_{2p} (MeV)	$T_{1/2}$ (ms) $Q_{1p} = -100$ keV	$T_{1/2}$ (ms) $Q_{1p} = 50$ keV
1.138	19.8	19.7
1.154	12.3	12.2
1.170	8.3	7.7

diproton decay

Q_{2p} (MeV)	$T_{1/2}$ (ms) $Q_{1p} = -100$ keV	$T_{1/2}$ (ms) $Q_{1p} = 50$ keV
1.138	258.6	171.2
1.154	164.9	109.9
1.170	106.6	71.4

sequential decay

- $T_{1/2}$ with mixing (previous slide) :

$$7.7 \leq T_{1/2}^{dip} \leq 19.8$$

$$49.0 \leq T_{1/2}^{seq} \leq 199.2$$

- $T_{1/2}$ without mixing :

diproton decay

Q_{2p} (MeV)	$T_{1/2}$ (ms)
1.138	21.4
1.154	13.3
1.170	8.3

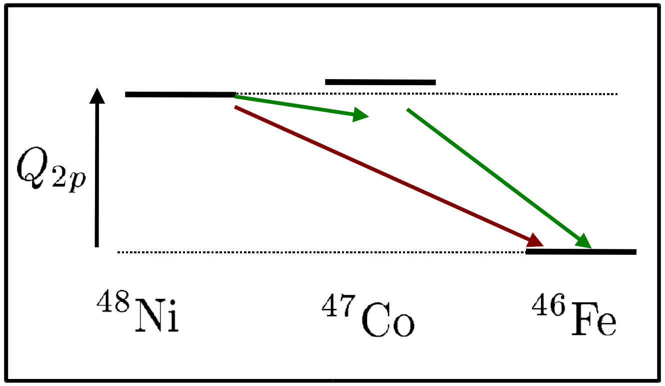
$$8.3 \leq T_{1/2}^{dip} \leq 21.4$$

sequential decay

Q_{2p} (MeV)	$T_{1/2}$ (ms) $Q_{1p} = -100$ keV	$T_{1/2}$ (ms) $Q_{1p} = 50$ keV
1.138	368.9	235.0
1.154	235.6	151.1
1.170	152.5	98.4

$$64.7 \leq T_{1/2}^{seq} \leq 273.2$$

^{48}Ni decay



- $Q_{2p} = 1.35(2)$ MeV
- $T^{exp}_{1/2} = 8.4^{+12.8}_{-7.0}$ ms

diproton decay

Q_{2p} (MeV)	$T_{1/2}$ (ms) IOKIN	$T_{1/2}$ (ms) KB3	$T_{1/2}$ (ms) GXPF1
1.33	10.3	11.4	12.3
1.35	6.2	6.9	7.4
1.37	3.7	4.2	4.5

$$3.7 \leq T^{dip}_{1/2} \leq 12.3$$

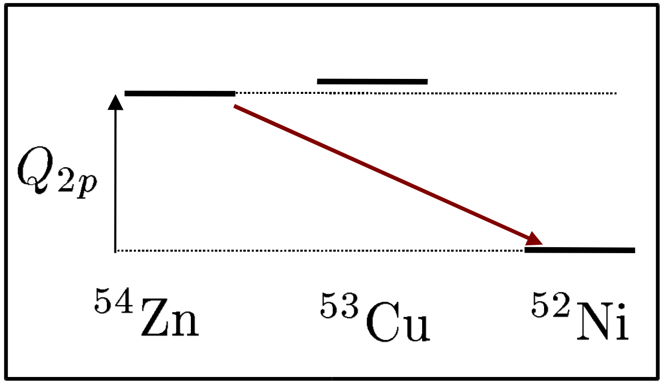
sequential decay

(IOKIN interaction)

Q_{2p} (MeV)	$T_{1/2}$ (ms) $Q_{1p} = -100$ keV	$T_{1/2}$ (ms) $Q_{1p} = 50$ keV
1.33	39.7	25.7
1.35	25.4	16.5
1.37	16.4	10.8

$$10.8 \leq T^{seq}_{1/2} \leq 39.7$$

^{54}Zn decay



- $Q_{2p} = 1.48(2)$ MeV
- $T_{1/2}^{exp} = 3.7^{+2.2}_{-1.0}$ ms

Q_{2p} (MeV)	$T_{1/2}$ (ms) KB3	$T_{1/2}$ (ms) GXPF1
1.46	27.3	22.18
1.48	16.9	13.8
1.50	10.6	8.67

diproton decay

$$8.67 \leq T_{1/2}^{dip} \leq 27.27$$

Conclusion

✔ Extension of the Shell Model Embedded in the Continuum (SMEC) with the two-particle continuum :

$\rightarrow$ direct decay with three body asymptotic

$\rightarrow$ cluster emission

$\rightarrow$ sequential emission

✔ Two-proton decay of the $J^{\pi} = 1_2^-$ state in $^{18}\mathrm{Ne}$ mainly via the correlated continuum of $^{17}\mathrm{F}$

✔ Diproton emission scenario for $^{48}\mathrm{Ni}$ $^{54}_{,}\mathrm{Zn}$ is compatible with experimental data

✔ Calculations with three-body asymptotic are in progress.