Theoretical investigations of nuclei far from stability

Kraków – Caen collaboration

Jacek Okołowicz[1] Marek Płoszajczak[2]

[1]Henryk Niewodniczański Institute of Nuclear Physics, Polish Academy of Sciences
Kraków, Poland

[2]Grand Accélérateur National d'Ions Lourds (GANIL), CEA/DSM - CNRS/IN2P3
Caen, France

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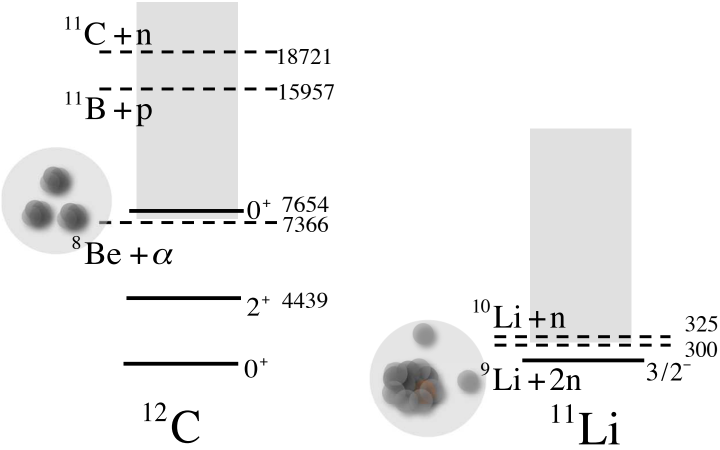
List of problems

Real-energy Continuum Shell Model (CSM):
Shell Model Embedded in the Continuum (SMEC)

1. Investigation of asymptotic normalisation constant (ANC) $\longrightarrow$ cross section for nucleon capture reaction
2. Influence of the continuum on (isospin) mirror nuclei energy levels
3. Systematics of binding energies of isotopic chains $\longrightarrow$ one- and two-nucleon separation energies
4. Exceptional points and their influence on near threshold states and scattering

Borromean systems ^{12}C and ^{11}Li



Formulation of the Continuum Shell Model

effective Hamiltonian

$$\mathcal{H}_{QQ}(E) = H_{QQ} + H_{QP} G_P^{(+)}(E) H_{PQ}$$

- H_{QQ} – closed system Hamiltonian ($H_{QQ} \equiv \hat{Q} H \hat{Q}$)
- $G_P^{(+)}(E)$ – Green function for single nucleon motion in $\mathcal{P}$
- E – energy of the nucleon (also total energy of the system)

eigenstates

$$\Phi_\alpha = \sum_i b_{\alpha\, i}\, \phi_i$$

- ϕ_i – eigenfunctions of H_{QQ}
- Φ_α – eigenfunctions $\mathcal{H}_{QQ}$
- $\{b_{\alpha\, i}\}$ – transformation matrix

Near threshold behaviour

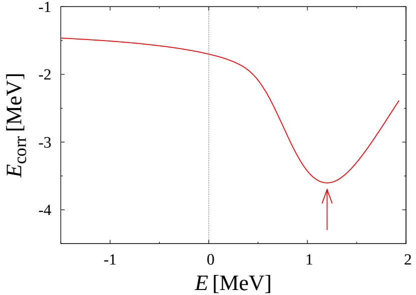
Two $J^{\pi} = 0^{+}$ states of nucleus $^{24}\mathrm{S}$
coupled to proton channel
$\left[{}^{23}\mathrm{P}(1/2^{+}) \oplus \pi s_{1/2}\right]^{0^{+}}$

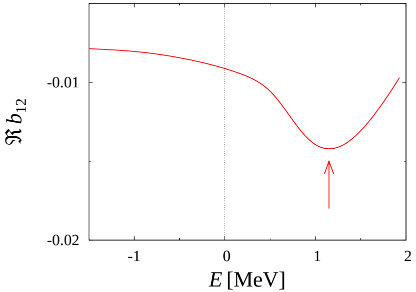
correction to eigenenergy

$$E_{\mathrm{corr}}(E) = \langle \Phi_\alpha | \mathcal{H}_{QQ}(E) - H_{QQ} | \Phi_\alpha \rangle$$

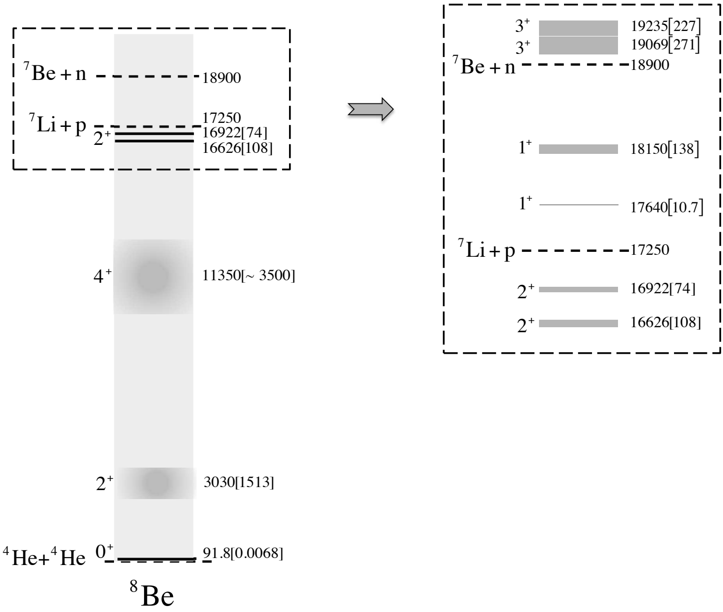
mixing of states

$$\Phi_\alpha = \sum_i b_{\alpha\, i}\, \phi_i$$





Near exceptional point in ^{8}Be



Exceptional points and exceptional point threads

- Complex extended SMEC

effective Hamiltonian

$$\mathcal{H}(E) = H_0 + H_1(E) \simeq H_0 + V_0^2 h(E)$$

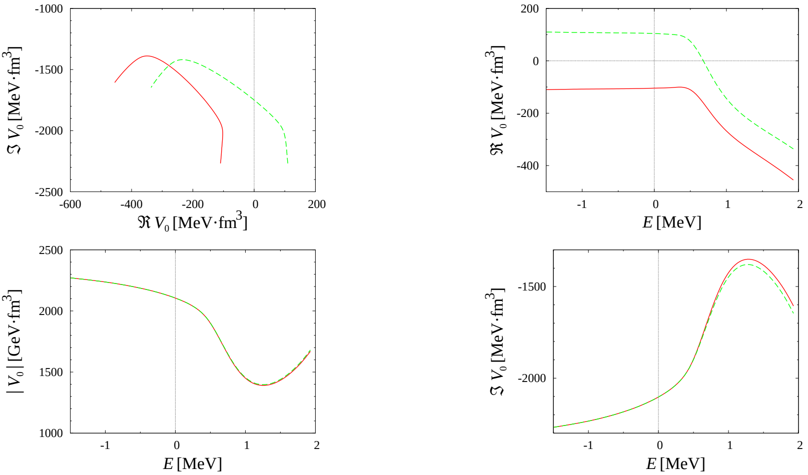
- V_0 – complex
- second equality exact for no channel couplings (or single channel)
- for every energy of the system there are:

conditions for an exceptional points

$$\frac{\partial^{(\nu)}}{\partial \mathcal{E}} \det \left[\mathcal{H}_{QQ}\left(E; V_0\right) - \mathcal{E}\, I \right] = 0, \qquad \nu = 0, 1$$

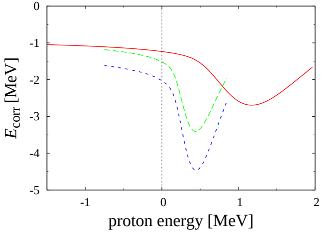
- the number of exceptional points is $M = 2\, n\, (n-1)$, where n is the number of states

Exceptional points threads



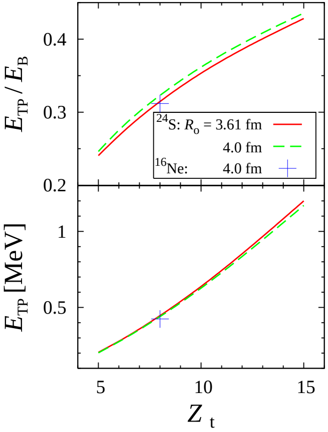
Two $J^{\pi} = 0^{+}$ states in ^{24}S coupled to scattering proton state

Other clusters (α, d, ^{3}He, ...)



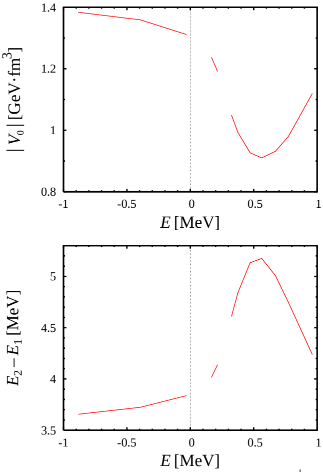
potential radius $R_0 = 4\,\text{fm}$,
$Z_1 \times Z_2 = 15$ – red curve

$Z_1 \times Z_2 = 8 \rightarrow \alpha + {}^{12}\text{C}$
radius $R_0 = 4\,\text{fm}$ – green curve
radius $R_0 = 3.61\,\text{fm}$ – blue curve

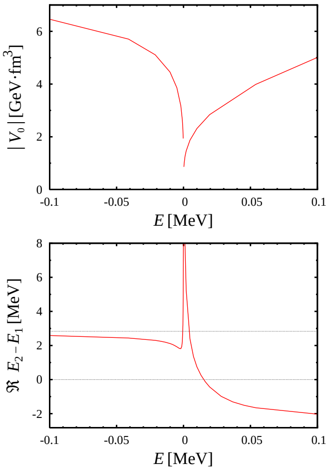


maximum E_{corr} vs. Z_t and R_0

Correlation of states spacing and EP threads



$$\left[{}^{15}\mathrm{F}(1/2^+) \oplus \pi s_{1/2}\right]^{0^+}$$



$$\left[{}^{15}\mathrm{C}(1/2^-) \oplus \nu p_{1/2}\right]^{0^+}$$

Two $J^\pi = 0^+$ states in ^{16}Ne / ^{16}C coupled to scattering states

Planned investigations

- Neutron and neutron clusters (di-neutron, tetraneutron) near threshold behaviour
- Comparison of different angular momentum ($\ell = 0$, 1, 2, ...) exceptional point threads fot proton and neutrons (breaking of isospin mirror symmetry)
- Continuum influence on nucleon transfer reactions (*eg* (d, p) reaction) $\rightarrow$ nearly bound and unbound final states