Transitions between rotational nuclear few-body states in the continuum

A.S. Jensen, D.V. Fedorov, Aarhus University, *Denmark*

E. Garrido, *IEM-CSIC, Madrid, Spain*

Krakow, September 2013

Cross sections after continuum to continuum γ-transitions: Properties of the ^{8}Be spectrum.

- ✓ Rotational character of the ^{8}Be spectrum
- ✓ Dependence on the α–α potential

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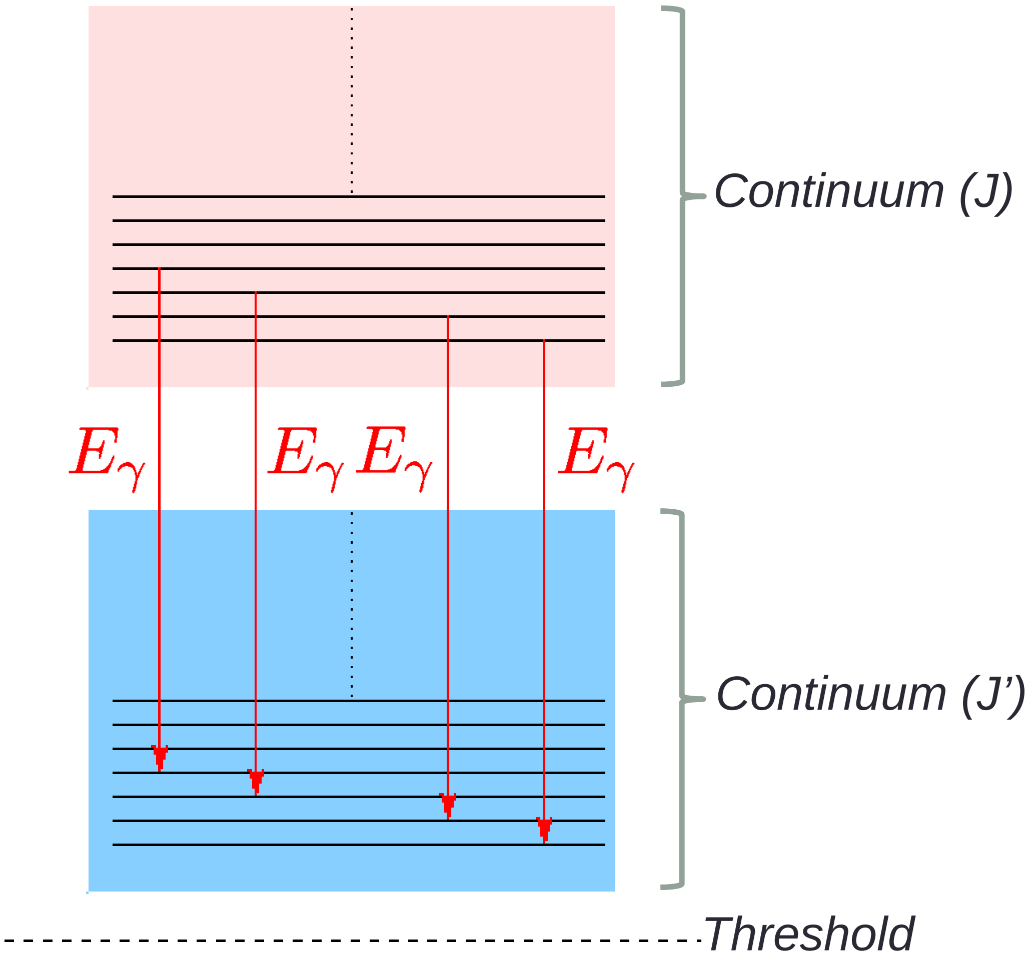

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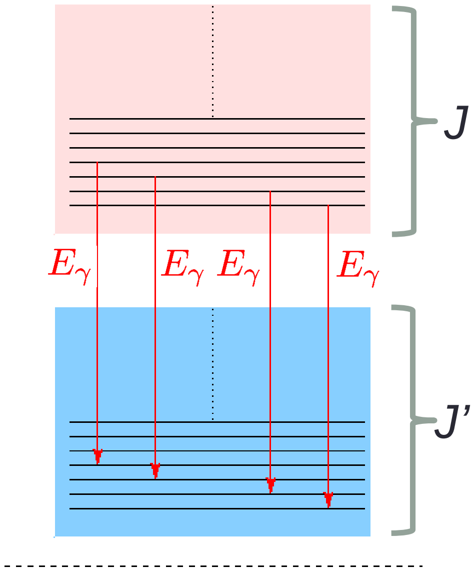

$$\int \Phi_J(E)\Phi_J(\tilde{E})d\tau = \delta(E-\tilde{E})$$

$$\left.\frac{d\mathcal{B}^{(\lambda)}}{dEdE'}\right|_{J\to J'} = \frac{1}{2J+1}\left|\langle \Phi_J(E)||\hat{\mathcal{O}}_\lambda||\Phi_{J'}(E')\rangle\right|^2$$

$$\frac{d\sigma^{(\lambda)}_{r.c.}}{dE'}(E) = \frac{2(2J+1)}{(2J_a+1)(2J_b+1)}\frac{(2\pi)^3(\lambda+1)}{\lambda[(2\lambda+1)!!]^2}\frac{1}{k^2}\left(\frac{E\gamma}{\hbar c}\right)^{2\lambda+1}\left.\frac{d\mathcal{B}^{(\lambda)}}{dEdE'}\right|_{J\to J'}$$

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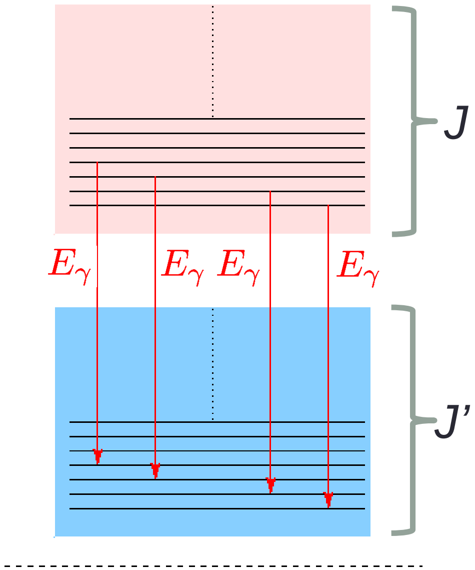

✓A given value of $E\gamma$ can be associated to infinitely many continuum to continuum transitions.

✓All final energies E' below the incident energy E are allowed.

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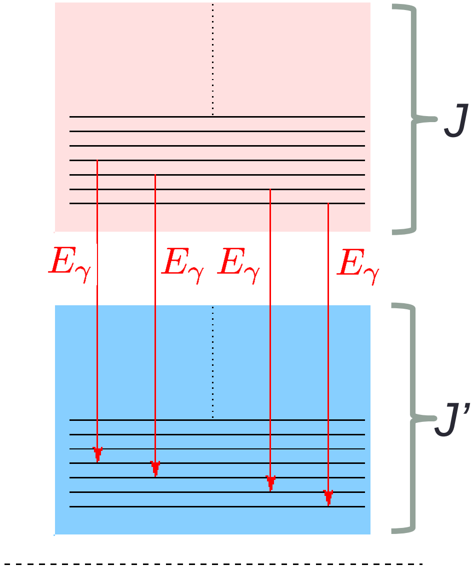

^{8}Be: two-body α-α states

α-α interaction: Ali-Bodmer potential

Two-body Schrödinger Eq. + Complex scaling ($r \rightarrow re^{i\theta}$)

↓

^{8}Be two-body resonances

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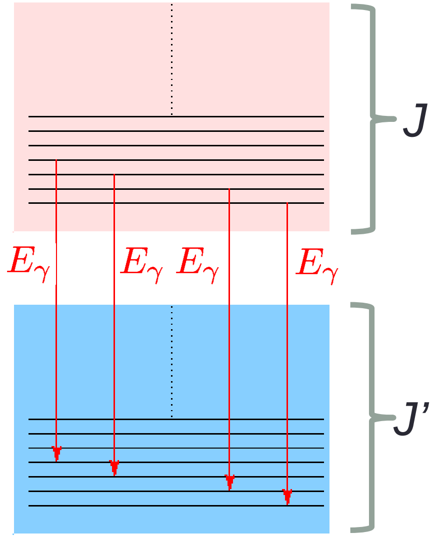

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J^π	0^+	2^+	4^+	6^+	8^+
E_r (Exp.)	0.0918	2.94 ± 0.01	11.35 ± 0.15	—	—
Γ_r (Exp.)	$(5.57 \pm 0.25)10^{-6}$	1.51 ± 0.02	~ 3.5	—	—
E_r (MeV)	0.092	2.90	11.70	34.38	53.65
Γ_r (MeV)	$3.1 \cdot 10^{-6}$	1.27	3.07	37.19	93.74

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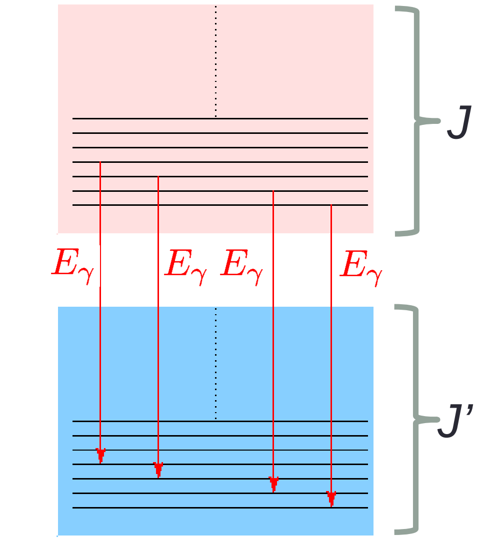

^{8}Be: two-body α-α states

$4^+ \rightarrow 2^+$ transition for given *E* and *E'*

$$\hat{\mathcal{O}}_{E2} = \frac{Ze}{2} r^2 Y_2(\Omega) \longrightarrow \langle u_{4^+}(E,r)|r^2|u_{2^+}(E',r)\rangle$$

$$\langle u_{4^+}(E,r)|r^2|u_{2^+}(E',r)\rangle = \lim_{\eta\to 0} \langle u_{4^+}(E,r)|e^{-\eta^2 r^2} r^2|u_{2^+}(E',r)\rangle$$

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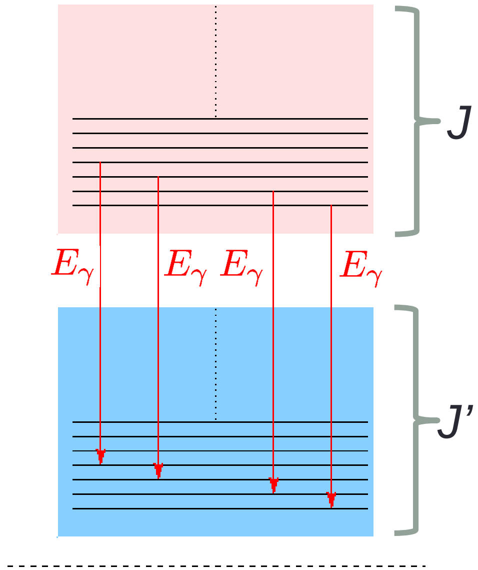

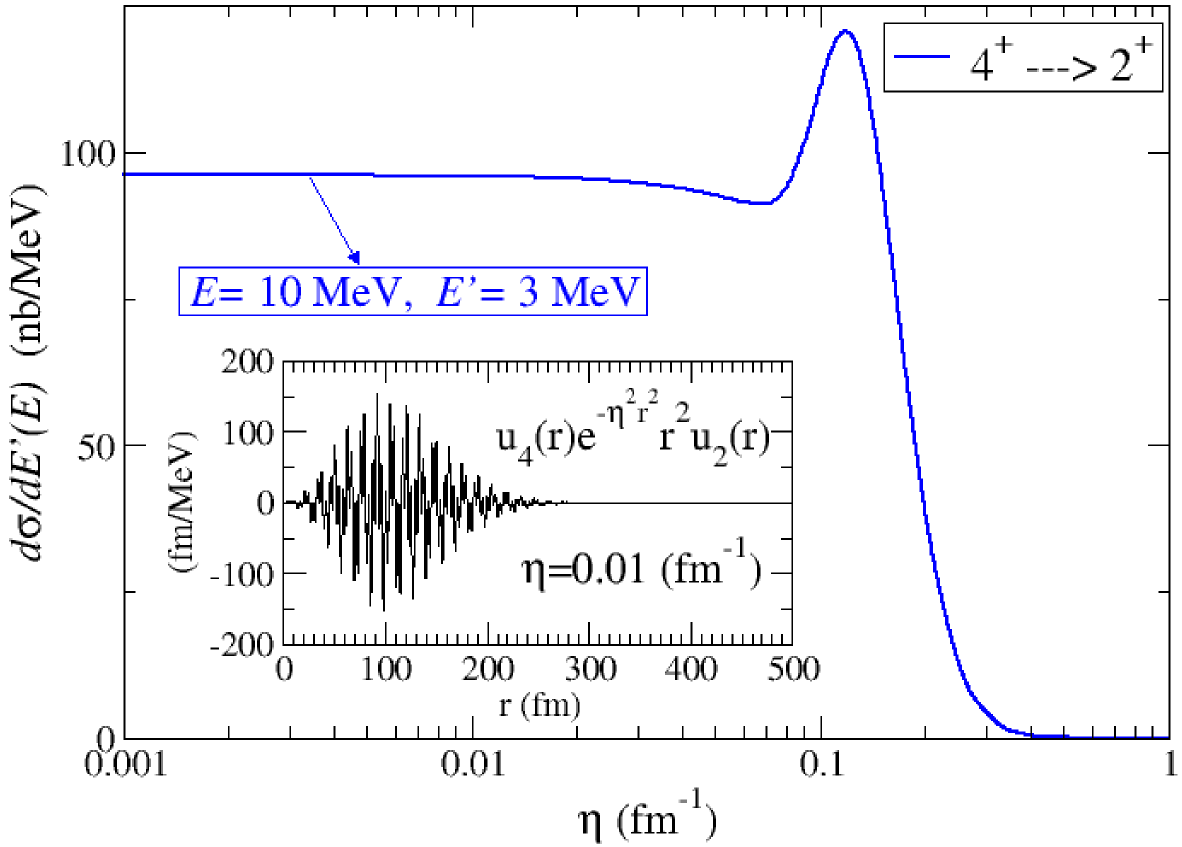

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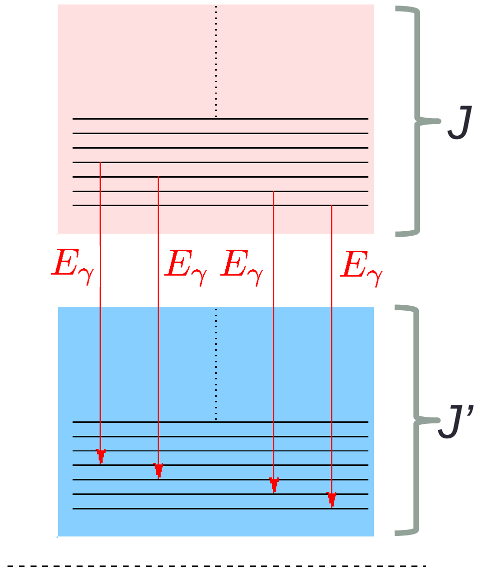

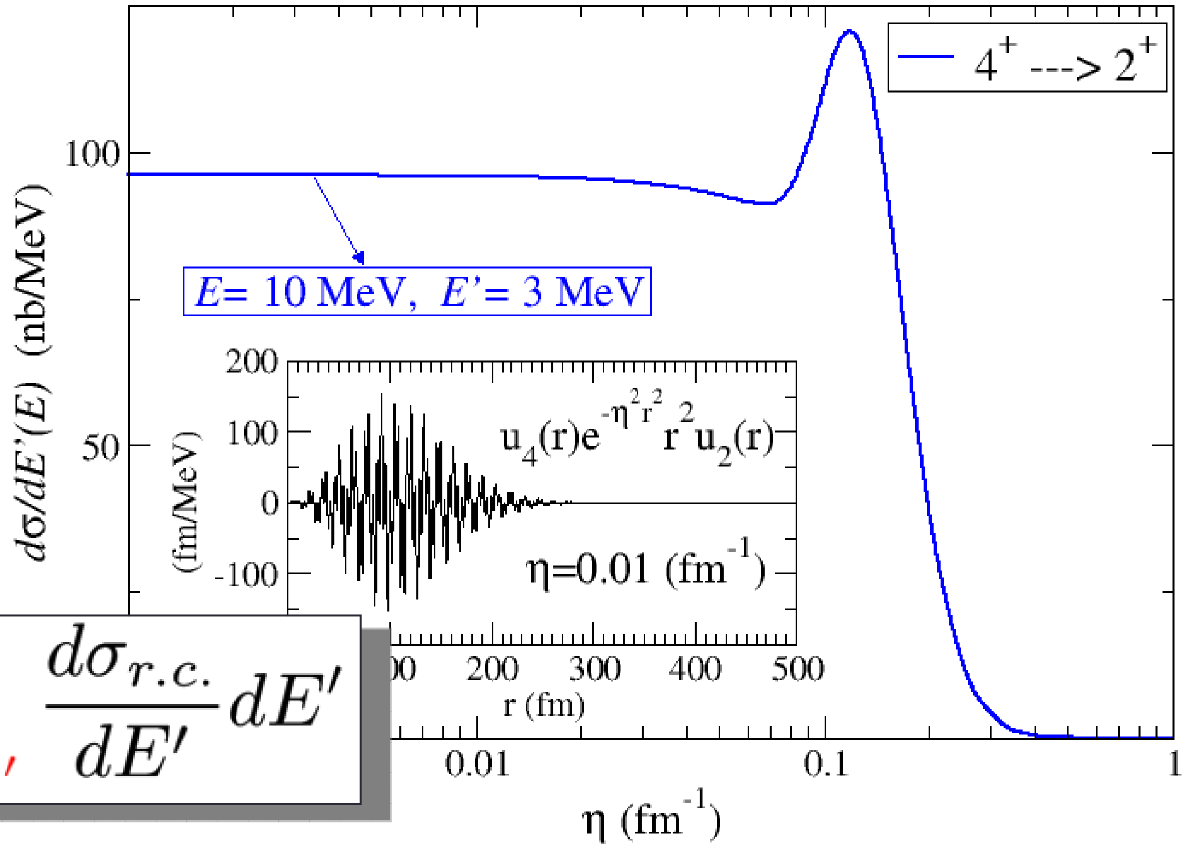

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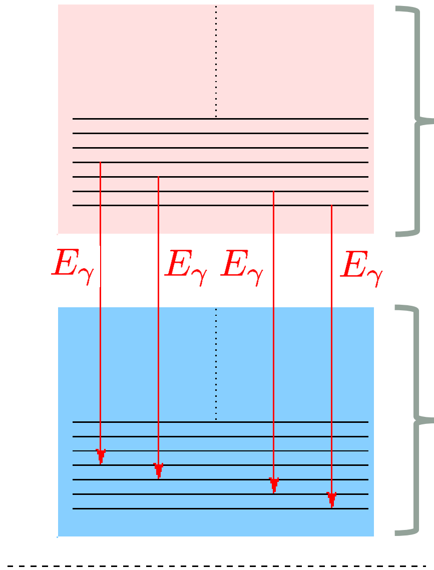

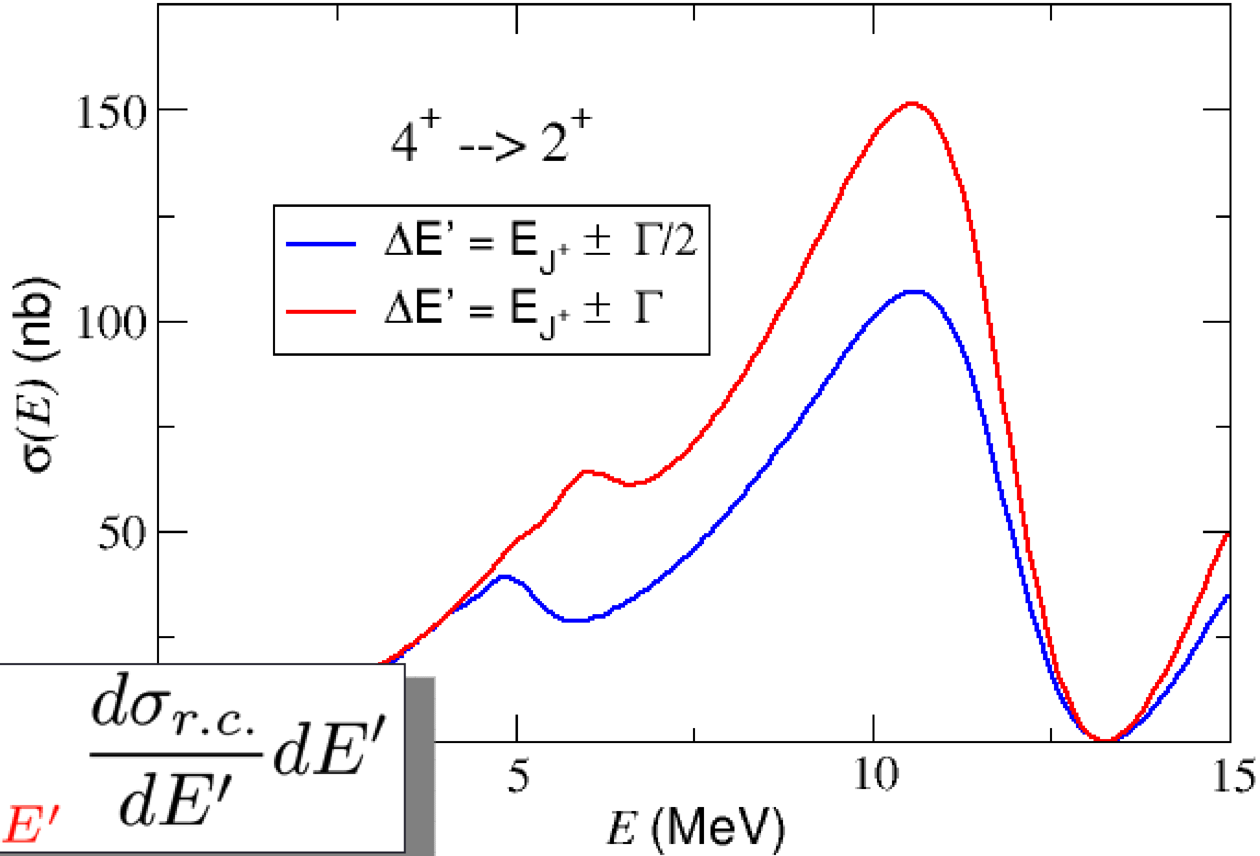

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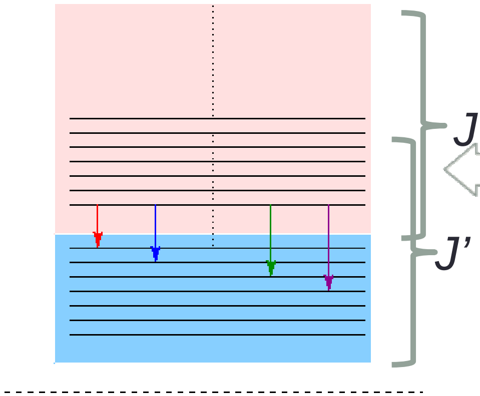
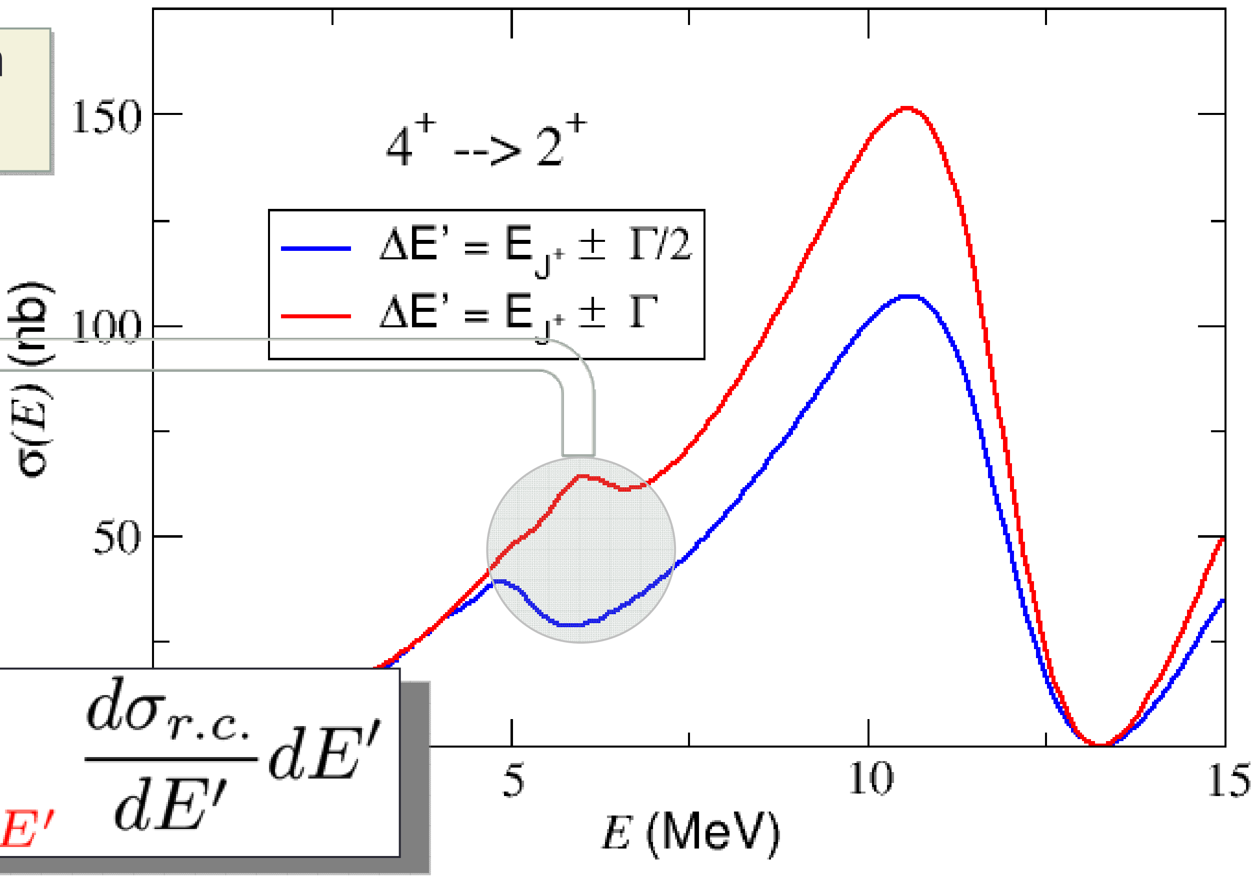
Soft-photon contribution

$E_\gamma \rightarrow 0$





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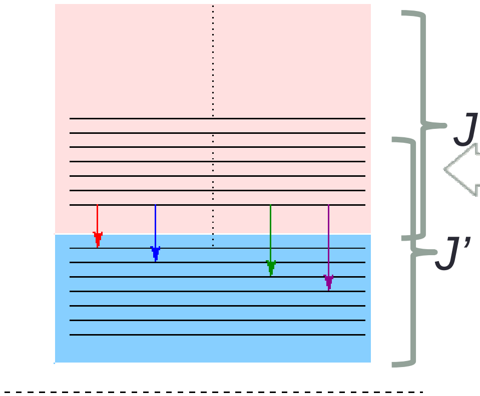

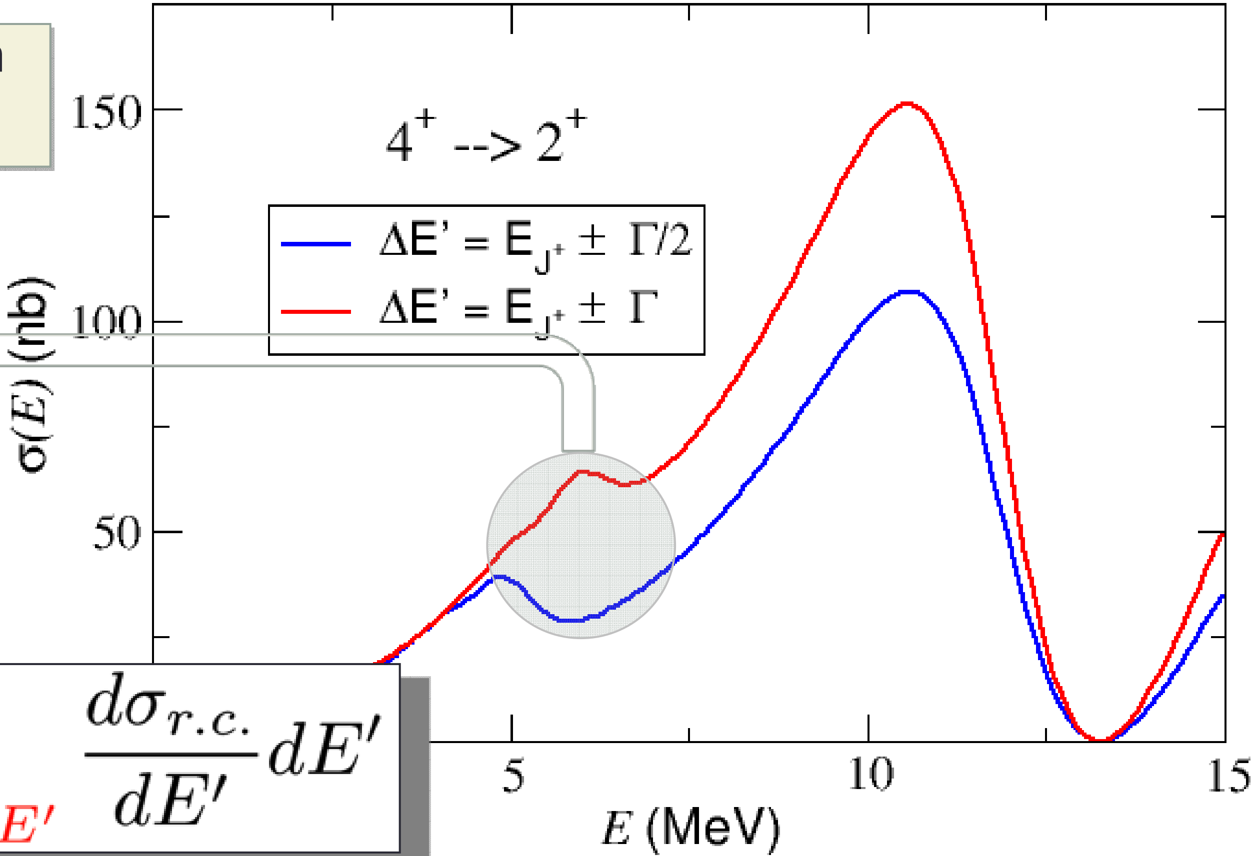

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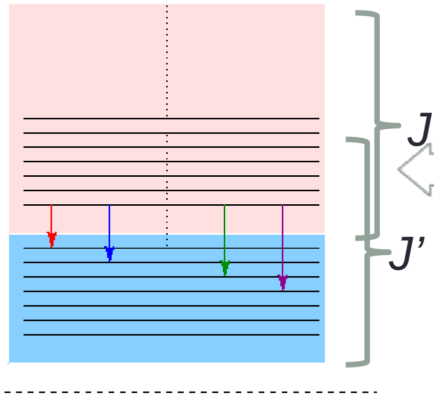

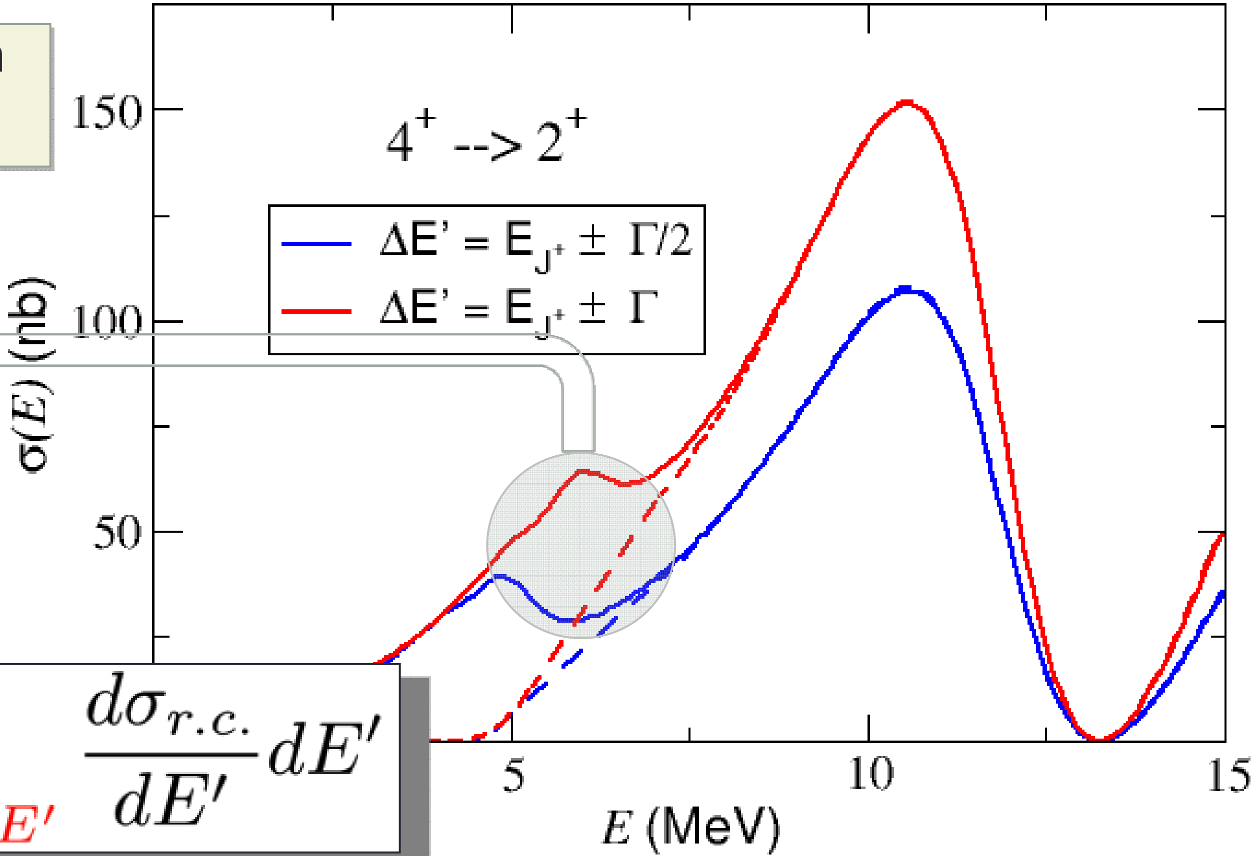

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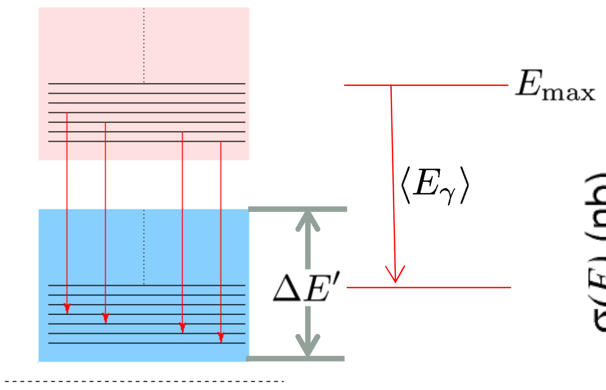

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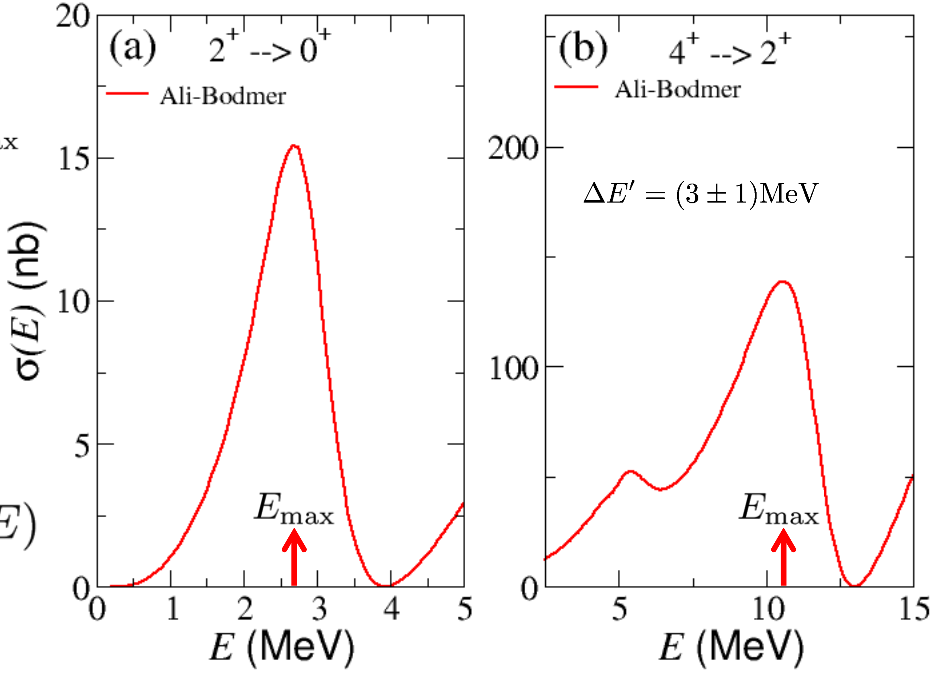

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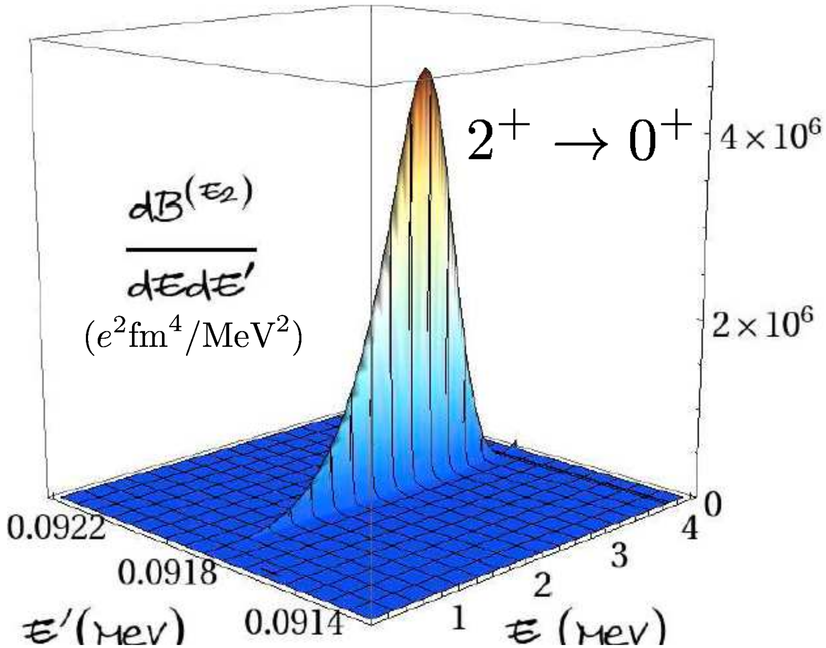

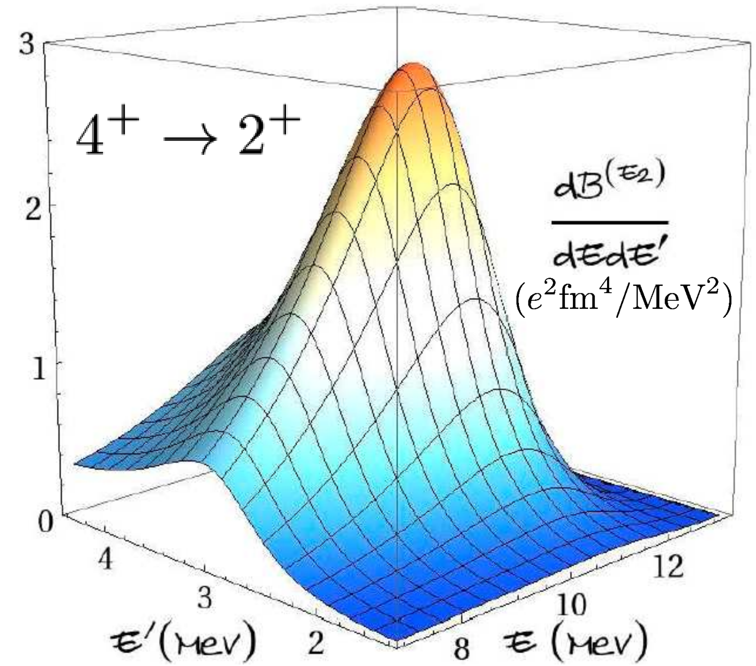

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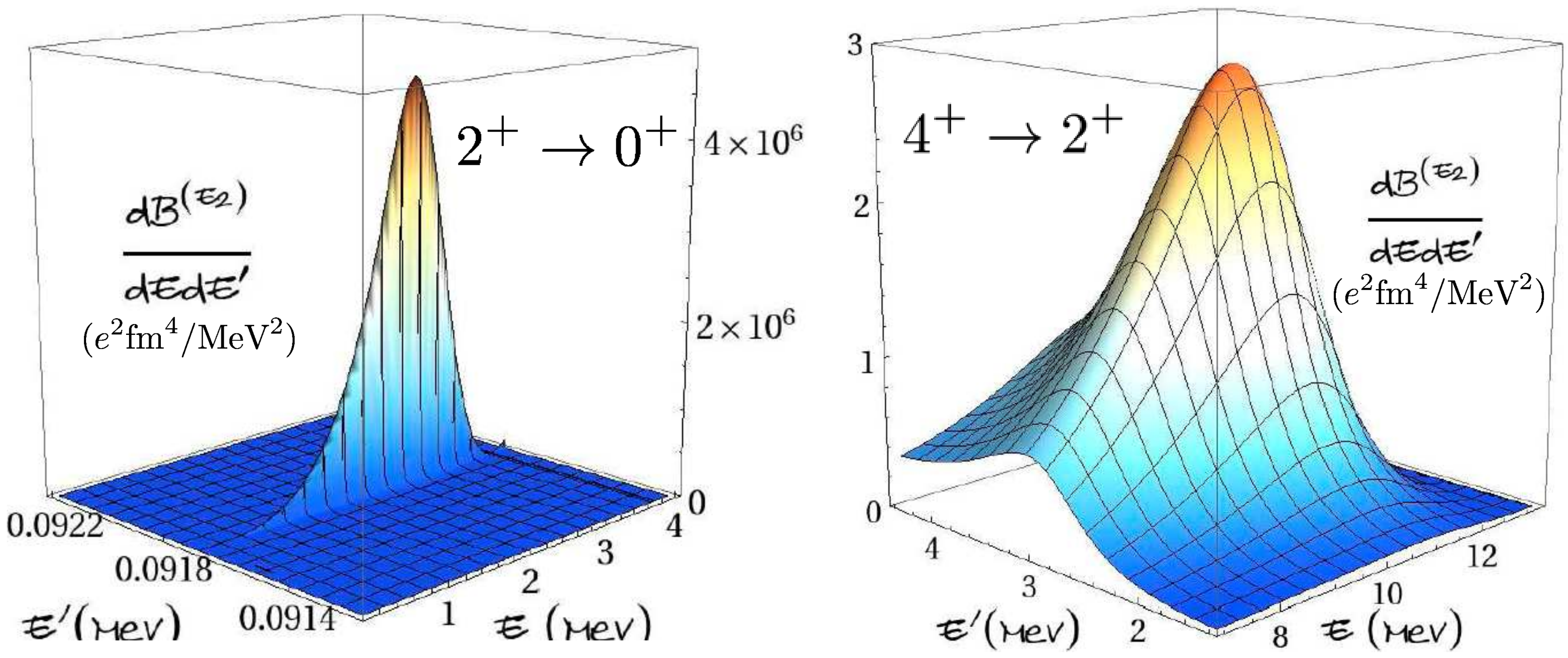

$\mathcal{B}^{(E2)}$ $(e^2\text{fm}^4)$	$E'_r \pm \Gamma'_r/2$ $\mathcal{B}^{(E2)}$	$E'_r \pm \Gamma'_r$ $\mathcal{B}^{(E2)}$	[K. Langanke] (Cluster)	[R.B. Wiringa] (QMC)	[V.M. Datar *et al.*] (PRL 111 (2013) 062502)
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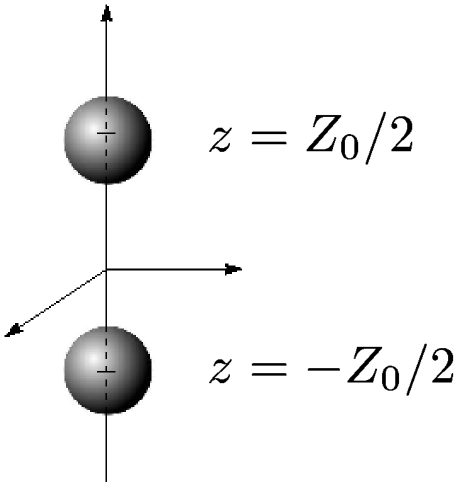

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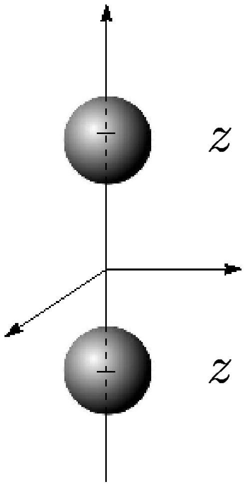

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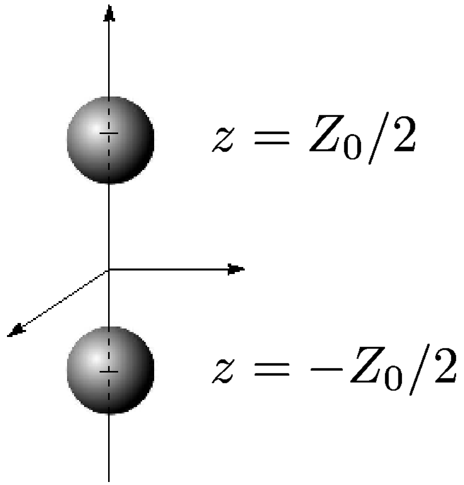

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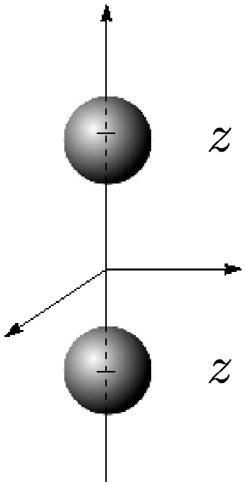

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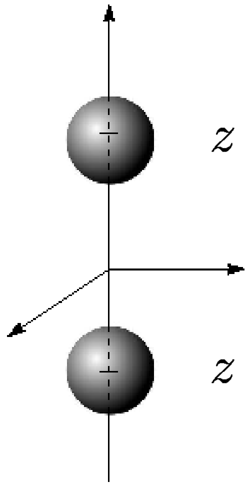
$4^+ \to 2^+$	15.5 (0.29)	22.1 (0.28)	18.0 (0.25)	9.2 (1.43)
$6^+ \to 4^+$	6.7 (0.13)	10.1 (0.13)	–	10.1 (1.57)
$8^+ \to 6^+$	6.6 (0.12)	13.0 (0.16)	–	10.6 (1.65)

Transition strengths: Rotational band in ^{8}Be?



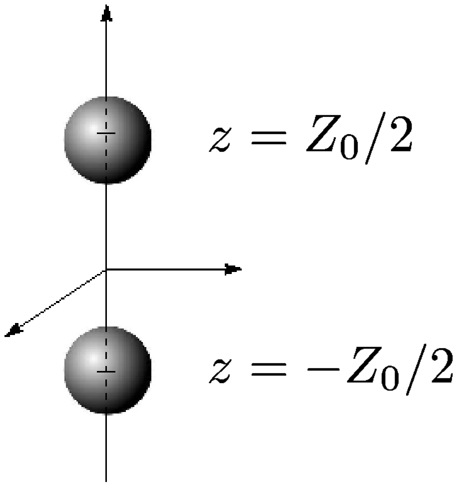
$$\mathcal{B}^{(E2)}(J \to J') = \frac{5e^2}{4\pi} Z_0^4 \langle J020|J'0\rangle^2$$

$$\frac{\mathcal{B}^{(E2)}(J \to J')}{\mathcal{B}^{(E2)}(\tilde{J} \to \tilde{J}')} = \frac{\langle J020|J'0\rangle^2}{\langle \tilde{J}020|\tilde{J}'0\rangle^2}$$

J^π	0^+	2^+	4^+	6^+	8^+
$\mathrm{Re}\sqrt{<r^2>}$ (fm)	5.80	3.58	2.91	2.70	2.73
$\mathrm{Im}\sqrt{<r^2>}$ (fm)	0.001	1.24	0.76	1.40	1.73

$\mathcal{B}^{(E2)}$ (e^2fm^4)	$E'_r \pm \Gamma'_r/2$ $\mathcal{B}^{(E2)}$	$E'_r \pm \Gamma'_r$ $\mathcal{B}^{(E2)}$	[K. Langanke] (Cluster)	Rotational model $Z_0 = 3$ fm
$2^+ \to 0^+$	53.4 (1)	79.1 (1)	71.3 (1)	6.4 (1)
$4^+ \to 2^+$	15.5 (0.29)	22.1 (0.28)	18.0 (0.25)	9.2 (1.43)
$6^+ \to 4^+$	6.7 (0.13)	10.1 (0.13)	–	10.1 (1.57)
$8^+ \to 6^+$	6.6 (0.12)	13.0 (0.16)	–	10.6 (1.65)

Transition strengths: Rotational band in ^{8}Be?



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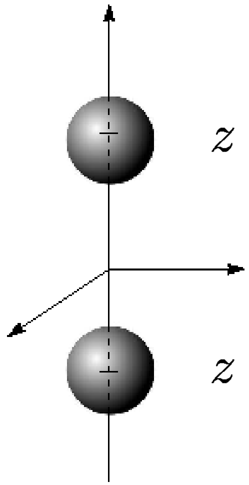
$\mathcal{B}^{(E2)}$ (e^2fm^4)	$E'_r \pm \Gamma'_r/2$ $\mathcal{B}^{(E2)}$	$E'_r \pm \Gamma'_r$ $\mathcal{B}^{(E2)}$	[K. Langanke] (Cluster)	Rotational model $Z_0 = 3$ fm	Rotational model $Z_0 = \mathrm{Re}\sqrt{\langle r^2\rangle}$
$2^+ \to 0^+$	53.4 (1)	79.1 (1)	71.3 (1)	6.4 (1)	84.0 (1)
$4^+ \to 2^+$	15.5 (0.29)	22.1 (0.28)	18.0 (0.25)	9.2 (1.43)	18.1 (0.22)
$6^+ \to 4^+$	6.7 (0.13)	10.1 (0.13)	–	10.1 (1.57)	9.1 (0.11)
$8^+ \to 6^+$	6.6 (0.12)	13.0 (0.16)	–	10.6 (1.65)	7.6 (0.09)

Transition strengths: Rotational band in ^{8}Be?



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- ✓ The idea of ^{8}Be as a rigid rotor of two α-particles at a given distance is questionable.
- ✓ The intrinsic α-particle structure is maintained, although the particle separation changes.

$\mathcal{B}^{(E2)}$ (e^2fm^4)	$E'_r \pm \Gamma'_r/2$ $\mathcal{B}^{(E2)}$	$E'_r \pm \Gamma'_r$ $\mathcal{B}^{(E2)}$	[K. Langanke] (Cluster)	Rotational model $Z_0 = 3$ fm	Rotational model $Z_0 = \mathrm{Re}\sqrt{\langle r^2\rangle}$
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$8^+ \to 6^+$	6.6 (0.12)	13.0 (0.16)	–	10.6 (1.65)	7.6 (0.09)

Rotational band in ^{8}Be?

$$E_J = E_0 + \frac{\hbar^2}{2\mathcal{I}} J(J+1)?$$

J^π	0^+	2^+	4^+	6^+	8^+
E_r (Exp.)	0.0918	2.94 ± 0.01	11.35 ± 0.15	—	—
Γ_r (Exp.)	$(5.57 \pm 0.25)10^{-6}$	1.51 ± 0.02	~ 3.5	—	—
E_r (Buck)	0.091	2.88	11.78	33.55	51.56
Γ_r (Buck)	$3.6 \cdot 10^{-5}$	1.24	3.57	37.38	92.38
E_r (A.-B.)	0.092	2.90	11.70	34.38	53.65
Γ_r (A.-B.)	$3.1 \cdot 10^{-6}$	1.27	3.07	37.19	93.74
$E_r^{(1)} = E_0 + B_1 J(J+1)$	$E_0 = 0.091$	3.8	12.5	26.2	44.8

- ✓ The idea of ^{8}Be as a rigid rotor of two α-particles at a given distance is questionable.
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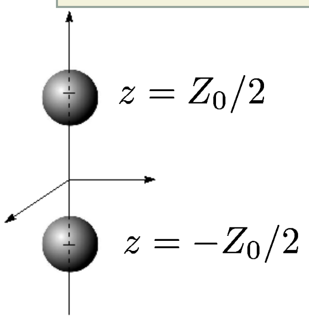

$$\mathcal{I}_{rig} = \frac{1}{2} m_\alpha Z_0^2 + \frac{4}{5} m_\alpha R_\alpha^2$$

$$R_\alpha^2 = \frac{5}{3}\langle r_\alpha^2 \rangle \qquad \langle r_\alpha^2 \rangle^{1/2} \approx 1.7 \text{ fm}$$

$$Z_0 = 3 \text{ fm}$$

$$B_1 = \frac{\hbar^2}{2\mathcal{I}_{rig}} = 0.621 \text{ MeV}$$

Rotational band in ^{8}Be?

$$E_J = E_0 + \frac{\hbar^2}{2\mathcal{I}} J(J+1)?$$

J^π	0^+	2^+	4^+	6^+	8^+
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$E_r^{(1)} = E_0 + B_1 J(J+1)$	$E_0 = 0.091$	3.8	12.5	26.2	44.8
$E_r^{(Z_0)} = E_0 + B_{Z_0} J(J+1)$	$E_0 = 0.091$	3.2	12.9	28.5	49.1

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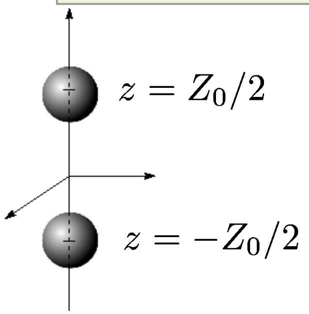

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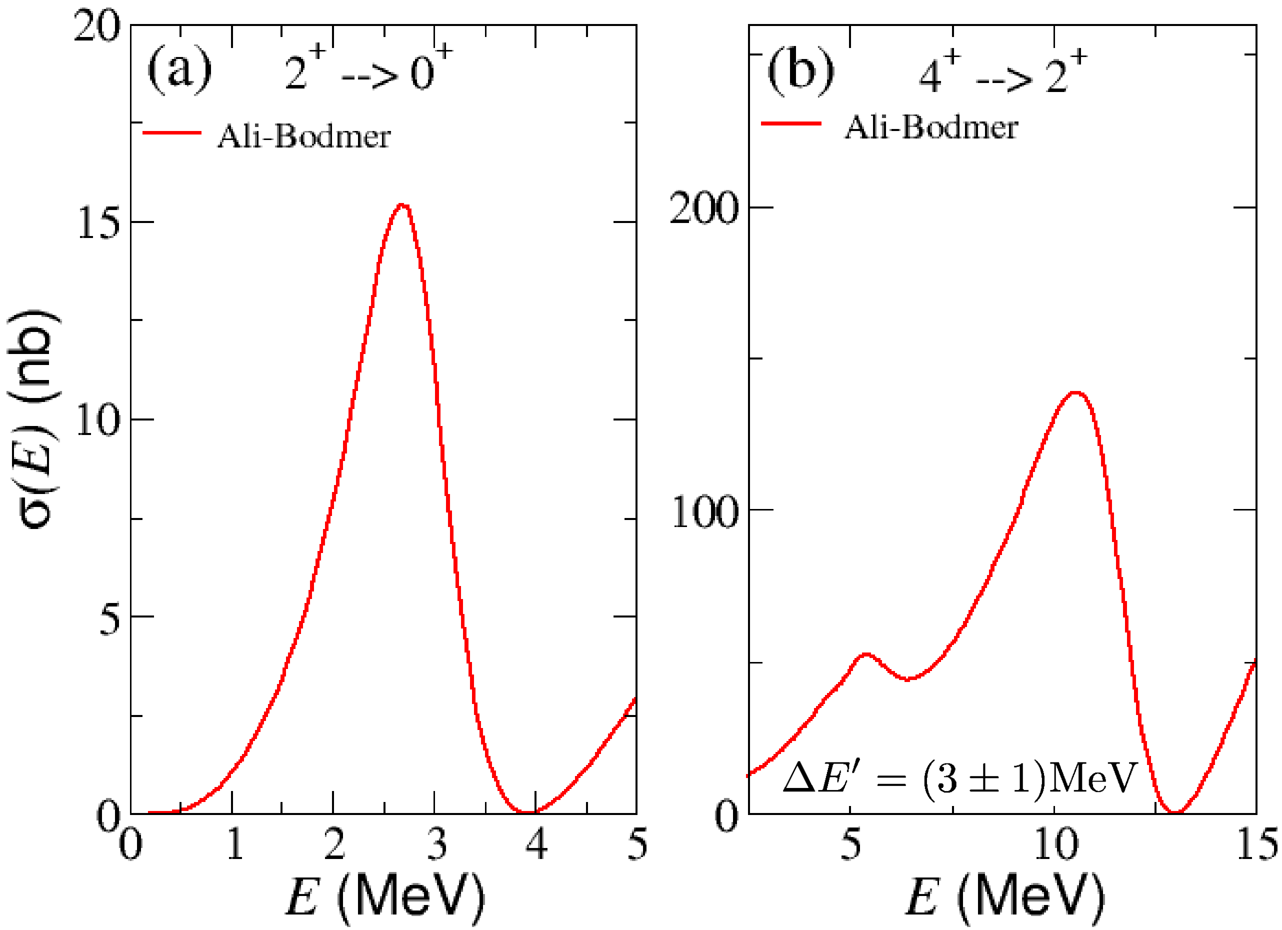
$$R_\alpha^2 = \frac{5}{3}\langle r_\alpha^2 \rangle \qquad \langle r_\alpha^2 \rangle^{1/2} \approx 1.7 \text{ fm}$$

$$Z_0 = \mathrm{Re}\sqrt{\langle r^2 \rangle}$$

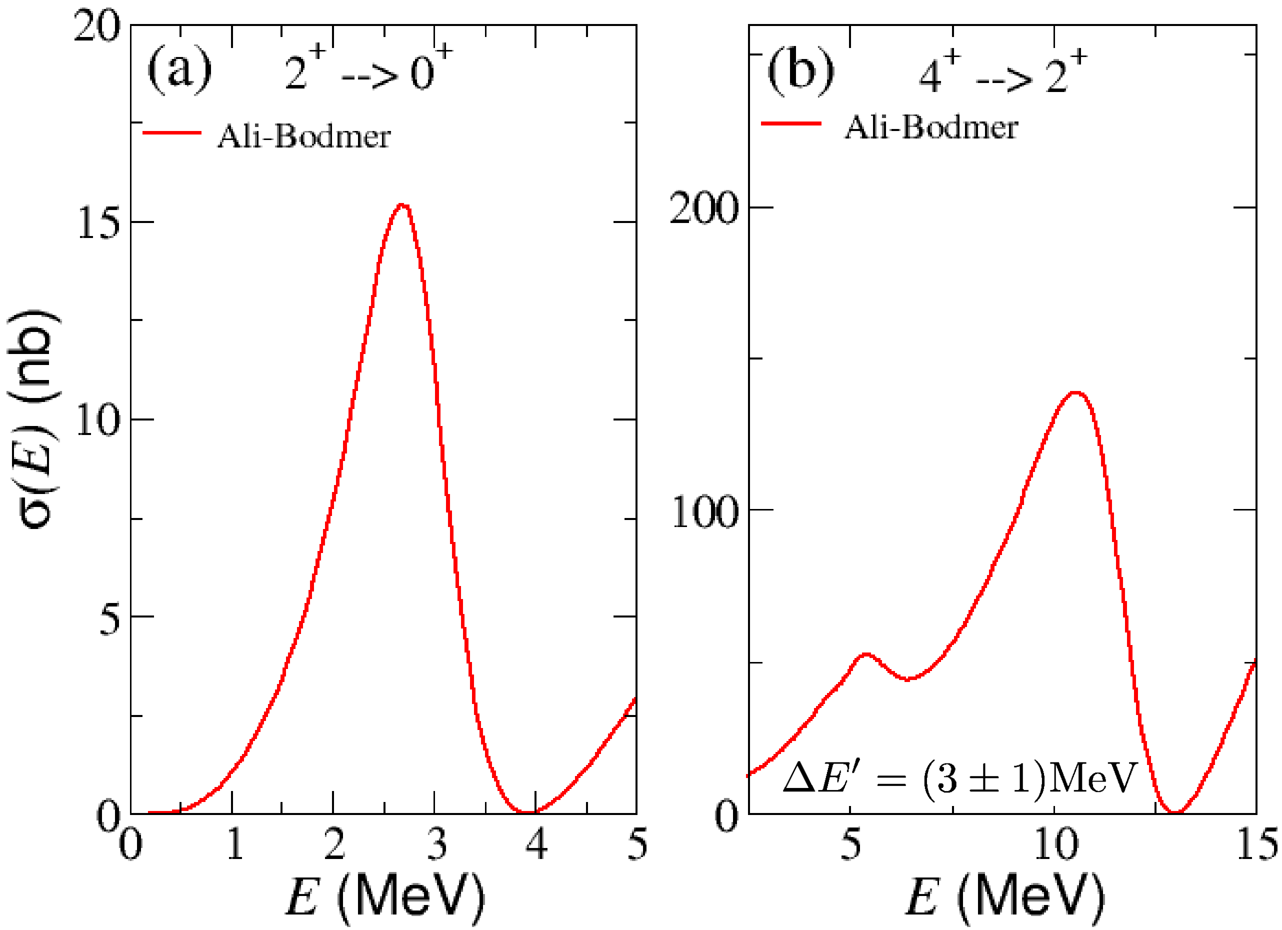
$$B_{Z_0} = \frac{\hbar^2}{2\mathcal{I}_{rig}}$$

Transitions between rotational nuclear few-body states in the continuum

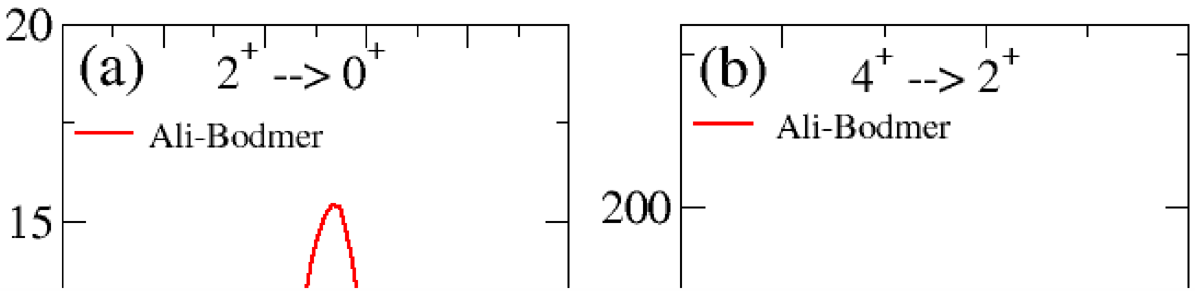


Ali-Bodmer potential

- ✓ Gaussian potential
- ✓ Partial wave dependent



Ali-Bodmer potential	Buck potential
✓ Gaussian potential	✓ Gaussian potential
✓ Partial wave dependent	✓ Partial wave independent



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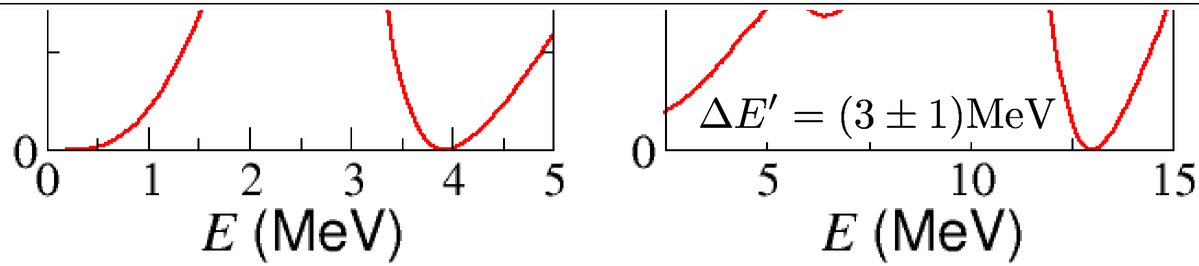


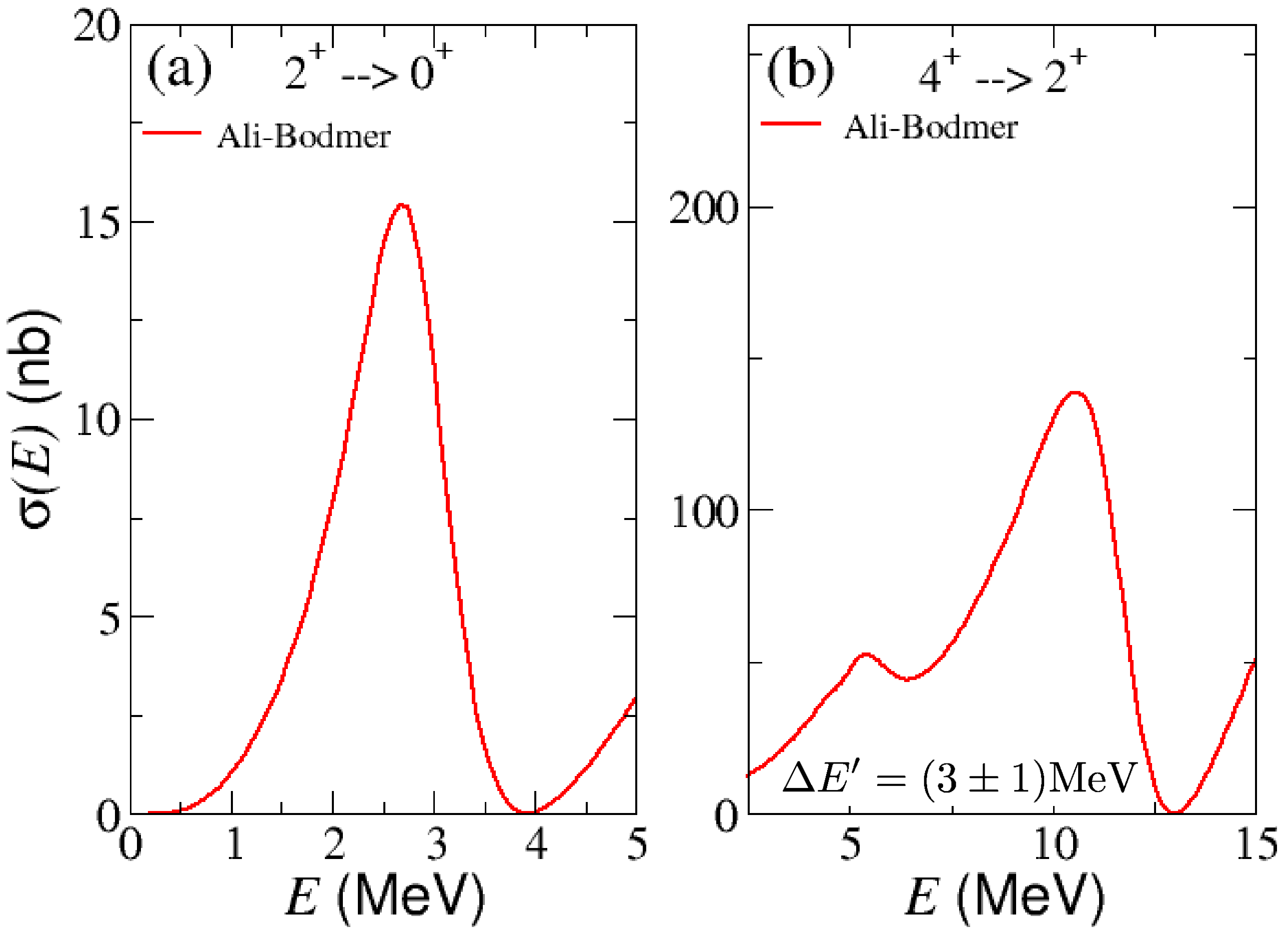
Ali-Bodmer potential

- ✓ Gaussian potential
- ✓ Partial wave dependent
- ✓ Reproduce the phase-shifts

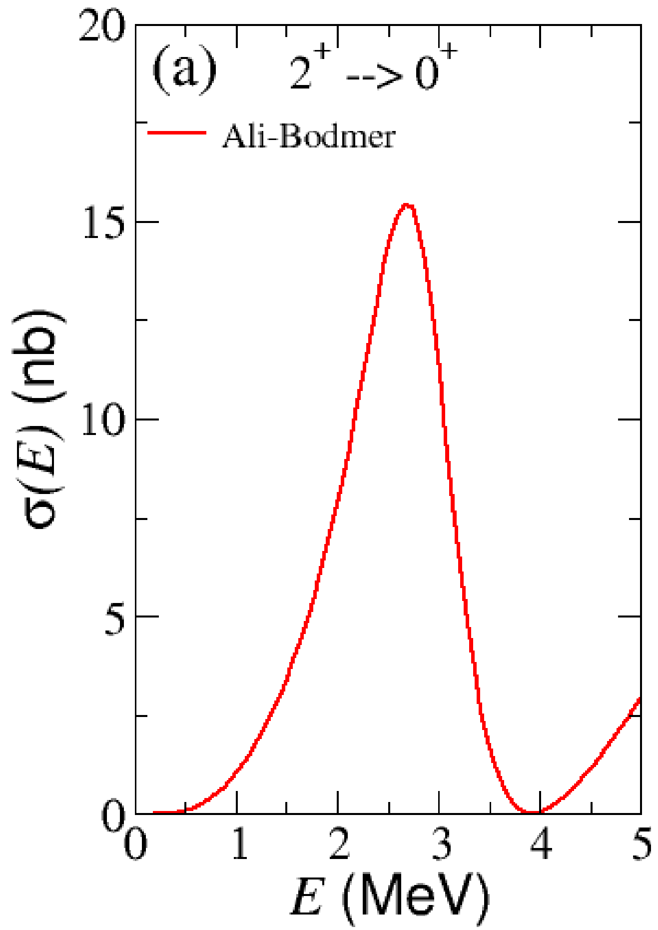
Buck potential

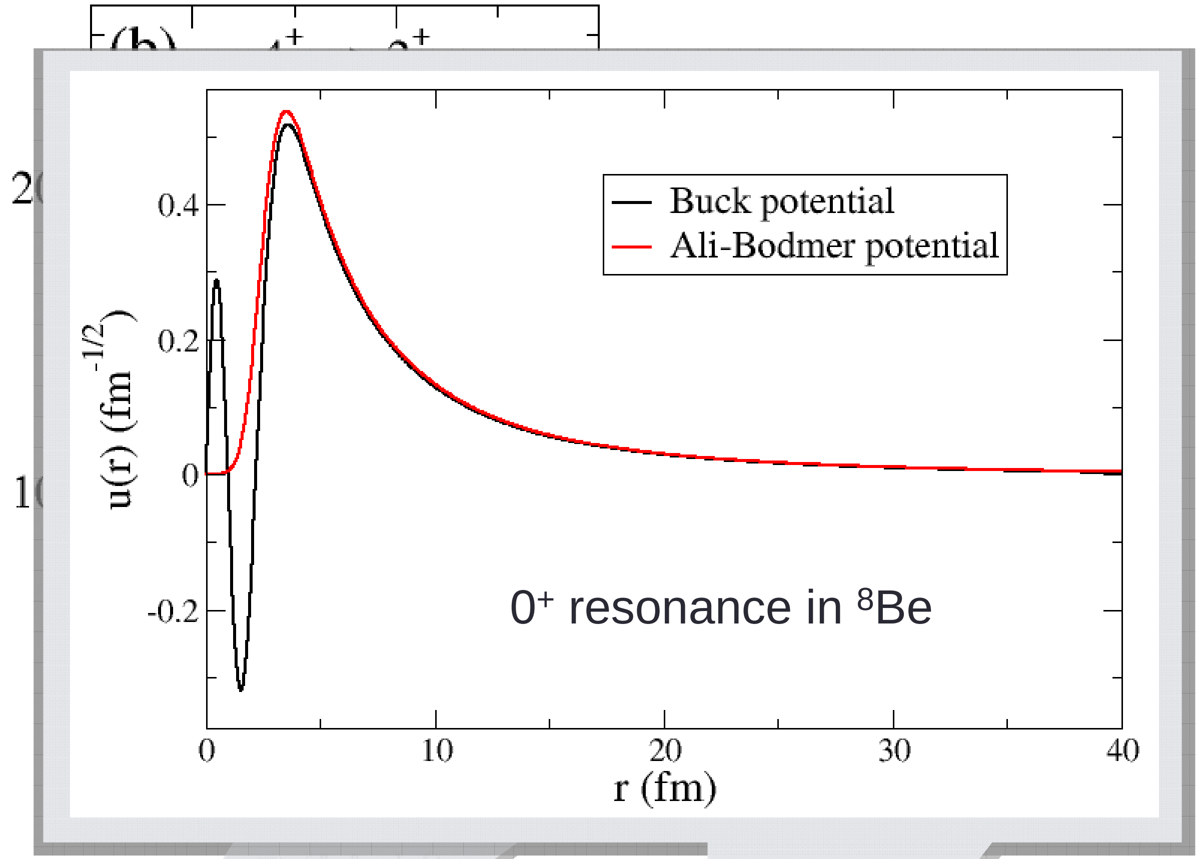
- ✓ Gaussian potential
- ✓ Partial wave independent
- ✓ Reproduce the phase-shifts

Transitions between rotational nuclear few-body states in the continuum



Ali-Bodmer potential	Buck potential
✓ Gaussian potential	✓ Gaussian potential
✓ Partial wave dependent	✓ Partial wave independent
✓ Reproduce the phase-shifts	✓ Reproduce the phase-shifts
✓ No bound two-body states	✓ 2 s- and 1 d- bound two-body states





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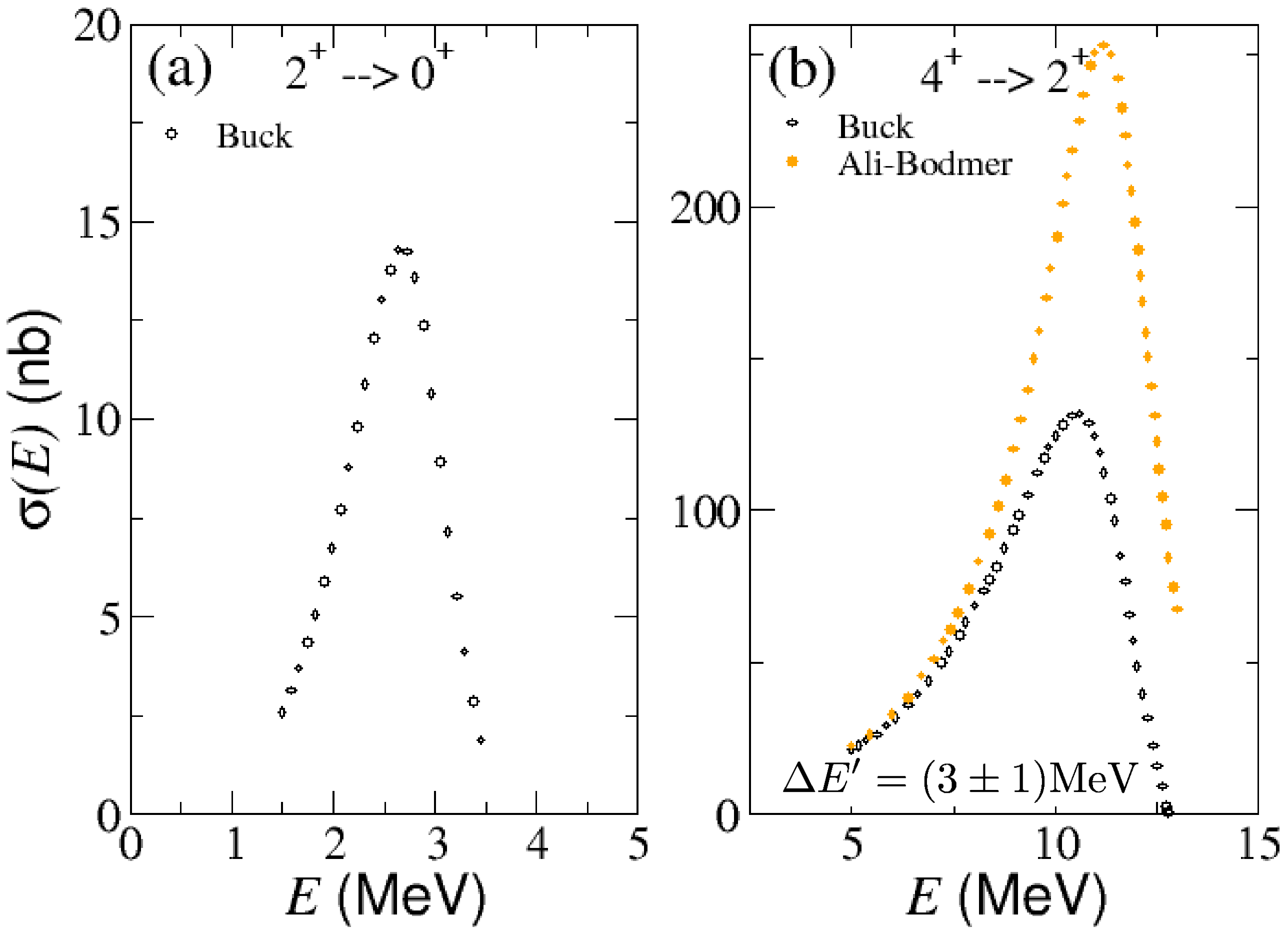

K. Langanke, C. Rolfs
PRC 33 (1986) 790

K. Langanke
PLB 174 (1986) 27

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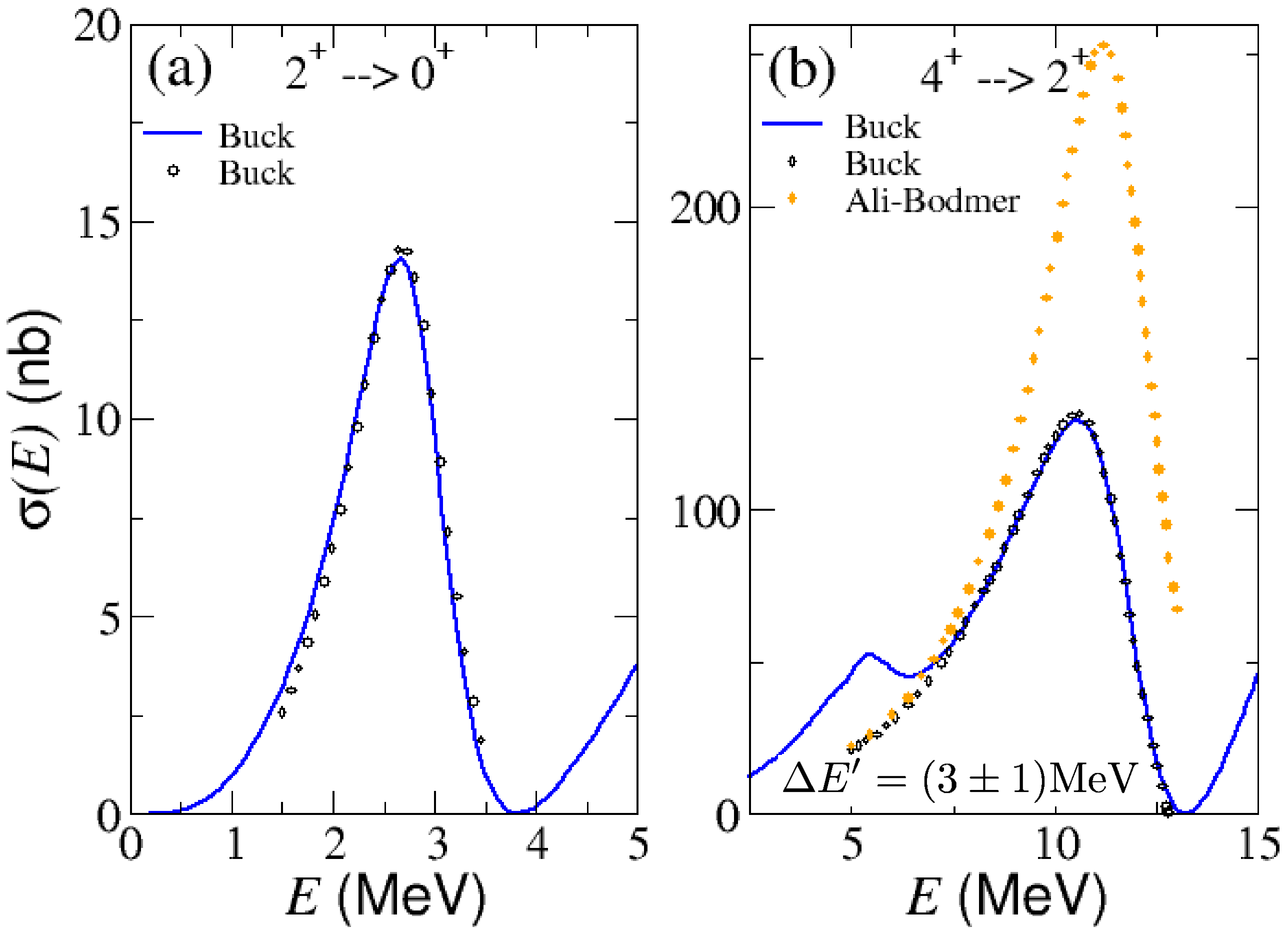
Transitions between rotational nuclear few-body states in the continuum



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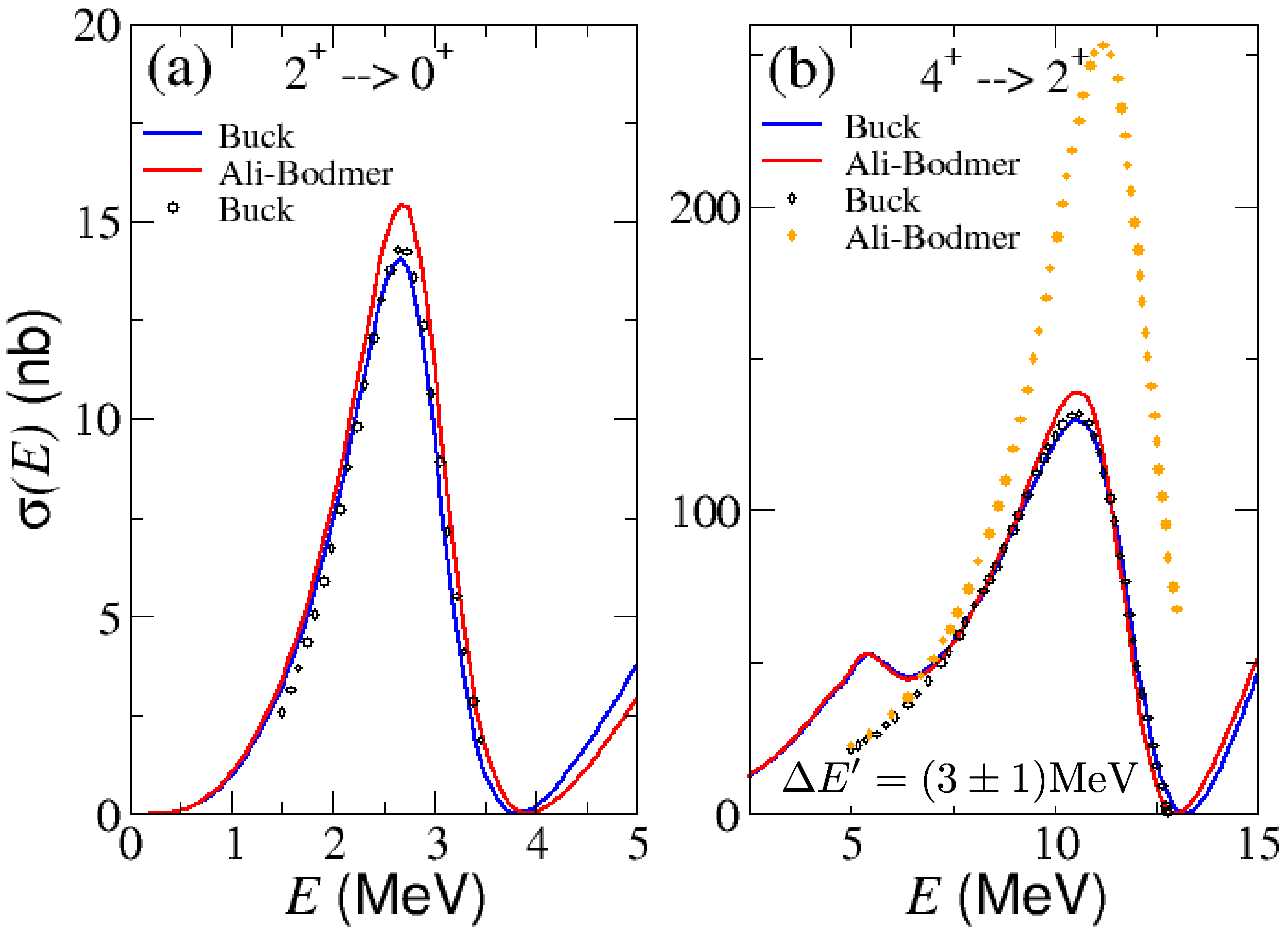

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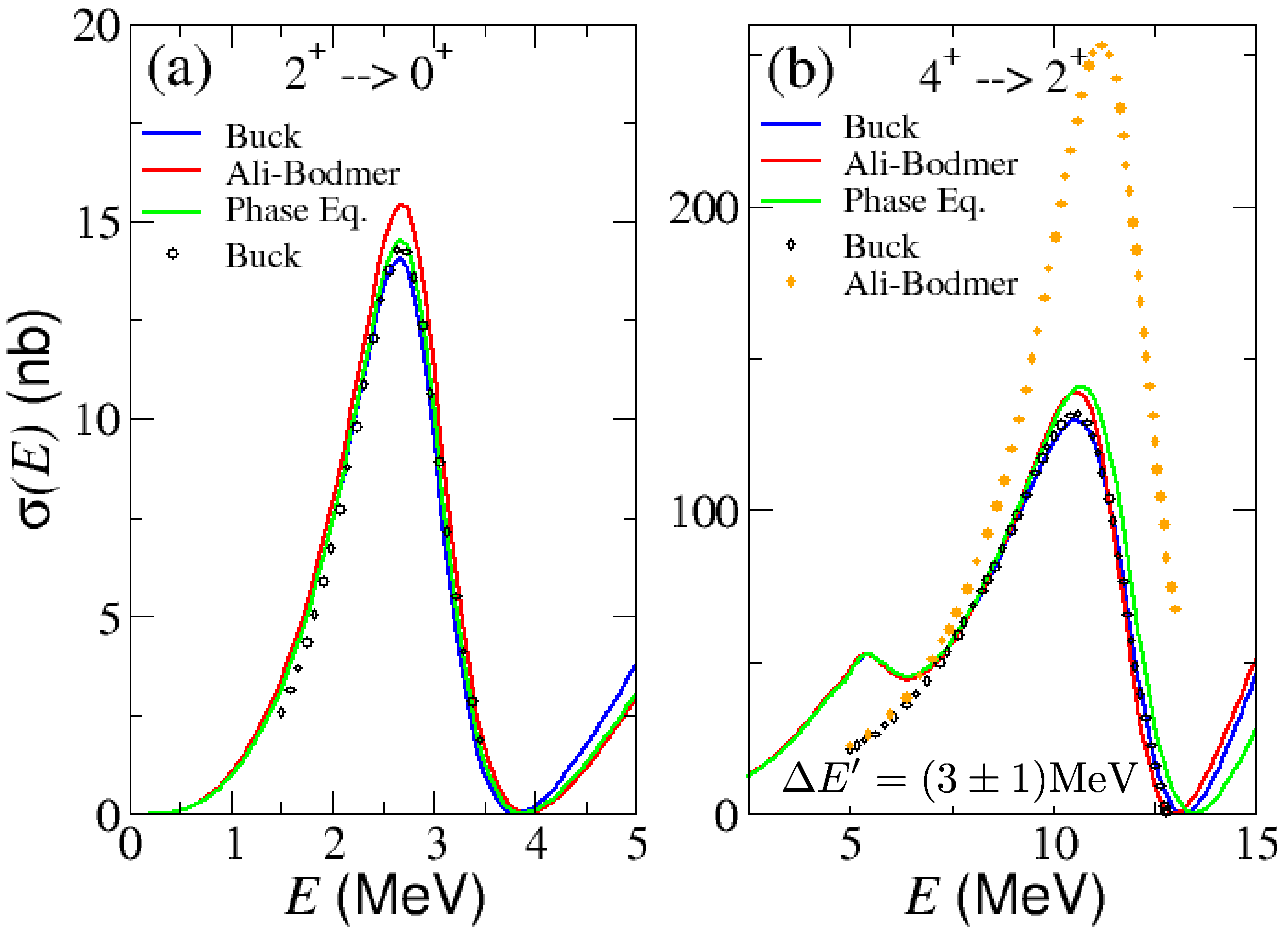

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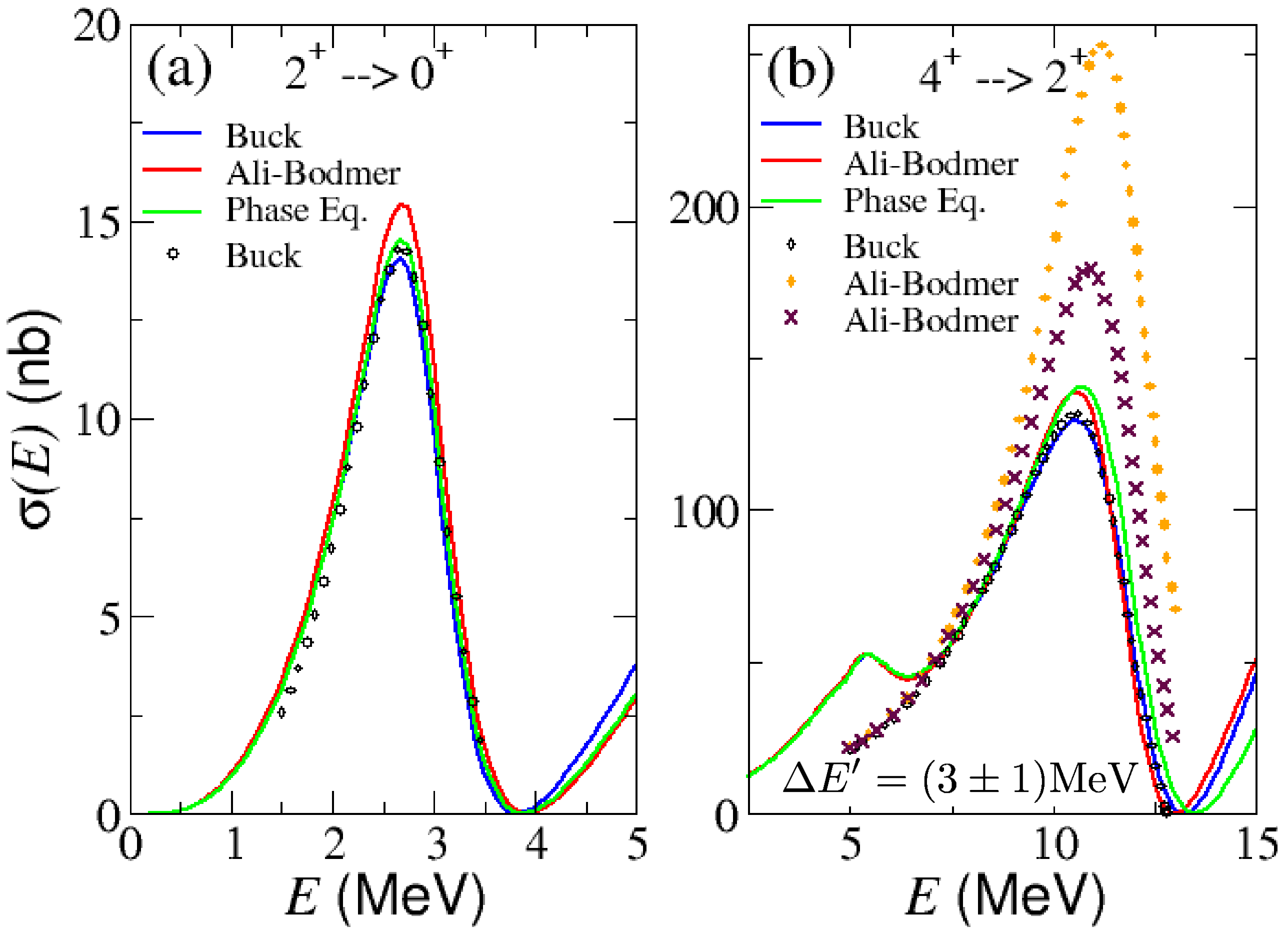

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PLB 174 (1986) 27

D. Krolle et al.
PRC 35 (1987) 1631

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Buck potential

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- ✓ 2 s- and 1 d- bound two-body states

THANK YOU !!!

A.S. Jensen, D.V. Fedorov, Aarhus University, *Denmark*

E. Garrido, *IEM-CSIC, Madrid, Spain*

Krakow, September 2013