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Theoretical basics and modern status of radioactivity studies

Lecture 5: Nonresonant phenomena. Astrophysical applications

Halo and excitation modes

Excitation MODES idea is introduced to describe strong enhancements of various cross sections connected ONLY with initial structure and reaction mechanism. This is in sharp contrast with RESONANCE phenomena, which should be, by definition, insensitive to initial conditions and method of population.

Nucleon halo

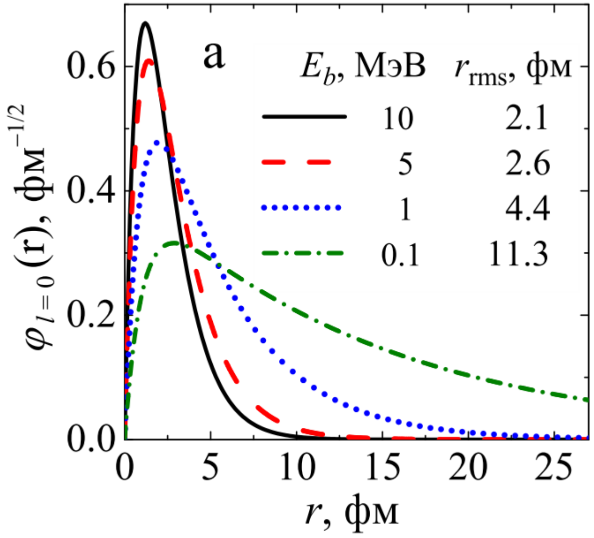
Nuclei near driplines can form kind of planetary system consisting of compact “core” and “valence” nucleons remotely orbiting it and residing mainly in classically forbidden region

$$\Psi(\mathbf{r}) = \Psi(r,\Omega) = \sum_{lm} \frac{\chi_l(\rho)}{r} Y_{lm}(\Omega) ,$$

$$\chi_{l=0}(r) \overset{r\to\infty}{\sim} \exp(-kr) , \quad k = \sqrt{-2ME_T} .$$

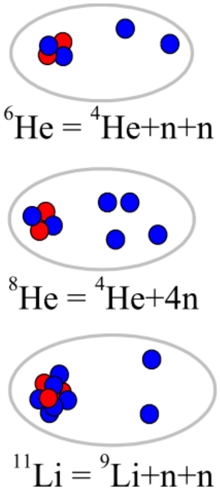
"Haloism coefficient"

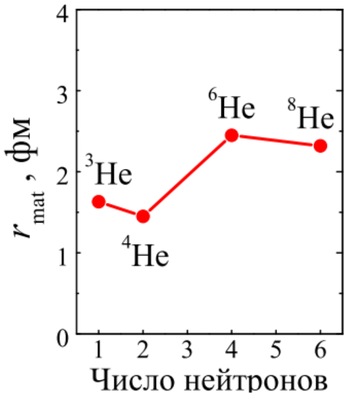
$$H = \frac{< R_{N\text{-}CM}(\text{halo}) >}{< R_{N\text{-}CM}(\text{core}) >}$$

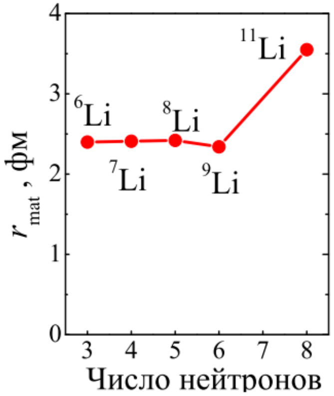


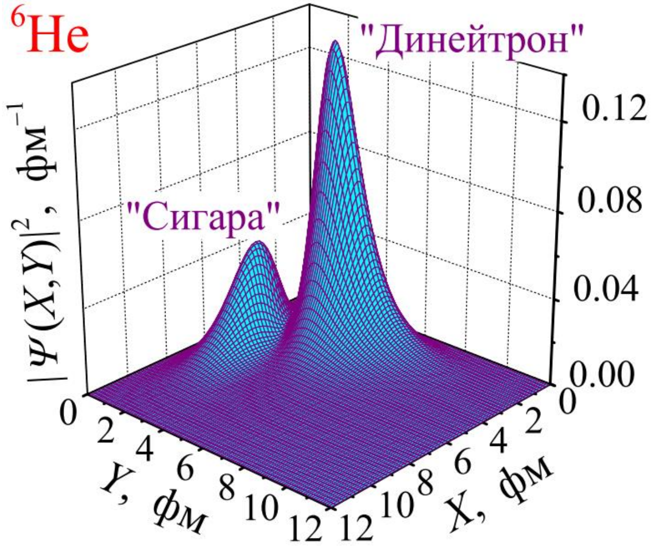
^{11}Be	H = 2.41
^{11}Li	H = 2.27
^{6}He	H = 1.81
^{8}B	H = 1.77
^{6}Li	H = 1.62
^{8}Li	H = 1.55

Nucleon halo. Borromean nuclei



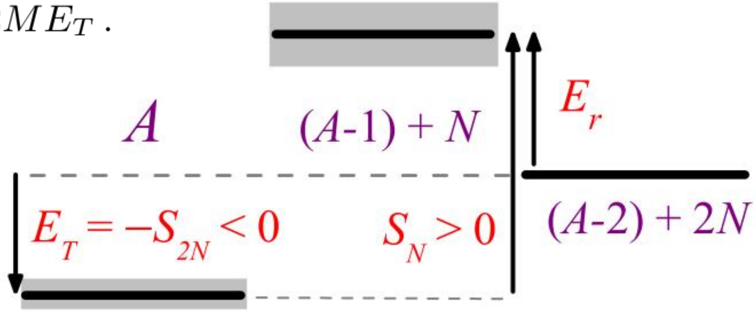






$$\Psi(\mathbf{X},\mathbf{Y}) = \Psi(\rho,\Omega_\rho) = \sum_{K\gamma} \frac{\chi_{K\gamma}(\rho)}{\rho^{5/2}} \mathcal{J}_{K\gamma}(\Omega_\rho)\,,$$

$$\chi(\rho) \overset{\rho\to\infty}{\sim} \exp\left(-\varkappa\rho\right)\,, \quad \varkappa = \sqrt{-2ME_T}\,.$$



A

$(A\text{-}1) + N$

E_r

$(A\text{-}2) + 2N$

$E_T = -S_{2N} < 0$

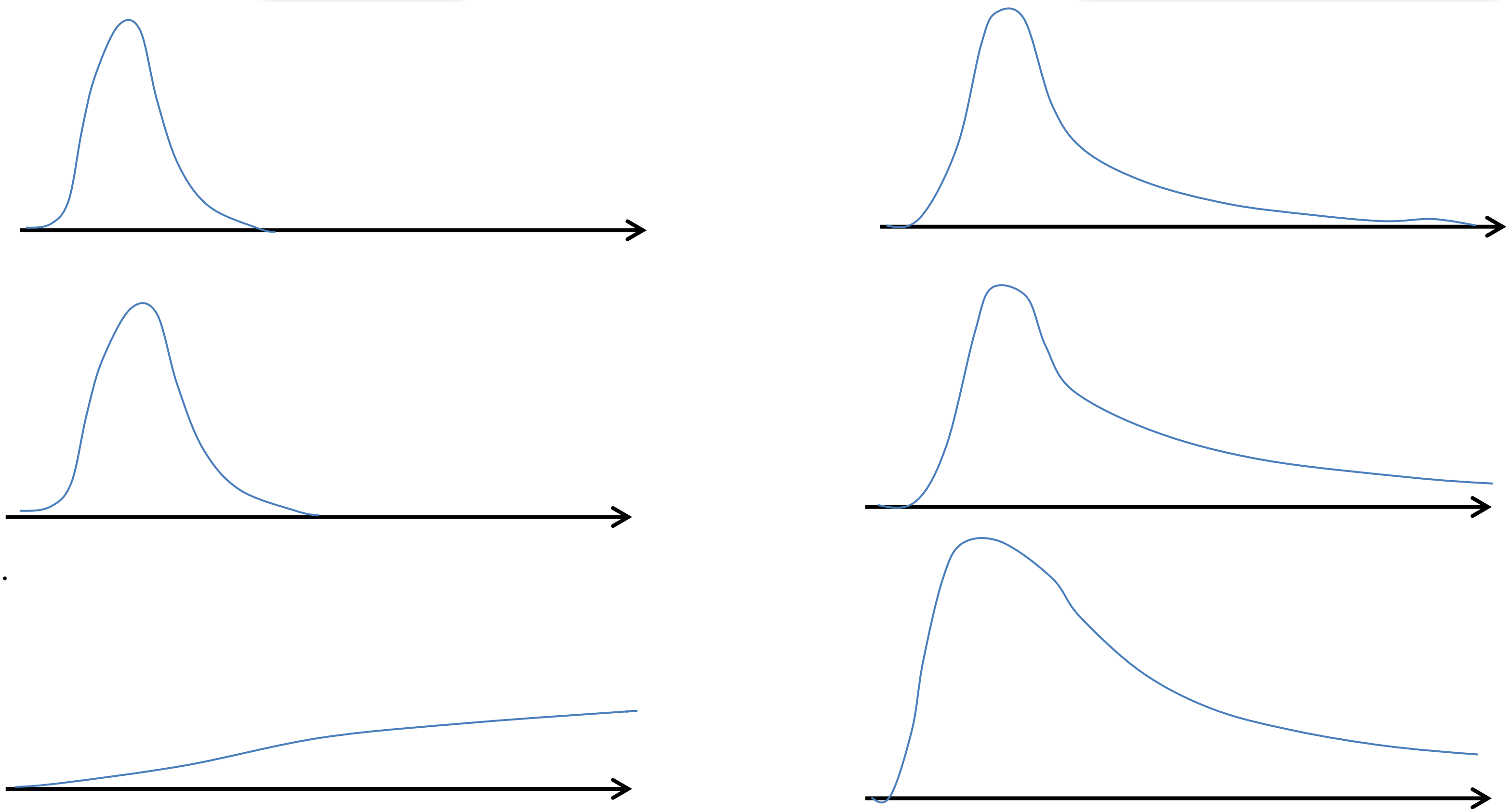
$S_N > 0$

Major example: soft dipole mode

- Proposed by Ikeda in 1988

Normal WF

Weakly bound (halo) WF



$\Psi_{g.s.}$

$\boldsymbol{D}\ \Psi_{g.s.}$

$| < \text{Plane wave} \mid \boldsymbol{D} \mid \Psi_{g.s.} > |^2$

- Photodissociation
- Coulex

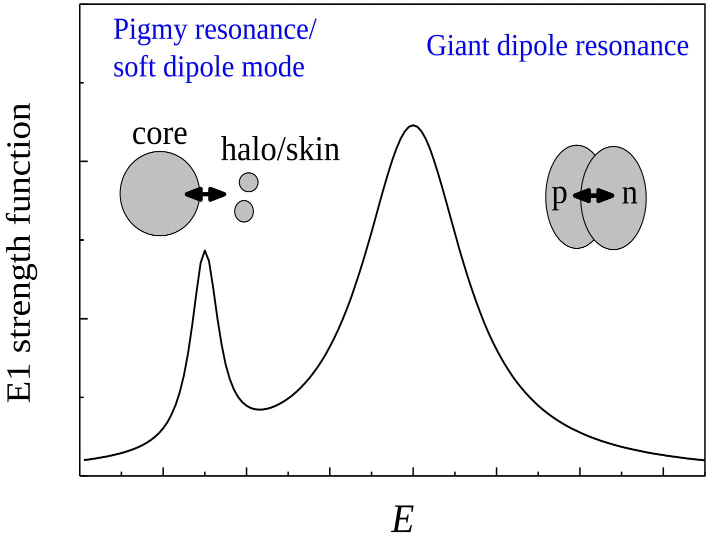
There is a strong low energy peak even without any final state interaction

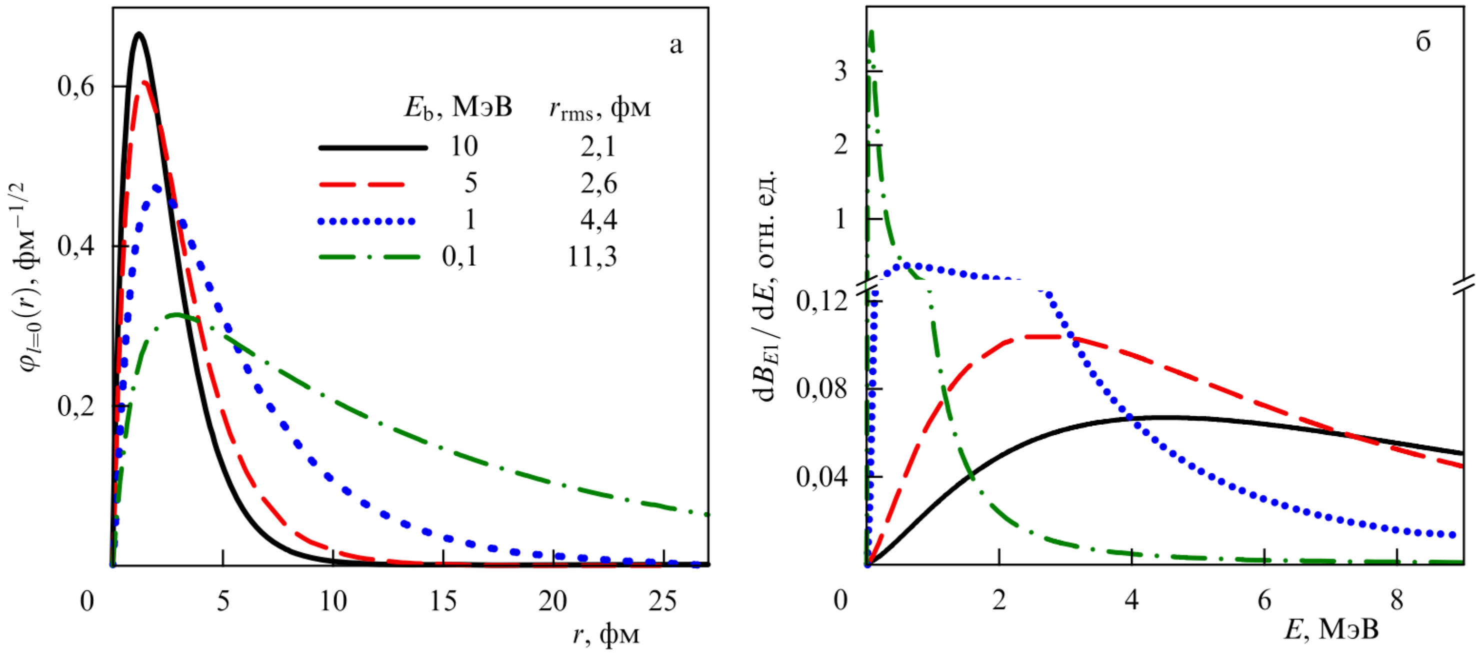
Estimate of soft dipole mode in on-neutron halo system

$$\phi_{l=0}(r) = N\left[\exp(-k_1 r) - \exp(-k_2 r)\right], \quad k_1 = \sqrt{2ME_b},$$

$$M_{E1}(E) = \int_0^\infty \mathrm{d}r\,(pr)\,j_{l=1}(pr)\,r\phi_{l=0}(r), \quad p = \sqrt{2ME},$$

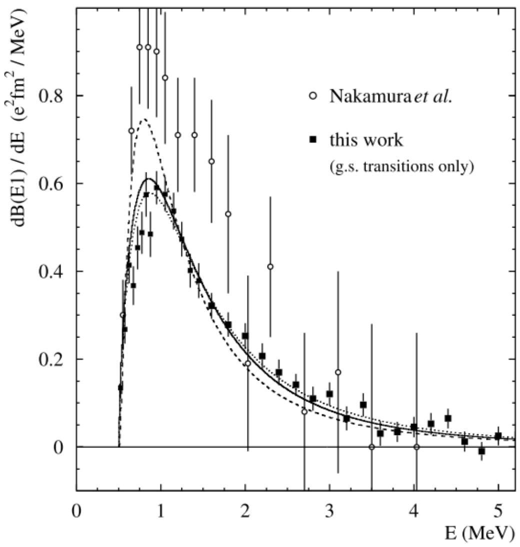
$$\frac{\mathrm{d}B_{E1}}{\mathrm{d}E} \sim \frac{|M_{E1}(E)|^2}{\sqrt{E}}.$$



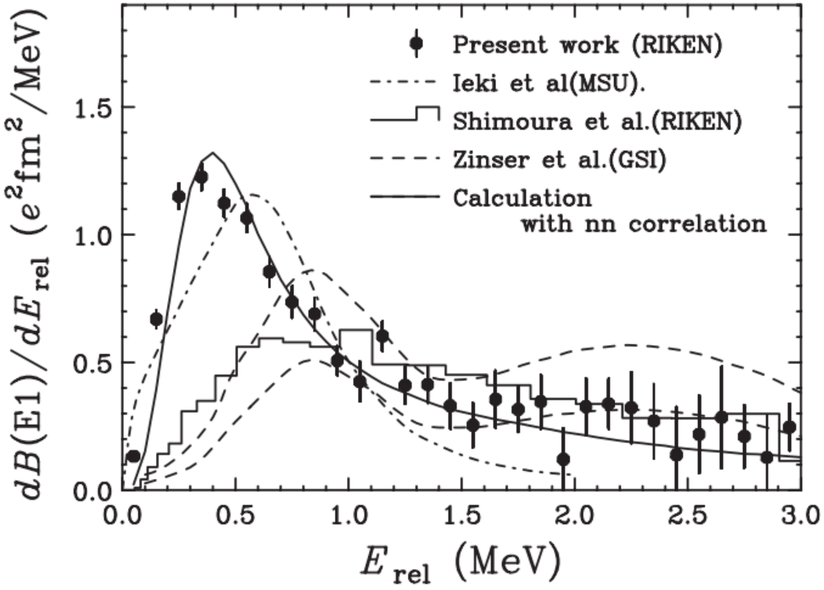


Soft dipole mode in two-body and three-body continuum

^{11}Be

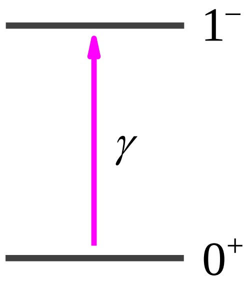


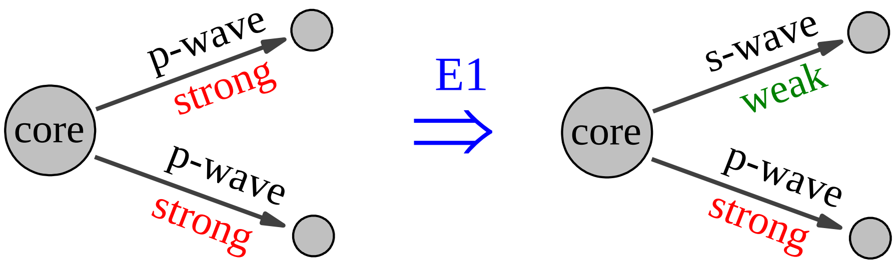
^{11}Li



Well understood in two-body systems

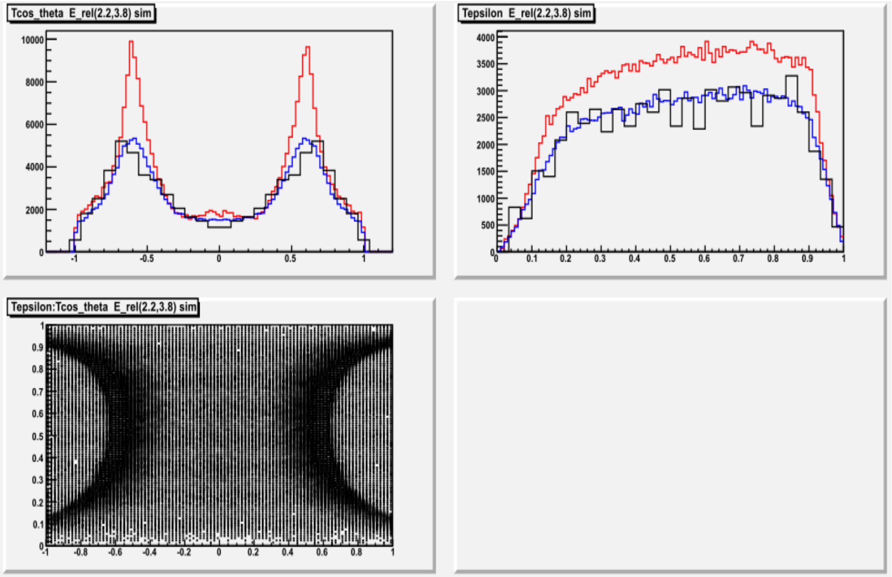
Poorly understood in two-body systems

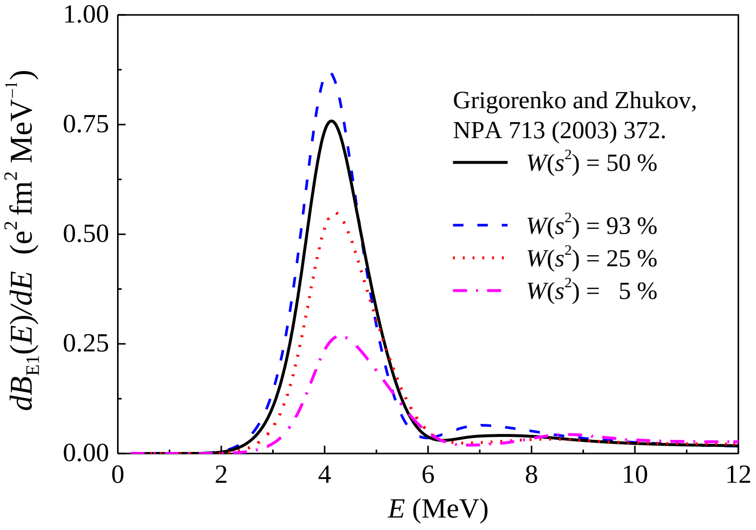


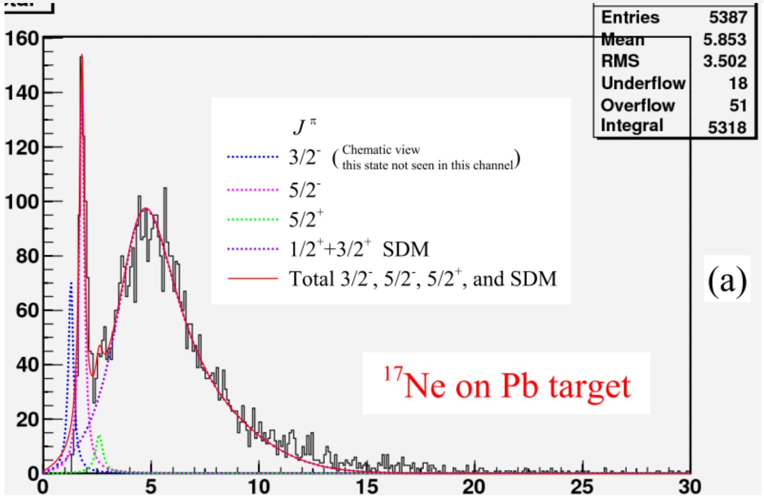


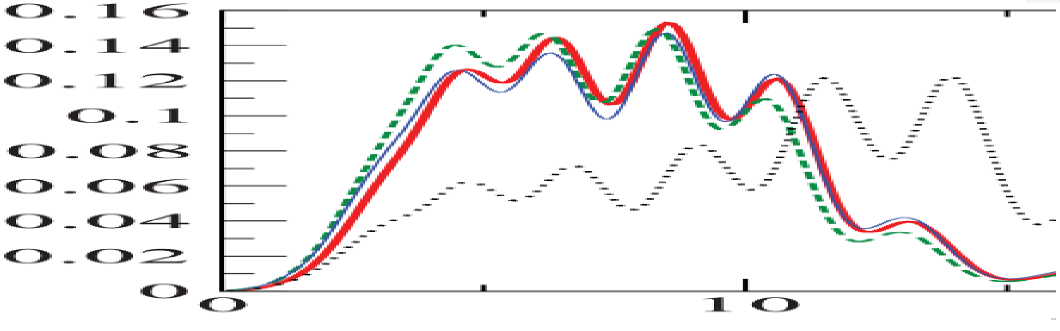
Soft dipole mode in ^{17}Ne

- L.V.Grigorenko, K.Langanke, N.B.Shul’gina, M.V.Zhukov, PLB **641** (2006) 254.
- Very expressed soft dipole peak has been predicted for ^{17}Ne
- For the recent results on GSI S318 experiment





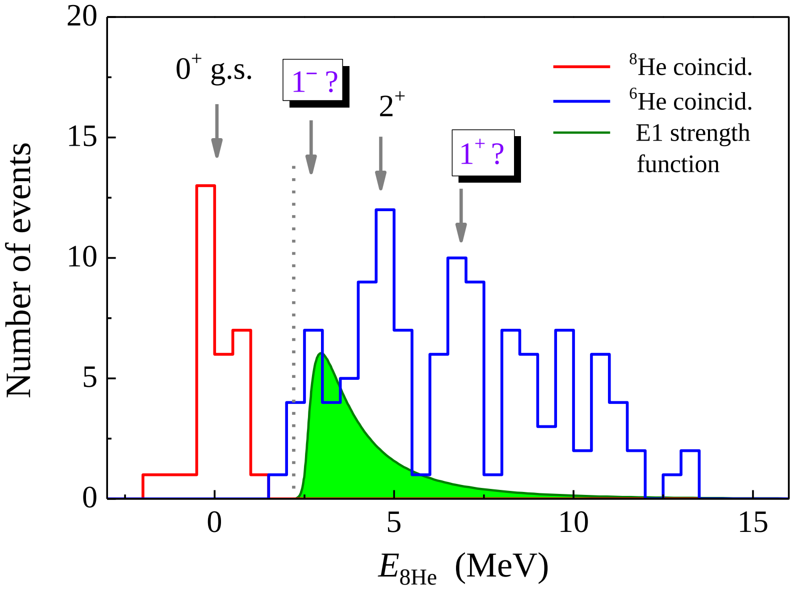




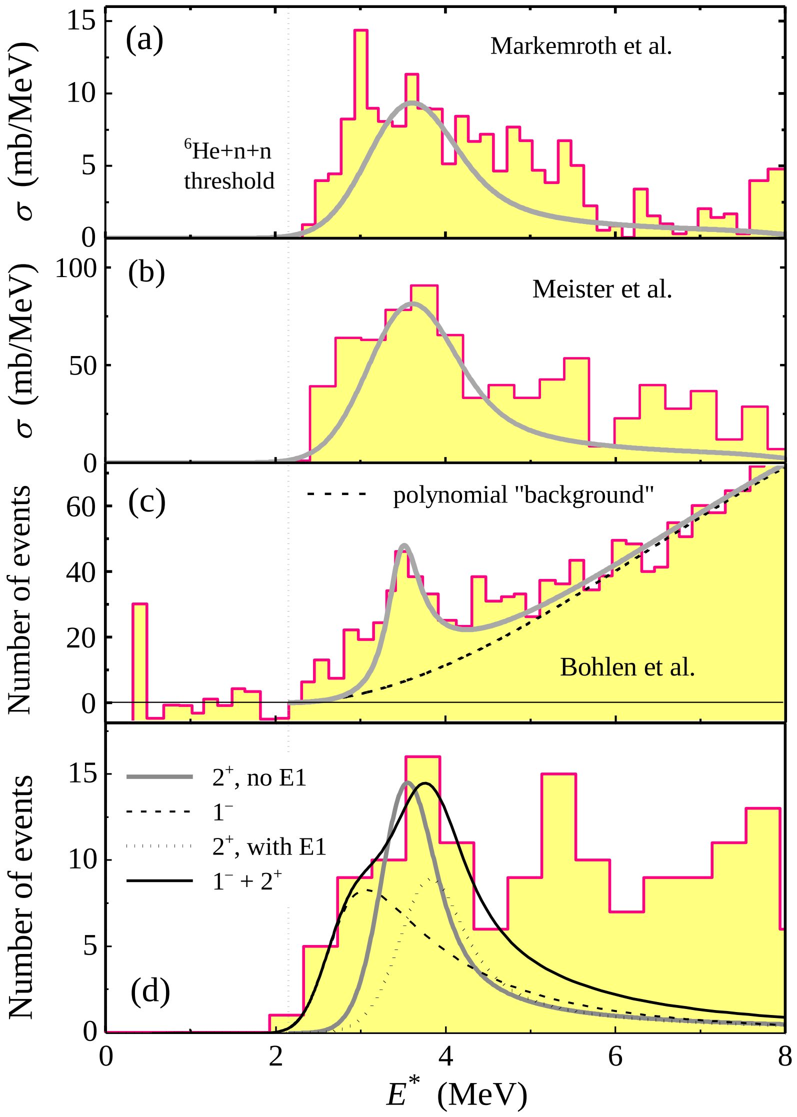
T. Oishi, K. Hagino, and H. Sagawa
PRC 84, 057301 (2011)
“Effect of proton-proton Coulomb repulsion on soft dipole excitations of light proton-rich nuclei”

Soft dipole mode in ^{8}He

M.S.Golovkov et al., PLB **672** (2009) 22
L.V. Grigorenko et al., Part. Nucl. Lett. **6** (2009) 118



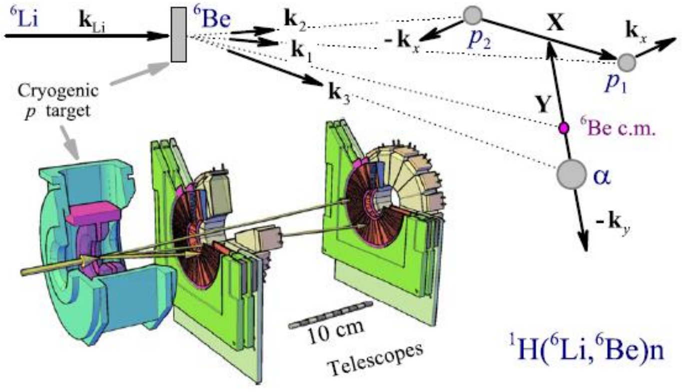
- Large uncertainty in the 2^+ ^{8}He state energy
  $E(2^+)$ = 2.7 - 3.6 MeV
  D.R. Tilley et al. NPA 745 (2004) 155
- "Standard" R-matrix: energy ~3.6 MeV and Wigner limit width ~0.6 MeV
- Low-energy events are not reproduced in any of the cases
- E1 contribution can modify the positions of 2+ state up to about 3.9 MeV

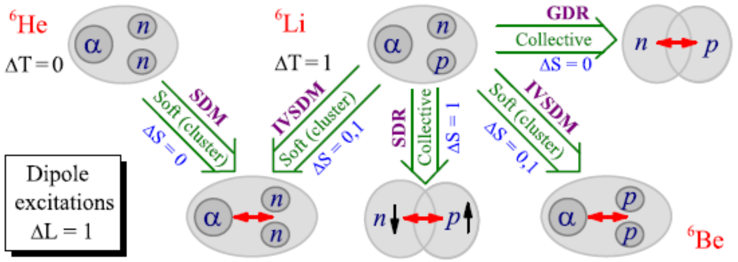


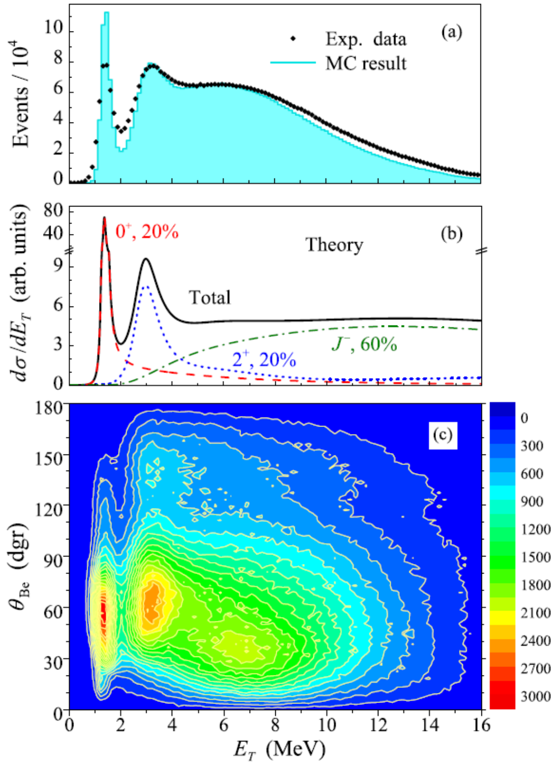
Corrected first 2^+ states position in ^{8}He

IsoVector Soft Dipole Mode in ^{6}Be

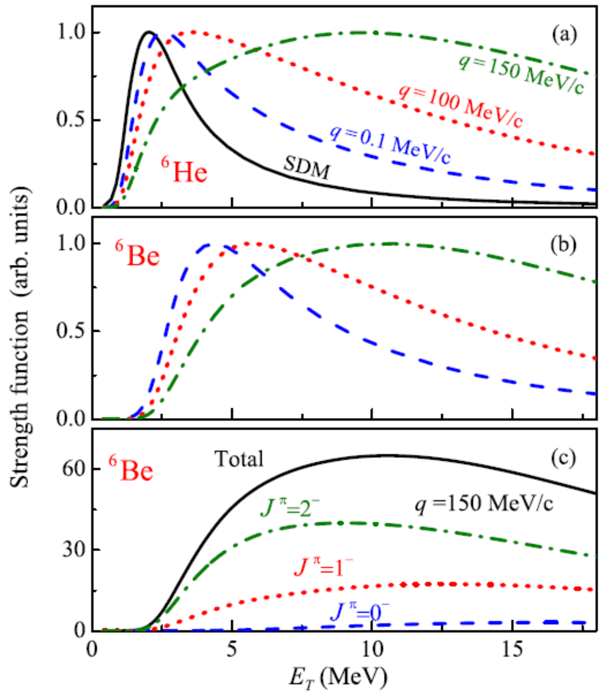
A.S.Fomichev et al., PLB **708** (2012) 6.







- Large cross section above 2^+ and no resonance
- ΔL = 1 identification – some kind of dipole response
- No particle stable g.s. – can not be built on spatially extended g.s. WF
- Built on the spatially extended ^{6}Li g.s.

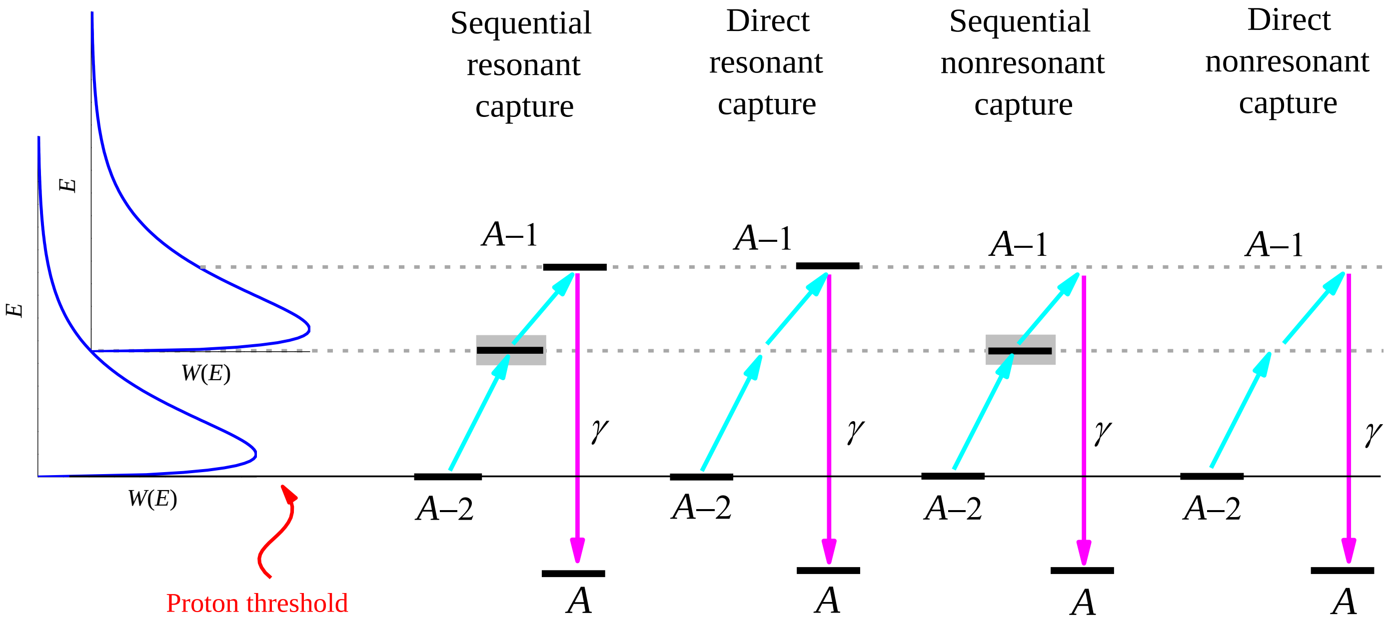


Experimentally observed and theoretically discussed: IVSDM as a specific form of SDM

Astrophysical applications

For astrophysical application knowledge of BOTH resonant and nonresonant radiative capture cross sections can be needed depending on specific situation. While RESONANT radiative capture requires the knowledge of resonance properties only, for understanding of nonresonant capture studies of excitation modes are required

Modes of (2p) radioactive capture



Reverse to sequential 2p decay

Reverse to true 2p decay

Reverse to soft dipole mode

2p				^{19}Mg	^{20}Mg	^{21}Mg
p				^{18}Na	^{19}Na	^{20}Na
2p			^{16}Ne	^{17}Ne	^{18}Ne	^{19}Ne
p			^{15}F	^{16}F	^{17}F	
2p	^{12}O	^{13}O	^{14}O	^{15}O	^{16}O	

- rp-process at high density and temperature.
- ^{15}O, ^{18}Ne, ^{38}Ca : J.Gorres, M.Wiescher, and F.-K.Thielemann, PRC **51** (1995) 392.
- ^{68}Se, ^{72}Kr, … ,^{96}Cd : H.Schatz et al., Phys. Rep. **294** (1998) 167.

Resonant radiative capture

Nucleosynthesis: Saha (chemical balance) equations

$$\dot{Y}^{(i)}_{A+1} = N_A\,\rho\langle\sigma_{p,\gamma}v\rangle_i\ Y_pY_A - \Gamma_i Y^{(i)}_{A+1}$$

$$\dot{Y}_{A+2} = (1/2)\ N_A^2\,\rho^2\langle\sigma_{2p,\gamma}v\rangle\ Y_p^2Y_A$$

$$\langle\sigma_{p,p}v\rangle_i = \int v\sigma_i(E_{12})w(k_{12})d^3k_{12}$$

$$w(k_{12}) = (2\pi m_{12}kT)^{-3/2}\exp[-E_{12}/kT]$$

$$\sigma(E) = \frac{\pi}{k_{12}^2}\,\frac{\Gamma_\alpha\Gamma_\beta}{(E-E_R)^2+\Gamma^2/4}\,\frac{2J_{2R}+1}{(2J_1+1)(2J_2+1)}$$

$$\int_{-\infty}^{\infty}\frac{dE}{(E-E_R)^2+\Gamma^2/4} = \frac{2\pi}{\Gamma}$$

Proton capture

$$\langle\sigma_{p,\gamma}v\rangle_i = \int v\sigma_i(E_{12})w(k_{12})d^3k_{12} = \left(\frac{A_1+A_2}{A_1A_2}\right)^{3/2} \times \frac{2J_{2R,i}+1}{2(2J_I+1)}\left(\frac{2\pi}{mkT}\right)^{3/2}\exp\left[-\frac{E_{2R,i}}{kT}\right]\frac{\Gamma_p\Gamma_\gamma}{\Gamma}$$

Two-Proton capture

$$\langle\sigma_{2p,\gamma}v\rangle = \left(\frac{A_1+A_2+A_3}{A_1A_2A_3}\right)^{3/2}\frac{2J_F+1}{2(2J_I+1)}\left(\frac{2\pi}{mkT}\right)^3 \times \exp\left[-\frac{E_{3R}}{kT}\right]\frac{\Gamma_{2p}\Gamma_\gamma}{\Gamma_{3R}}.$$

Problem of resonant radiative capture is just time-reversed problem of radioactive decay

Need to know ONLY particle and gamma widths

Nonresonant radiative capture

$$(\hat{H} - E)\Psi_E^{(+)}(\rho, \Omega_\rho) = \hat{D}\Psi_{\text{g.s.}}(\rho, \Omega_\rho),$$

$$\hat{H} = \hat{T} + \hat{V}_{cp}(\mathbf{r}_{cp_1}) + \hat{V}_{cp}(\mathbf{r}_{cp_2}) + \hat{V}_{pp}(\mathbf{r}_{p_1 p_2}),$$

$$\frac{dB_{E1}(E)}{dE} = \frac{2J_f + 1}{2J_i + 1} \frac{1}{2\pi M} \operatorname{Im} \sum_{K\gamma}^{K_{\max}} \chi_{K\gamma}^{(+)*} \frac{d}{d\rho} \chi_{K\gamma}^{(+)} \Big|_{\rho \to \infty}$$

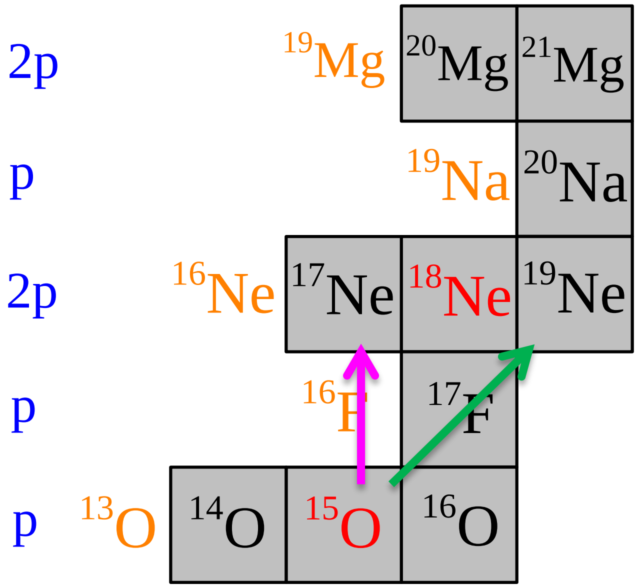
$$\langle \sigma_{2p,\gamma} v \rangle = \left(\frac{A_1 + A_2 + A_3}{A_1 A_2 A_3} \right)^{3/2} \left(\frac{2\pi}{mkT} \right)^3 \frac{2J_f + 1}{2(2J_i + 1)} \times \int dE \frac{16\pi}{9} e^2 E_\gamma^3 \frac{dB_{E1}(E)}{dE} \exp\left[-\frac{E}{kT} \right]$$

For nonresonant radiative capture to halo nucleus we need to understand soft dipole excitations

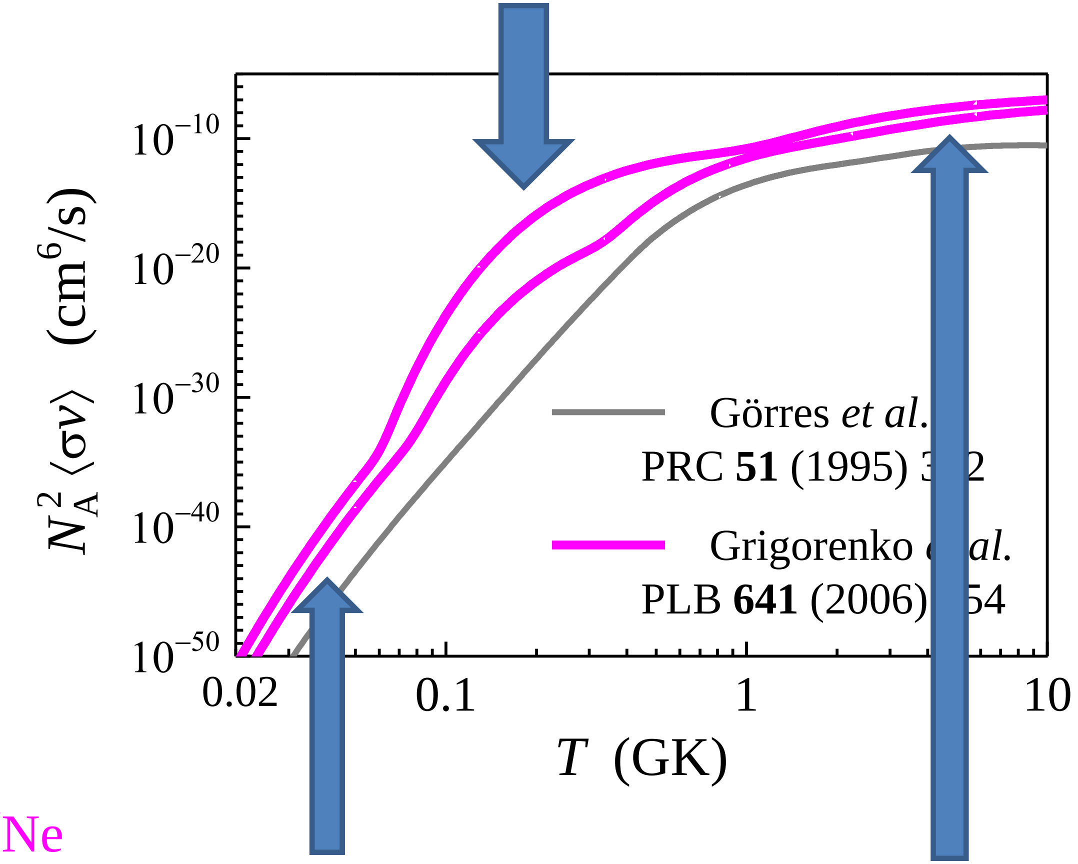
Application to nuclear astrophysics

«waiting point»

^{15}O $T_{1/2} = 122$ s



Resonant radiative capture on 3/2$^-$



Nonresonant radiative capture on 1/2$^+$, 3/2$^+$

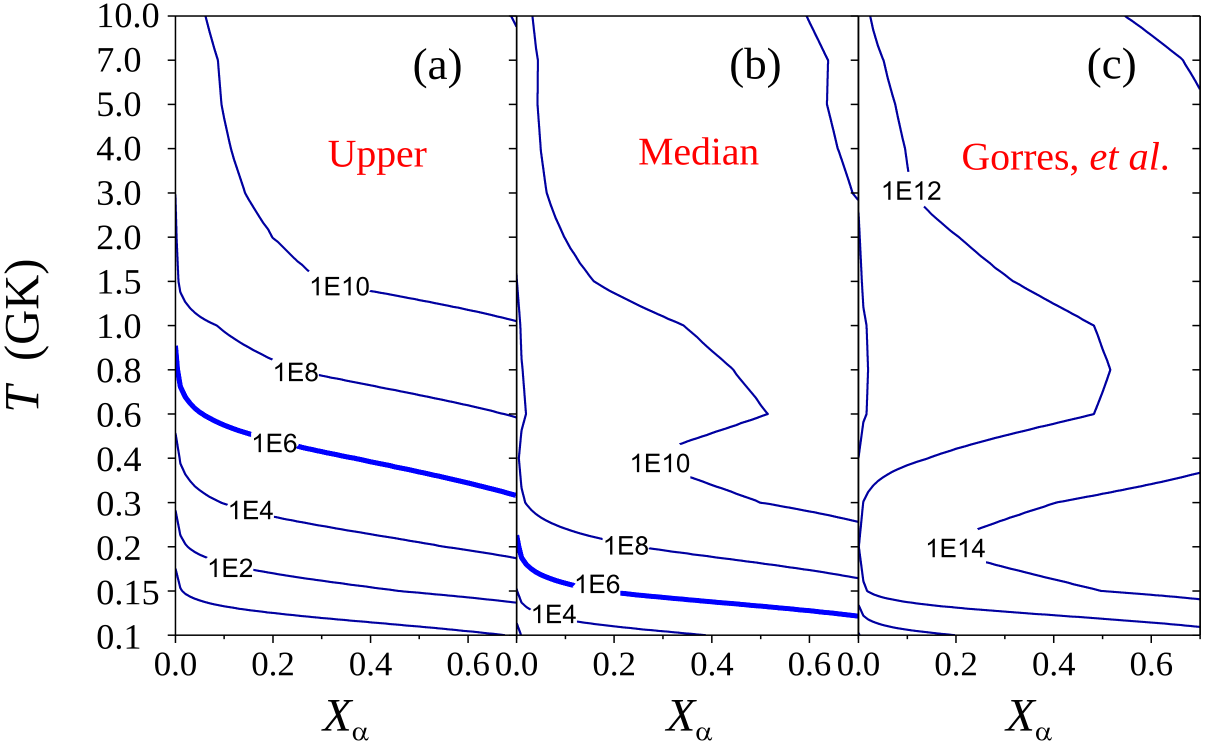
2p radiative capture competes with

^{15}O(2p,γ)^{17}Ne

^{15}O(α,γ)^{19}Ne

Competition between α and 2p capture

- $^{15}O(2p,\gamma)^{17}Ne$ versus $^{15}O(\alpha,\gamma)^{19}Ne$
- Densities (in g/ccm) at which the production rate of ^{17}Ne by 2p-capture on ^{15}O equals the production rate of ^{19}Ne by α capture as function of temperature and α-particle mass abundance $X_\alpha = 4\,Y_\alpha$.



Democratic decay

^{10}He. Extreme importance of reaction mechanism

The resonance is, by definition, something insensitive to population conditions. However, when resonances become sufficiently broad, their OBSERVABLE properties may become sensitive to initial state properties and reaction mechanism details. Thus, such broad resonances may obtain properties characteristioc for excitation modes. Broad ground state resonances are typical for democratic 2n decays of nuclei beyond the neutron dripline.

Origins of ideas

Democratic decay concept:
Inspired by experimental data

Two-proton radioactivity:
Predicted theoretically

Goldansky, NPA **19** 482 (1960)

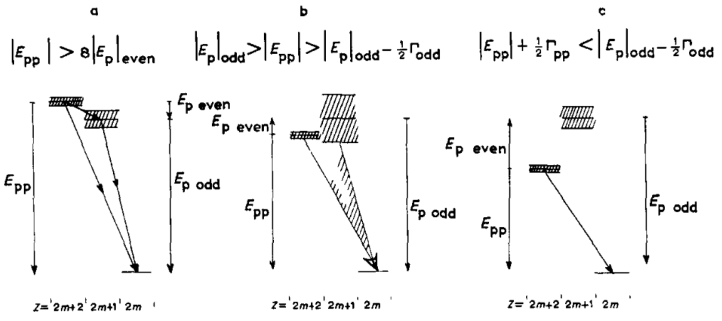
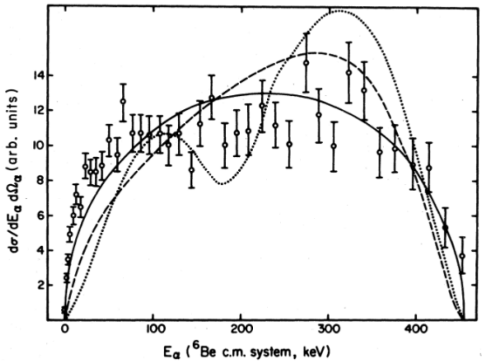
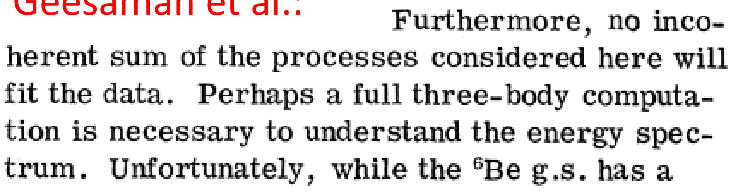


Fig 3 Two-proton radioactivity.

Geesaman et al., PRC **15** 1835 (1977)

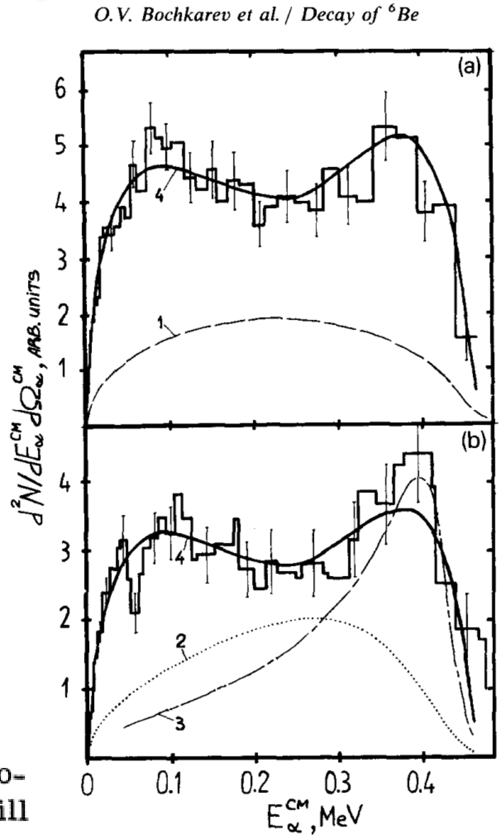


Geesaman et al.:



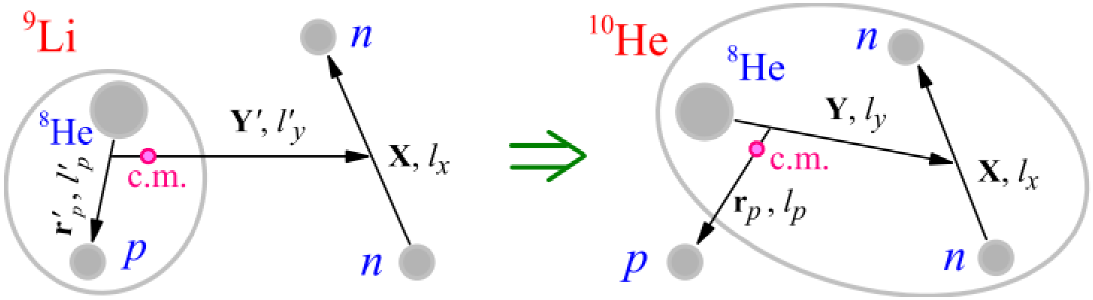
Furthermore, no incoherent sum of the processes considered here will fit the data. Perhaps a full three-body computation is necessary to understand the energy spectrum. Unfortunately, while the ^{6}Be g.s. has a

Bochkarev et al., NPA **215** (1989) 215 (1989)



p-p scatering length *a* ~ 30 fm

^{10}He populated from ^{11}Li in a sudden removal model



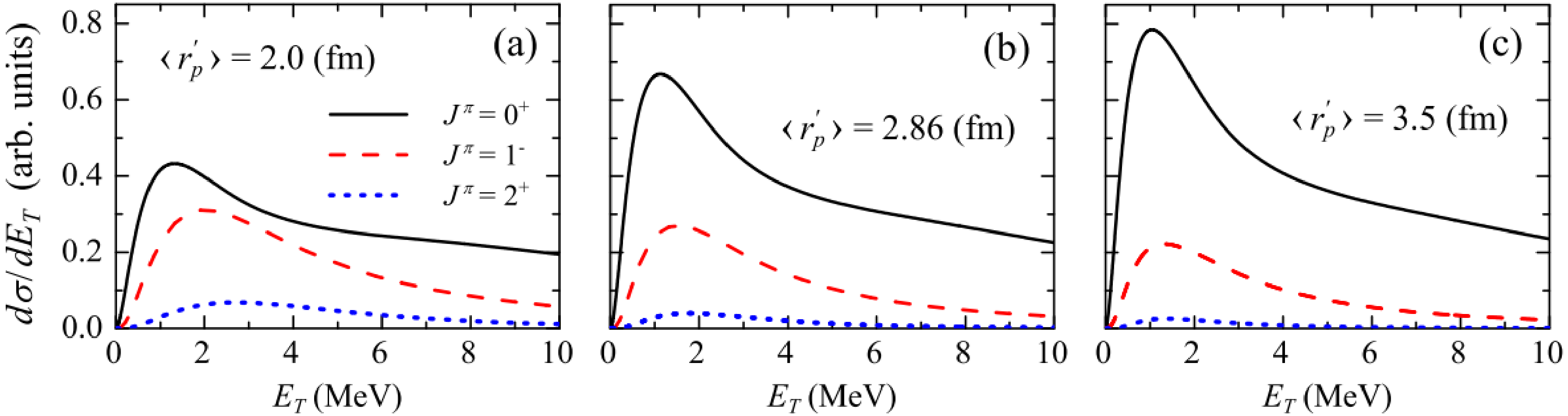
$$(\hat{H}_3 - E_T)\Psi^{JM(+)}_{E_T}(X,Y) = \Phi^{JM}_q(X,Y).$$

$$\Phi_{\mathbf{q}}(\mathbf{X},\mathbf{Y}) = \int d^3\mathbf{r}_p e^{i\mathbf{q}\mathbf{r}_p}\Psi_{^{11}\mathrm{Li}}(\mathbf{X},\mathbf{Y},\mathbf{r}_p).$$

Removal of a deeply bound proton from ^{11}Li

Large center-of-mass recoil effects, population of different J^{π}

Abnormal radial extents for formfactors of excited states



^{10}He populated in transfer and in knockout from ^{11}Li

^{10}He spectrum from ^{11}Li is dominated by the initial state contribution

^{10}He spectrum from ^{11}Li is a pileup of different J^{π}

Recently studied true 2n emitters:

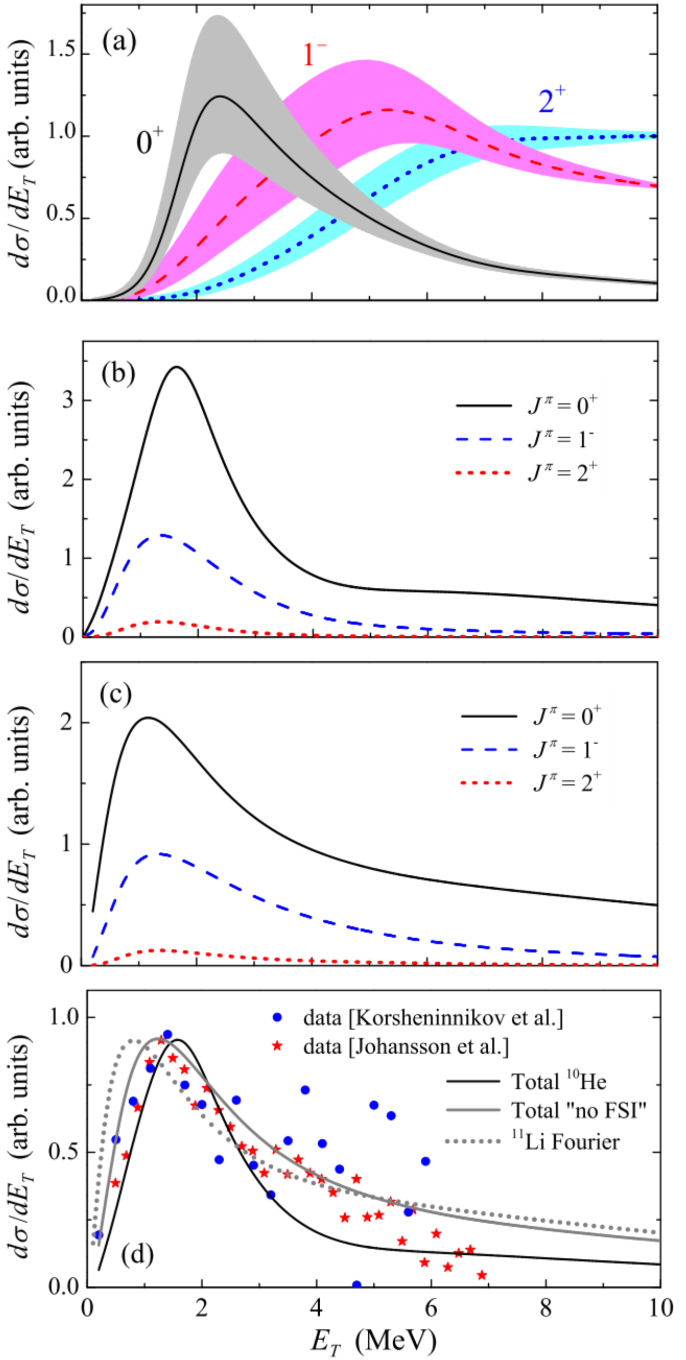
- ^{10}He: Golovkov et al., PLB 672, 22 (2009),
  Johansson et al., NPA 842, 15 (2010),
  Sidorchuk et al., PRL 108, 202502 (2012),
  Z. Kohley et al., PRL 109, 232501 (2012).
- ^{13}Li: Aksyutina et al., PLB 666, 430 (2008),
  Z. Kohley et al., PRC 87, 011304(R) (2013).
- ^{16}Be: Spyrou et al., PRL 108, 102501 (2012).
- ^{26}O: Lunderberg et al., PRL 108, 142503 (2012),
  Caesar et al., PRC 88, 034313 (2013),
  Z. Kohley et al., PRL 110, 152501 (2013).

^{10}He spectrum from transfer

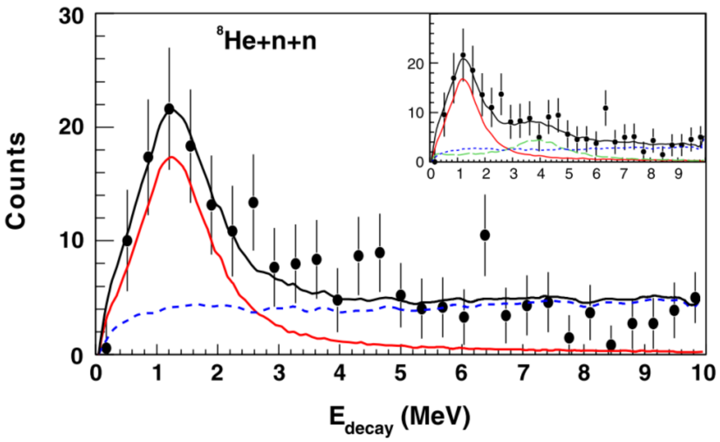
^{10}He spectrum from ^{11}Li

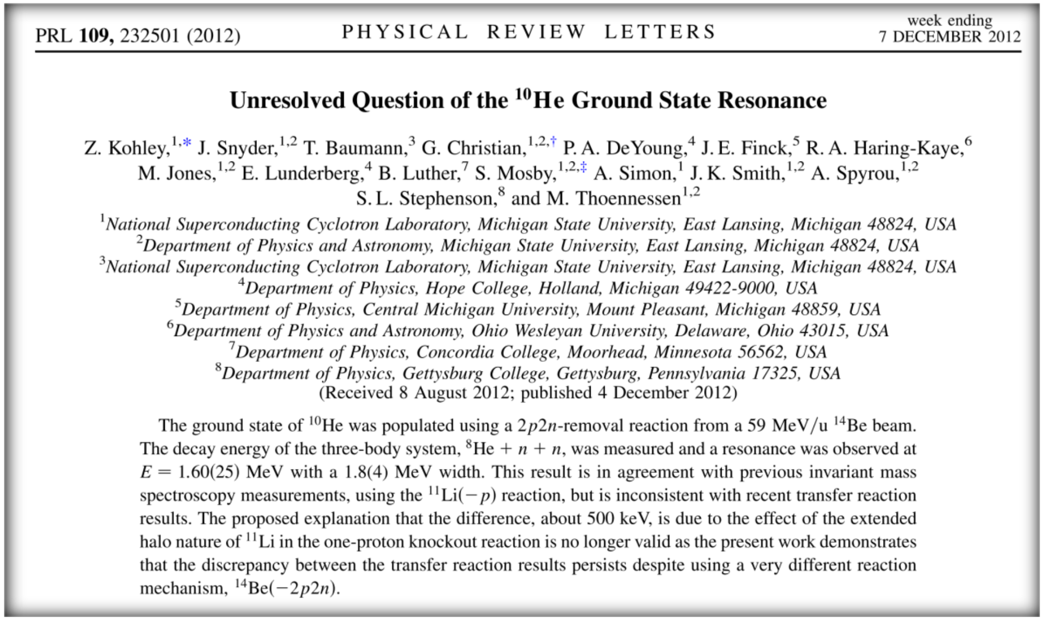
Fourier transform of ^{11}Li source function (no ^{10}He FSI)

^{10}He data calculation with FSI calculation “no FSI”



^{10}He populated in transfer and alpha removal from ^{14}Be





PRL **109,** 232501 (2012) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2012

Unresolved Question of the ^{10}He Ground State Resonance

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The ground state of ^{10}He was populated using a $2p2n$-removal reaction from a 59 MeV/u ^{14}Be beam. The decay energy of the three-body system, ^{8}He + n + n, was measured and a resonance was observed at $E = 1.60(25)$ MeV with a 1.8(4) MeV width. This result is in agreement with previous invariant mass spectroscopy measurements, using the ^{11}Li($-p$) reaction, but is inconsistent with recent transfer reaction results. The proposed explanation that the difference, about 500 keV, is due to the effect of the extended halo nature of ^{11}Li in the one-proton knockout reaction is no longer valid as the present work demonstrates that the discrepancy between the transfer reaction results persists despite using a very different reaction mechanism, ^{14}Be($-2p2n$).

^{14}Be has extreme halo configuration

^{6}Be example from MSU