Soft E1 mode in the 2p Borromean nucleus ^{17}Ne

Yu. Parfenova, L. Grigorenko, I. Egorova, N. Shulgina, M. Zhukov

JINR, Dubna, Russia
GSI, Darmstadt, Germany
Kurchatov Institute, Moscow, Russia
INP MSU, Moscow, Russia
Chalmers University of Technology, Gothenburg, Sweden

- Introduction: What is beyond the dripline.
- Why do we study ^{17}**Ne?**

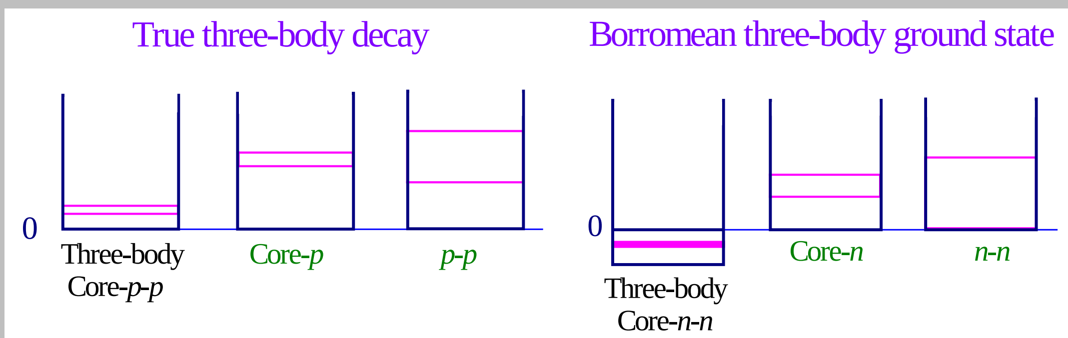
1. Analogy between 2p emitters and 2p halo nuclei.
2. Atrophysical aspect
3. Understanding of asymmetric nuclear matter Eos
4. Soft E1 mode (pigmy resonance) and GDR in dripline nuclei

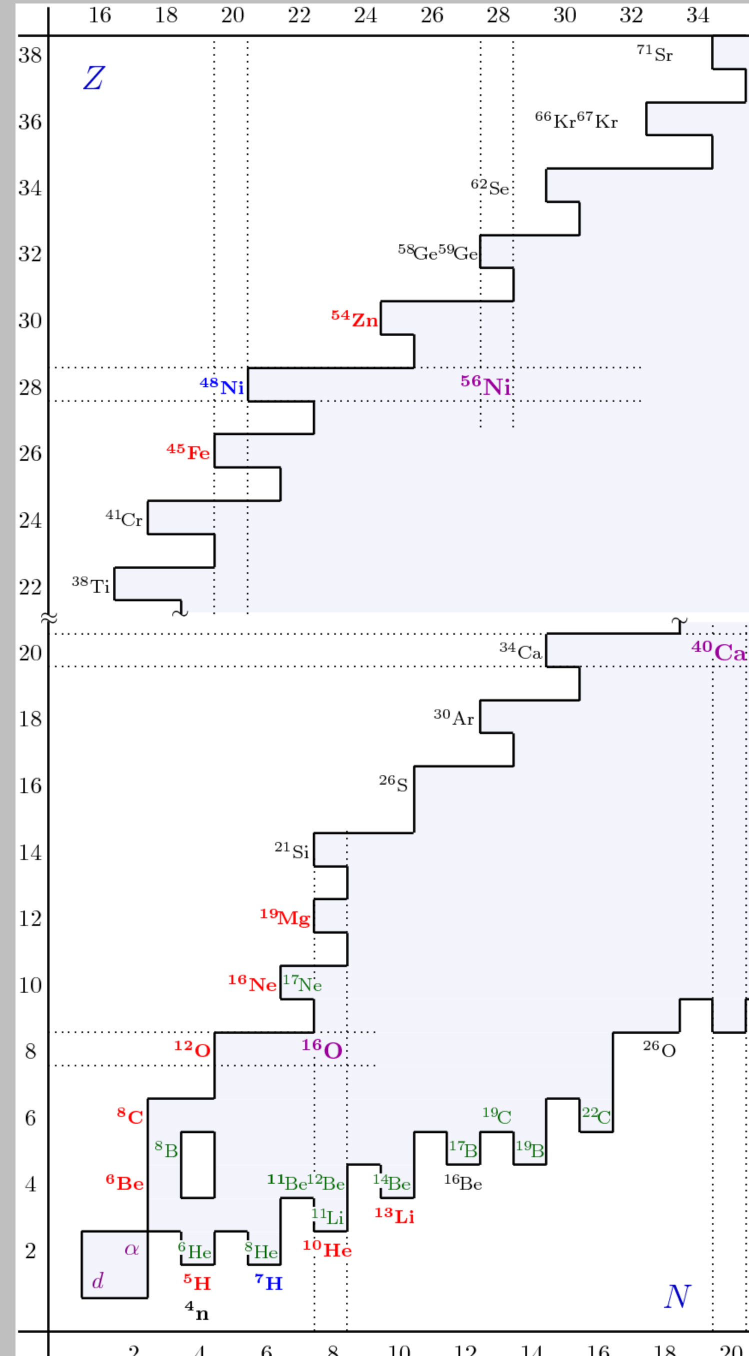
- Combined **model 2012**
- Simulation of experimental setup
- Results of calculations
- Conclusions; Outlook

What is known beyond the driplines? Why do we study ^{17}Ne

- Red – true 2p/2n emitters studied
- Green – halo systems
- Black – **nothing** is known

Analogy: 2p decay & Borromean property of halo nuclei





What is known beyond the driplines?
Why do we study ^{17}Ne

- Red – true 2p/2n emitters studied
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- Black – **nothing** is known

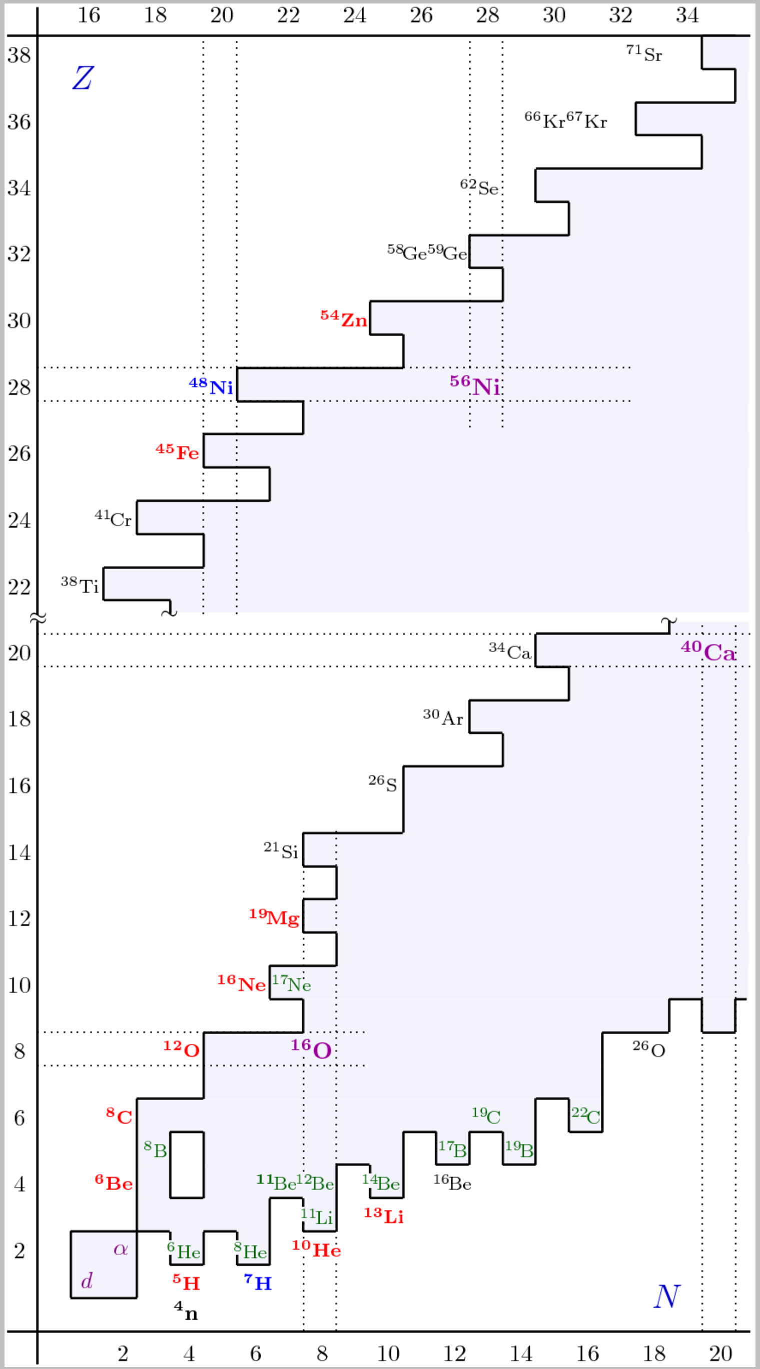
Analogy: 2p decay & Borromean property of halo nuclei

Every second nucleus beyond the proton dripline is or is expected to be true 2p emitter

- Known true 2p emitters: ^{6}Be, ^{12}O, ^{16}Ne, ^{19}Mg, ^{45}Fe, ^{48}Ni, ^{54}Zn.

Pretending to understand asymmetric nuclear matter EOS one need to extend our knowledge as far as possible beyond the driplines.

Astrophysical application : 2p capture reaction is time inversed 2p decay reaction



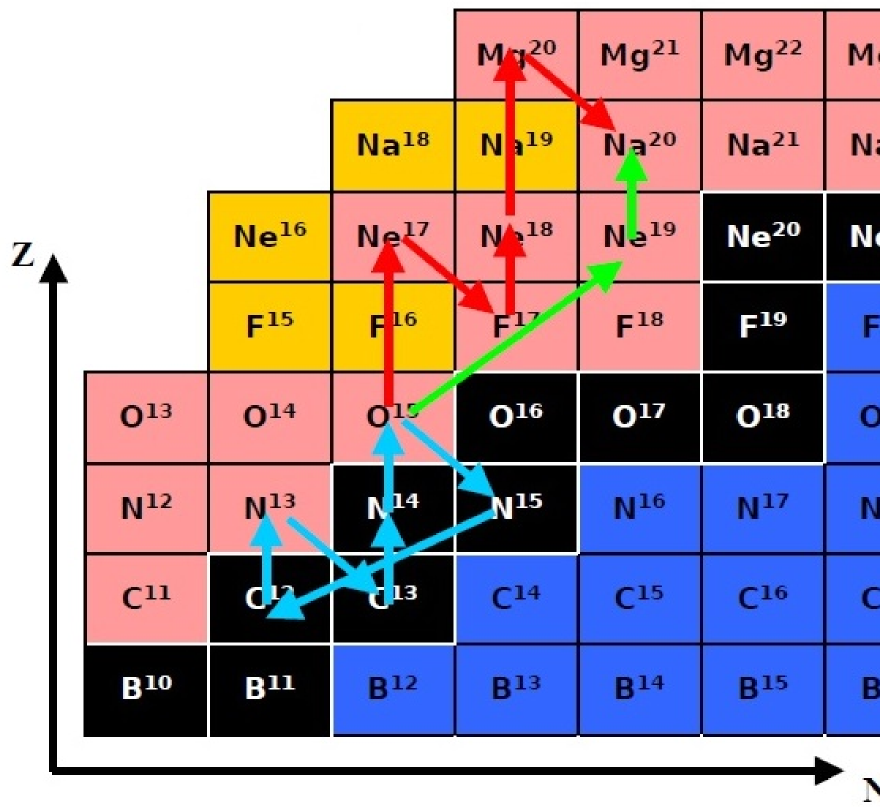
Astrophysical application

CNO cycle: $^{12}C(p,\gamma)^{13}N(e,\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(e,\nu)^{15}N(p,\alpha)^{12}C$

the nucleus ^{15}O => a waiting point for the break-out of the CNO cycle

COMPETITION OF

- $^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$
- $^{15}O(2p,\gamma)^{17}Ne(\beta)^{17}F(p,\gamma)^{18}Ne(2p,\gamma)^{20}Mg(\beta)^{20}Na$



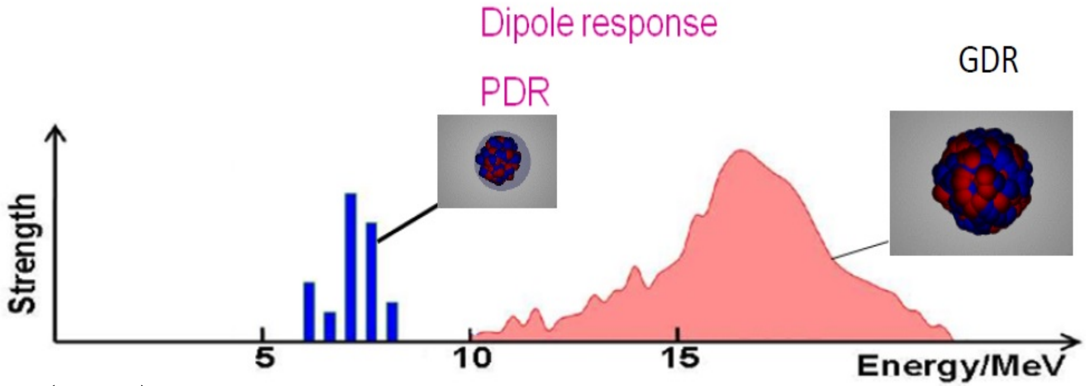
According to the **detailed balance theorem,** this reaction can be accessed as time-reversal one for E1 Coulomb dissociation of ^{17}Ne in lead target.

$^{17}Ne+\gamma \rightarrow {}^{15}O+2p$

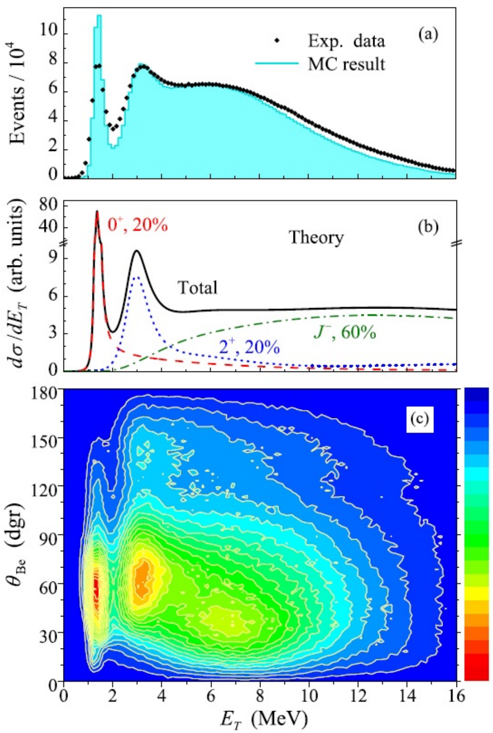
Kinematically complete measurements
LAND-R³B, ALADIN (GSI),S318

The Coulomb excitation has high selectivity for E1 excitation

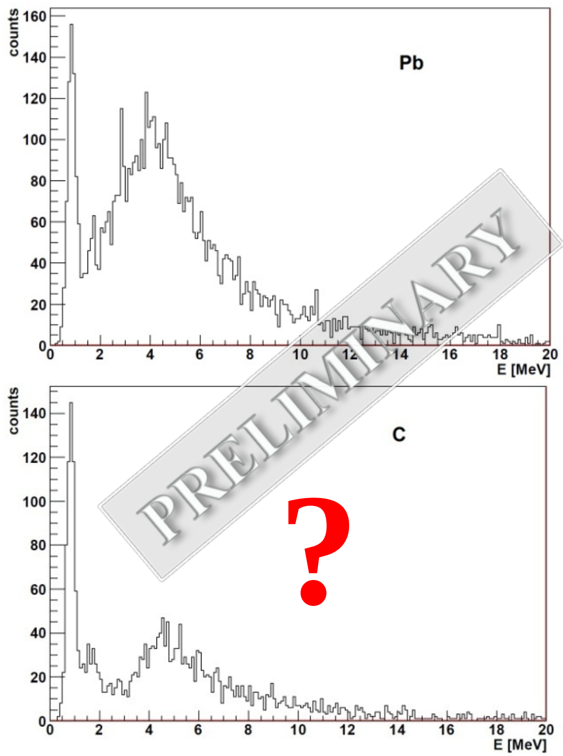
Soft E1 mode (Pigmy resonance) & GDR



PLB *708 (2012) 6*

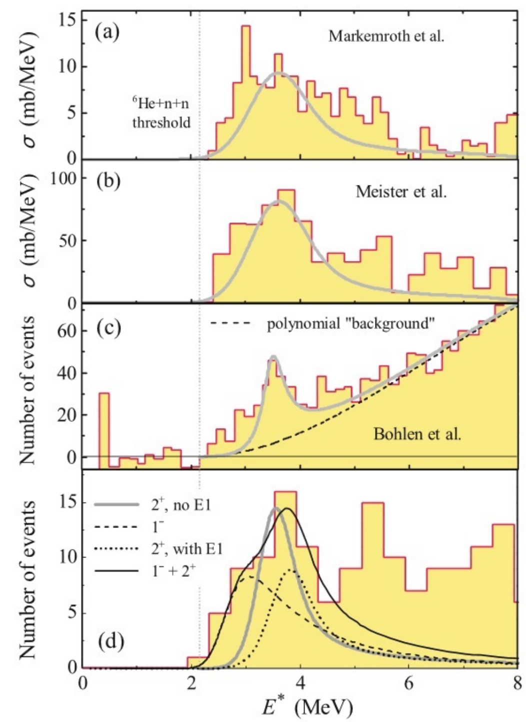


^{6}Be IVSDM



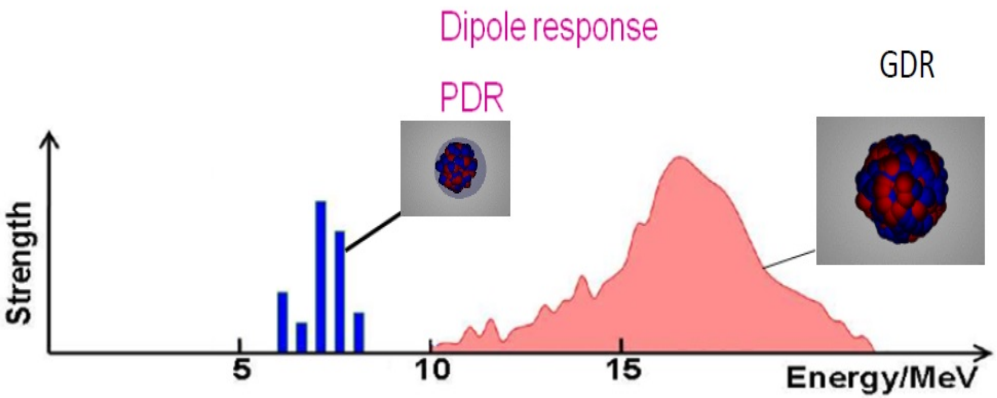
^{17}Ne

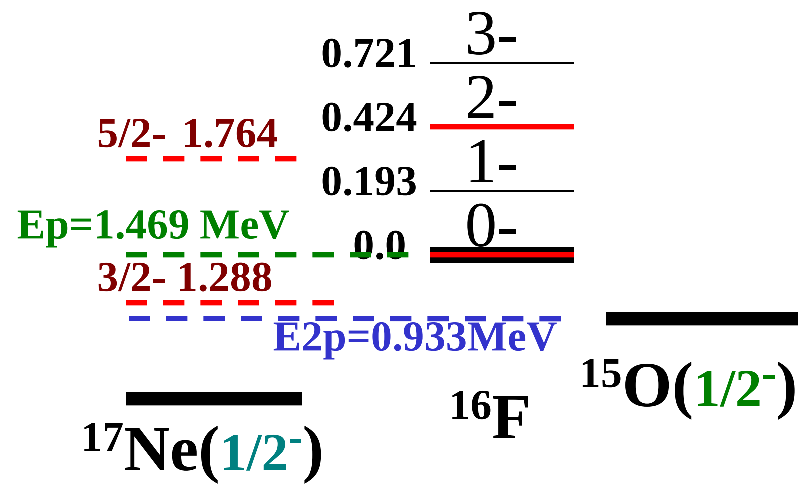
EPJA *42 (2009) 465*



^{8}He SDM

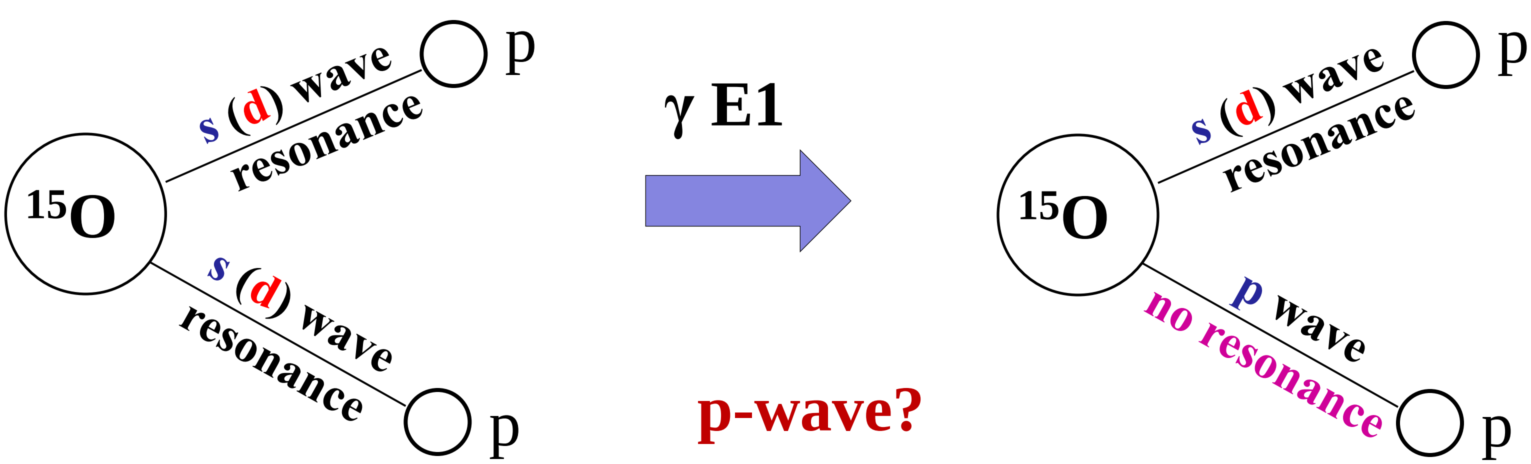
Soft E1 mode (Pigmy resonance) & GDR





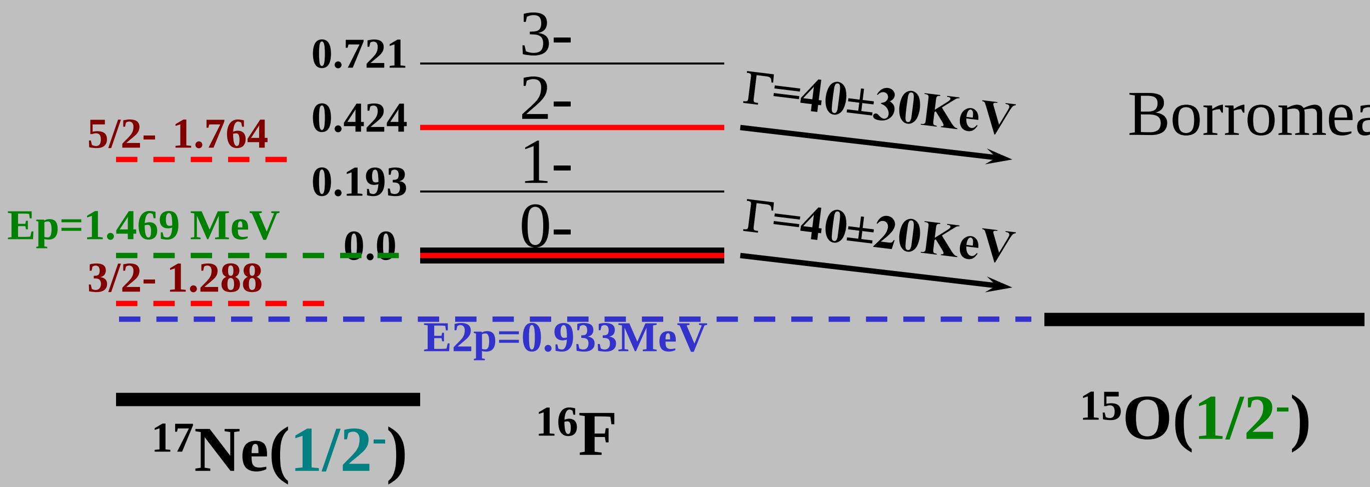
Soft E1 excitation in 3-body nucleus – not a resonace one

- p-wave state does not have a resonance
- position depends on mechanism of reaction



2p radioactivity and decay

2p -radioactivity was predicted by V. I.Goldansky in 1960 as an essentially quantum-mechanical phenomenon. True three-body decay, in his terms, occurs when sequential emission of 2p is energetically prohibited and all the final-state fragments are emitted simultaneously. The examples are: **^{17}Ne, ^{6}Be, ^{45}Fe, ^{54}Zn, ^{19}Mg**, and, maybe, **^{48}Ni**. All these decays exhibit specific correlation patterns. It is argued that studies of these patterns could provide important information on structure of the decaying nuclei.



Available experimental data on ^{17}Ne

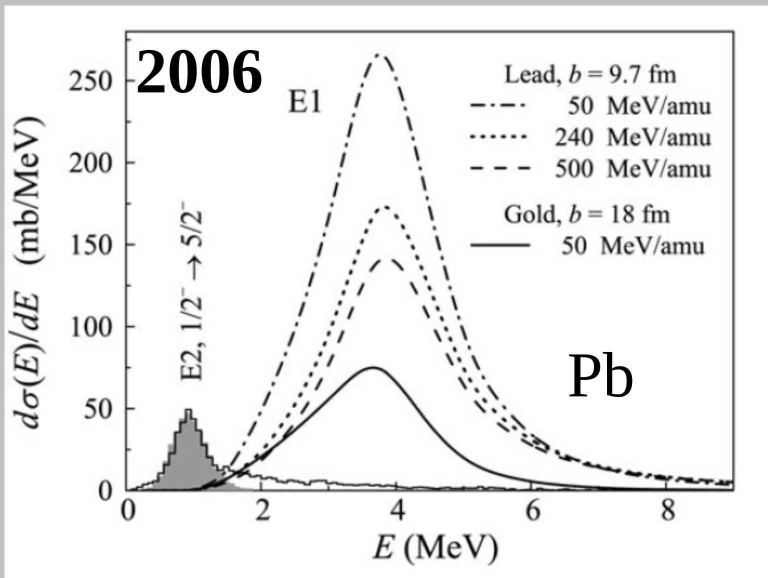
- Spectroscopic data (M.J. Chromik, et al., PRC **66** (2002) 024313).
- Mass and charge radii (W. Geithner et al, PRL 101 (2008) 252502)
- Magnetic moment $\mu=0.7873(14)\ \mu_N$ (W. Geithner et al, CERN-PH-EP/2005-016)
- Interaction cross section (A.Ozawa, et as, NPA693 (2001) 32)
- 2p removal cross section and ^{15}O momentum distributions (R. Kanungo et al, EPJA 25 (2005)327, NPA 734 (2004) 337)
- ^{16}F momentum ditributions (F. Wamers et al, EPJ Web of Conf., 66 (2014) 03094)
- Decay $3/2^-$(1.275 MeV) $\Gamma_{2p}/\Gamma \leq 8\ 10^{-5}$ (Dubna, JINR FLNR)

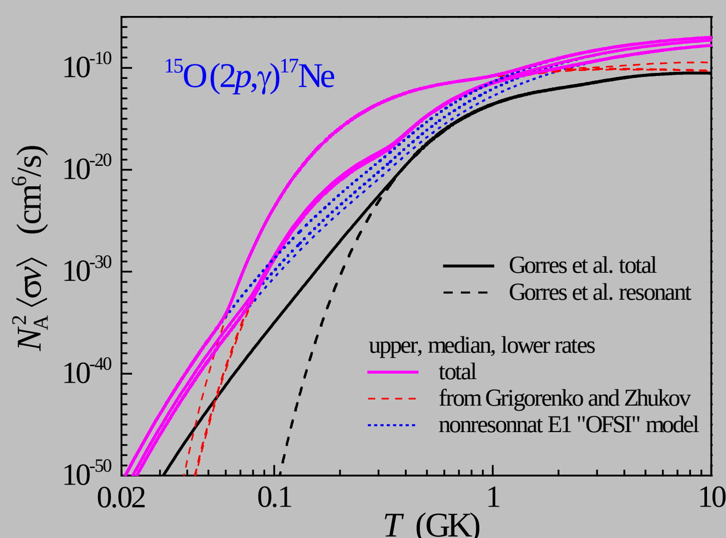
New generation of experimental facilities are used now, allowing the angular and energy distributions of the ^{15}O core fragment, correlation data (LAND-R^{3}B, ALADIN (GSI); missing mass, invariant mass, combined mass method in JINR, FLNR)

This **calls for predictive theoretical model**, where all these values can be obtained, which handle the modern experimental situation.

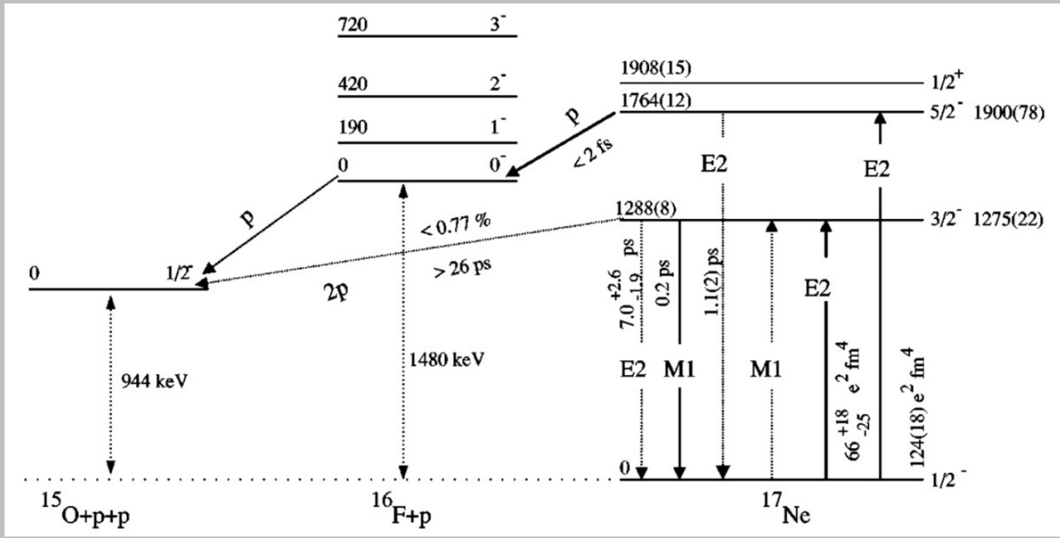
Where the "Soft E1" mode is supposed to be?

M.J. Chromik, et al., PRC **66** (2002) 024313.
L.V. Grigorenko, et al., PLB **641** (2006) 254





In 2-neutron halo nuclei, such as ^{6}He and ^{11}Li , the peak is placed at about 1 – 1.5 MeV. Theoretical predictions of L. Grigorenko et.al (PLB **641** (2006) 254) are: 4 MeV.



The astrophysical reaction rate can be enhanced by few orders of magnitude due to contributions of the non-resonant radiative 2p capture from continuum, for temperatures

T < 0.05–0.08 GK and T > 0.4–1.0 GK

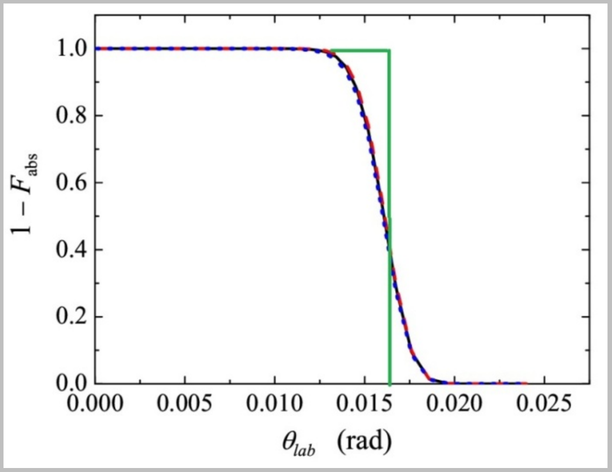
Model 2012

Quantity	σ_{-p}	σ_I	$d\sigma/dE$	$d\sigma/d\theta$	$d\sigma/dE/d\theta$	dB/dE	Θ,E-corr.
Eikonal Glauber model [1]	v	v		v		need	
Bertulani&Bauer model [2]	v		v	v	v	need	
Green Function method [3]	v		v			v	v

[1] H. Esbensen, G. F. Bertch, PRC **59**(1999) 3240
[2] C. Bertulani, G Bauer, NPA**442**(1985) 739
[3] L.V. Grigorenko, et al., PLB **641** (2006) 254

$$\frac{d\sigma_{tot}(E_T,\theta_{lab})}{dE_T\, d\theta_{lab}} = |A_C(E_T,\theta_{lab}) + A_N(E_T,\theta_{lab})|^2$$

$$A_C \approx \sqrt{\frac{d\sigma_C}{d\theta}\frac{dB_C}{B_C dE_T}\mathcal{F}_{abs}(\theta)} \;\; ; \;\; A_N \approx e^{i\phi_{rel}}\sqrt{\frac{d\sigma_N}{d\theta}\frac{dB_N}{B_N dE_T}}$$



$$\mathcal{F}_{abs} =< \psi_i|\; |S_1(\mathbf{b},\mathbf{r}_1)S_2((\mathbf{b},\mathbf{r}_2)S_3((\mathbf{b},\mathbf{r}_3)|^2\; |\psi_i >$$

Assumptions

- in the Bertulani-Bauer model the stepwise function at grazing angle is now replaced by smooth absorption function (no free parameter any more)
- strength function for the Coulomb and nuclear excitation is supposed to be similar
- angular distribution in nuclear interaction corresponds to classical trajectories obtained with Coulomb and nuclear potential

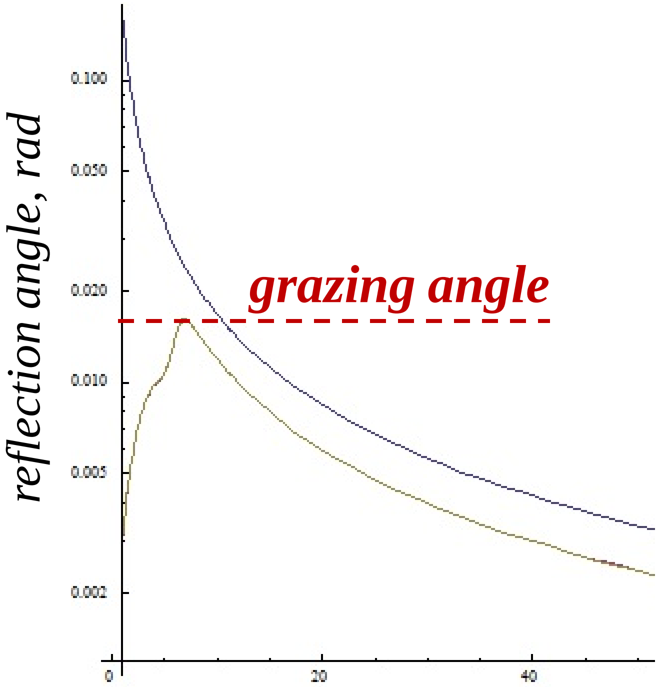
In use

- 3-body wave function of ^{17}Ne obtined with hyperspherical harmonics method
- Glauber model parameters are fitted [4] using available experimental data

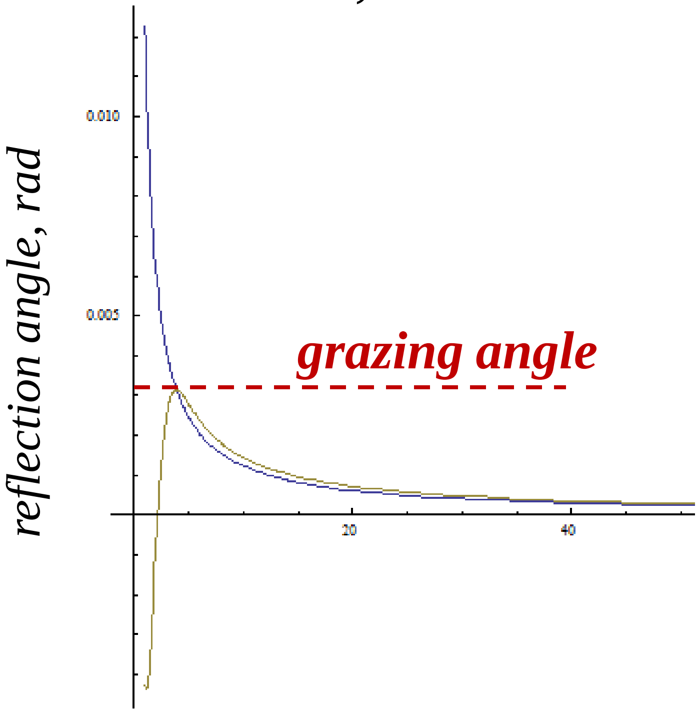
[2] Yu. Parfenova, Zhukov, M. V. (2006). *AIP Conf. Proc., September 2005*, 526

Concerning...angular distribution in nuclear interaction corresponds to the classical trajectories - these scattering angles are not realized

Ne+Pb, 200 A MeV

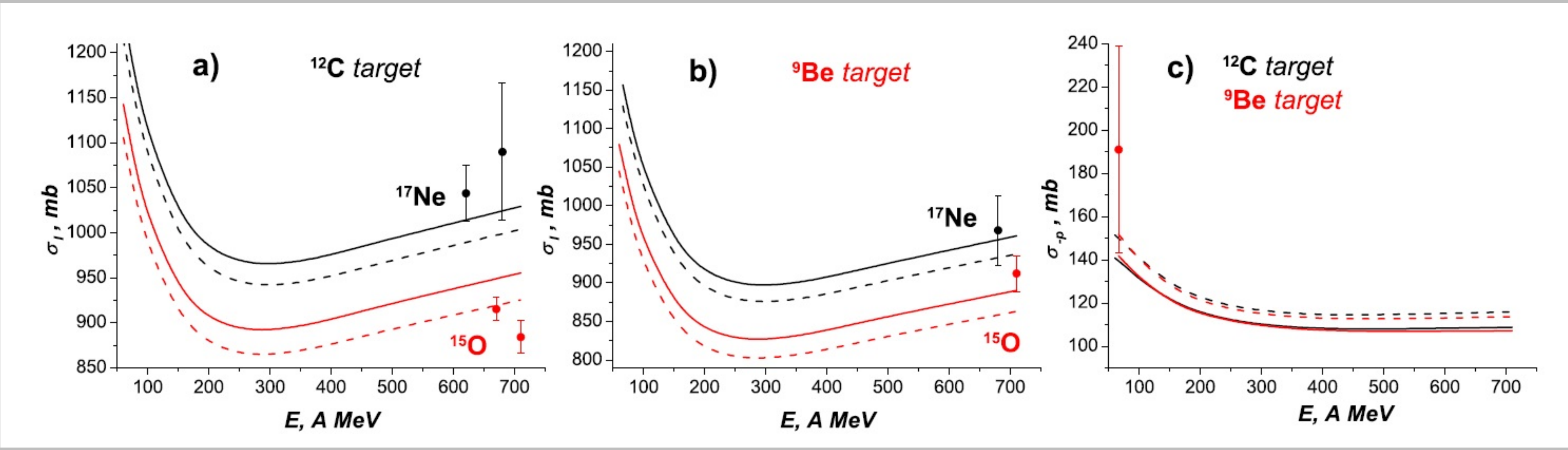


Ne+C, 200 A MeV



Eikonal Approximation of the Glauber model PARAMETERS

Data of Ozawa, R. Kanungo etc.



This model was combined with Monte Carlo simulations of observables (code GENERATOR), taking into account the apparatus bias and resolution in an experiment.

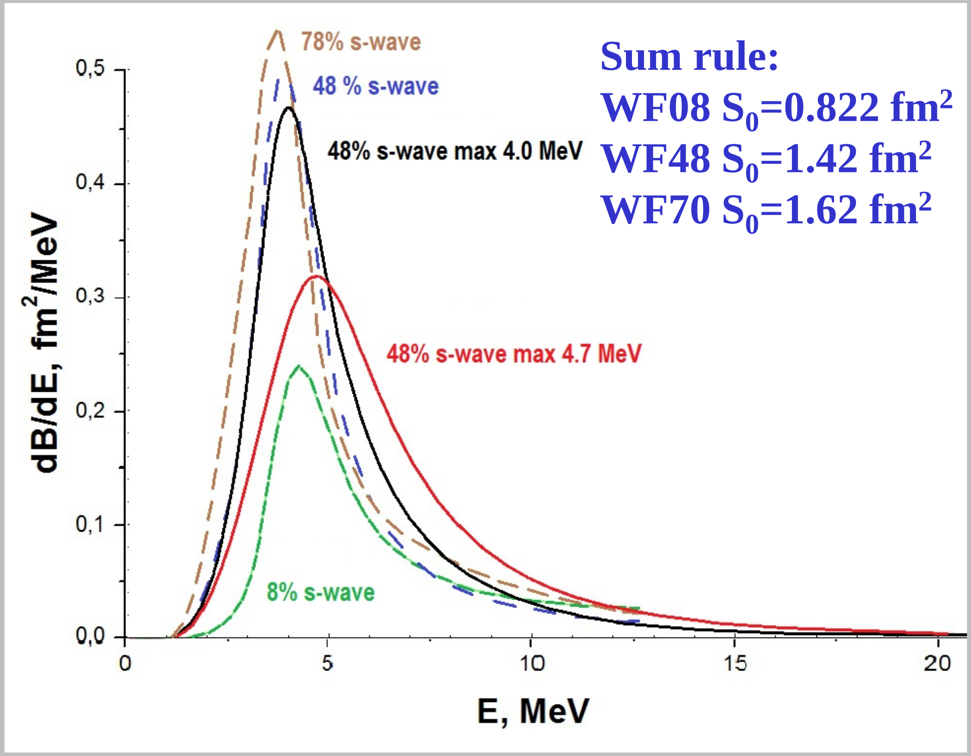
Strength function in PWIA using Green Function method

$$\frac{dB_{E1}}{dE} = \frac{j(E)}{2\pi} = 2\frac{2J_f+1}{2J_i+1}\left(\frac{2}{\pi}\right)^2\sqrt{\mu_X\mu_Y}\int_0^{\pi/2} d\vartheta |A(\varepsilon(\vartheta))|^2$$

where $|A(\varepsilon(\vartheta))|^2 = \sum_{SS_x} || \sum_{KLl_xL_y} A_{KLl_xL_ySS_x}|^2|$ the amplitude is found as

$$A_{KLl_xL_ySS_x}(\varepsilon) = Z_{eff} < J_f||Y_1(\hat{\mathbf{Y}})||J_i > C^{(n)} \int_0^\infty dX \int_0^\infty dY \phi_X(k_X,X)\phi_Y(k_Y,Y)Y\Psi_{KLl_xL_ySS_x}(X,Y)$$

WF: L.V. Grigorenko, et al., PLB **641** (2006) 254



Strength functions

[sp] and [dp] in ^{17}Ne

Resonances in ^{16}F (s,d waves)

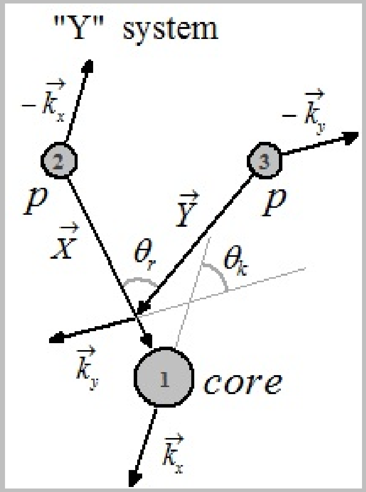
0.535 MeV 0^-

0.738 MeV 1^-

0.959 MeV 2^-

1.256 MeV 3^-

5.856 MeV 2^-



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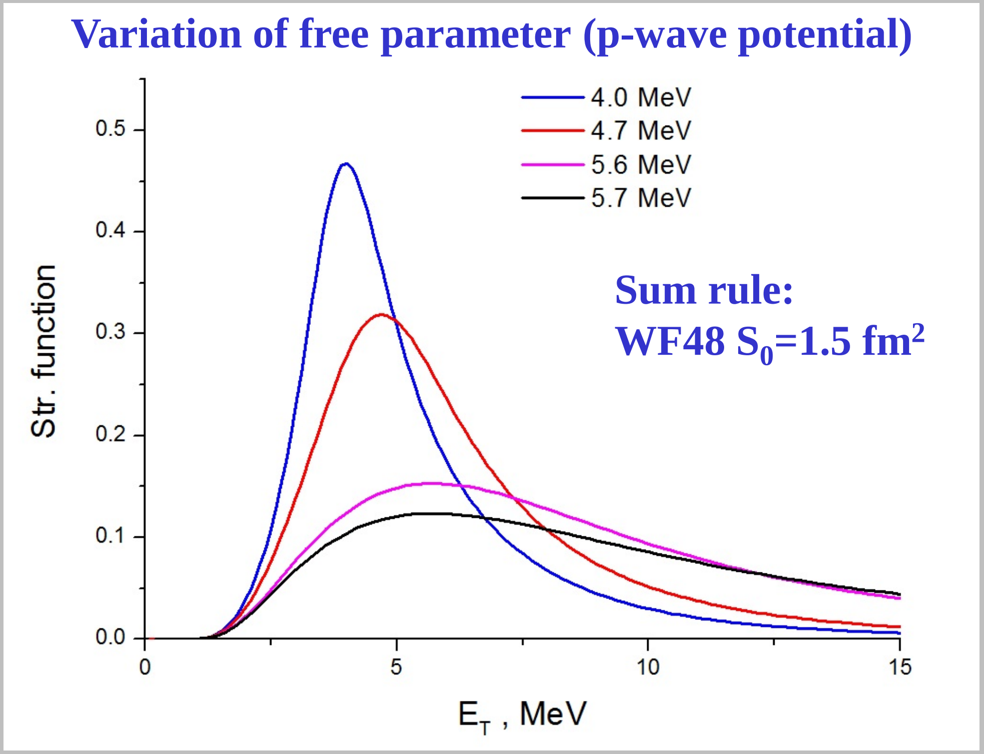

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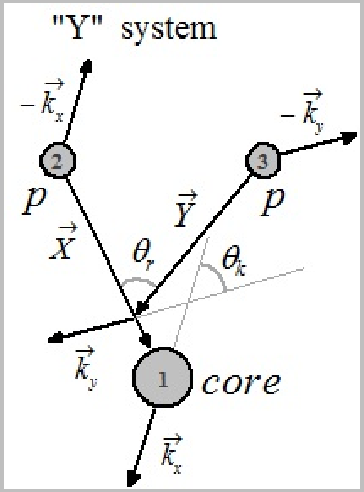
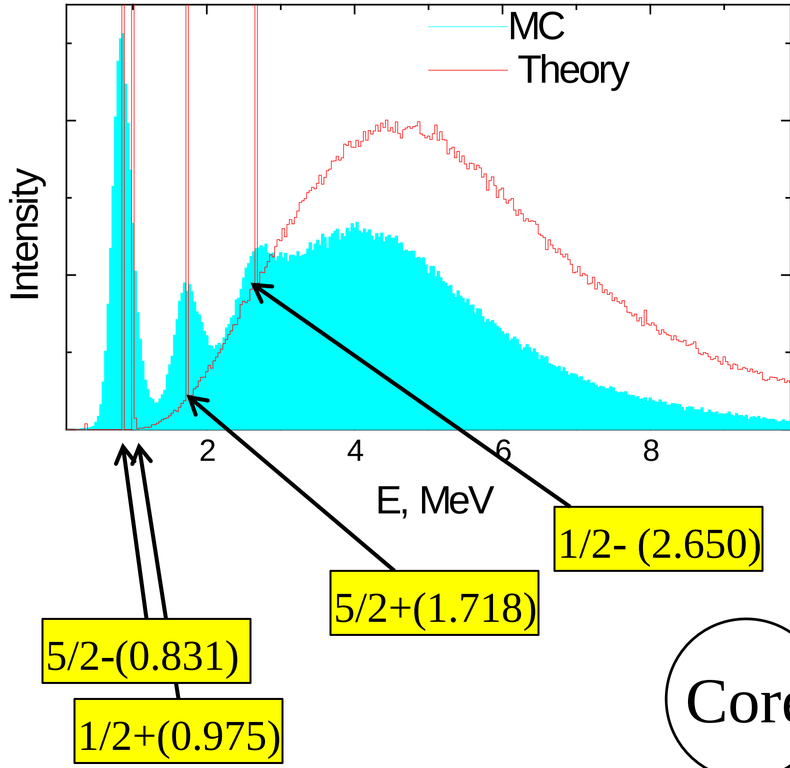
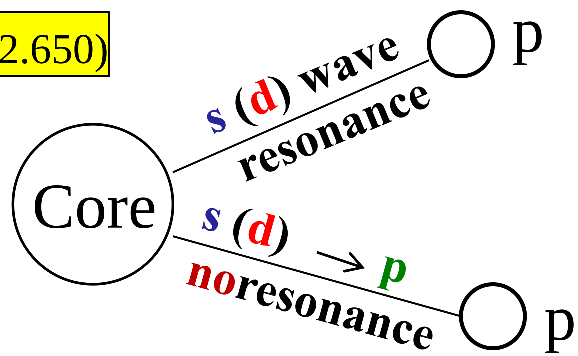
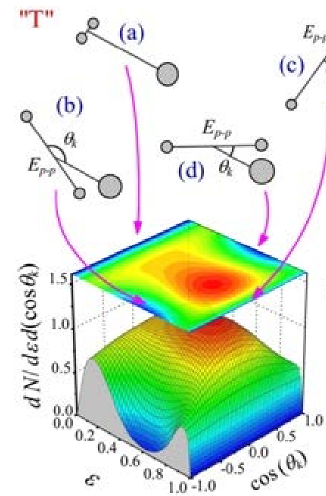


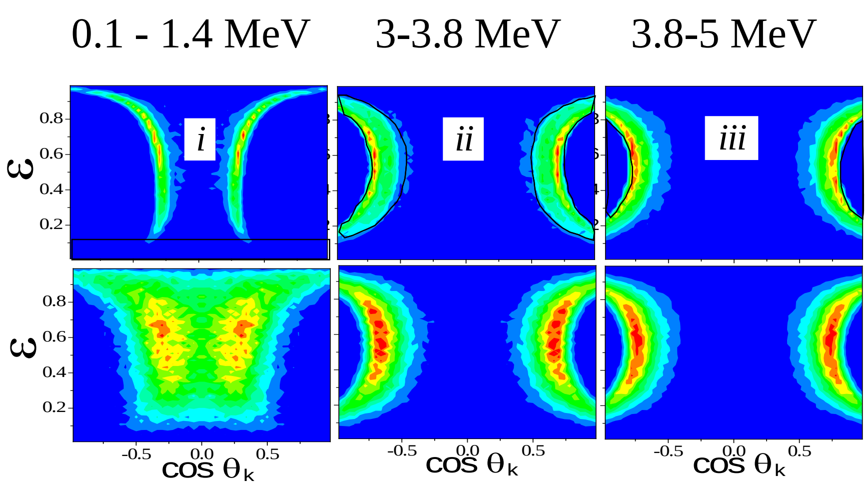
Results

Theoretical result (red line) calculated with the ^{17}Ne ground state wave function with 48% of the [s2] congfiguration, and MC simulation (blue histogram) taking into account the bias induced by the experimental setup in the GSI experiment S318 at E=500 A MeV on Pb.





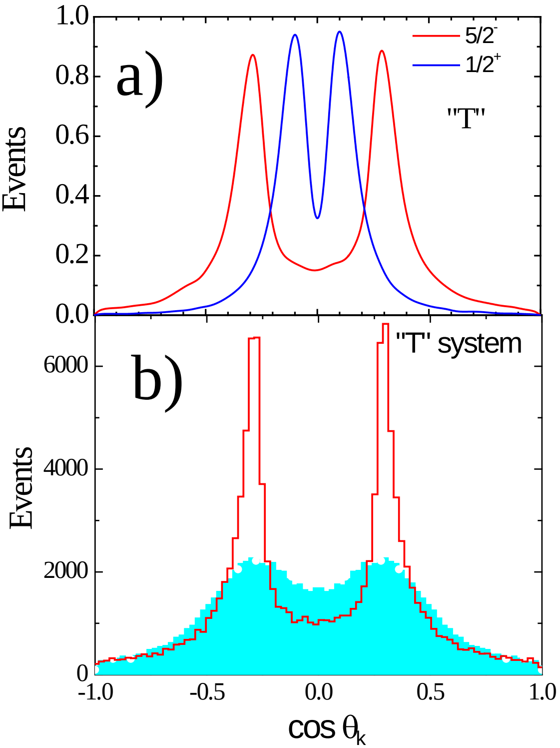




$$\varepsilon = E_x/E\,, \qquad \cos(\theta_k) = (\mathbf{k}_x \cdot \mathbf{k}_y)/(k_x\,k_y)$$

Complete energy-angular correlations. Theoretical and MC correlation patterns. Here the ^{17}Ne ground state WF with 48% of the [s2] configuration is used.

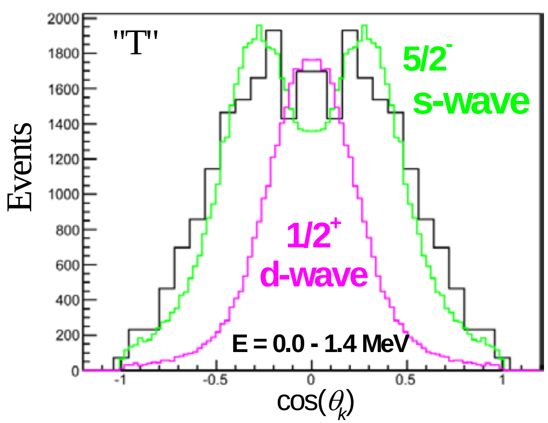
Results

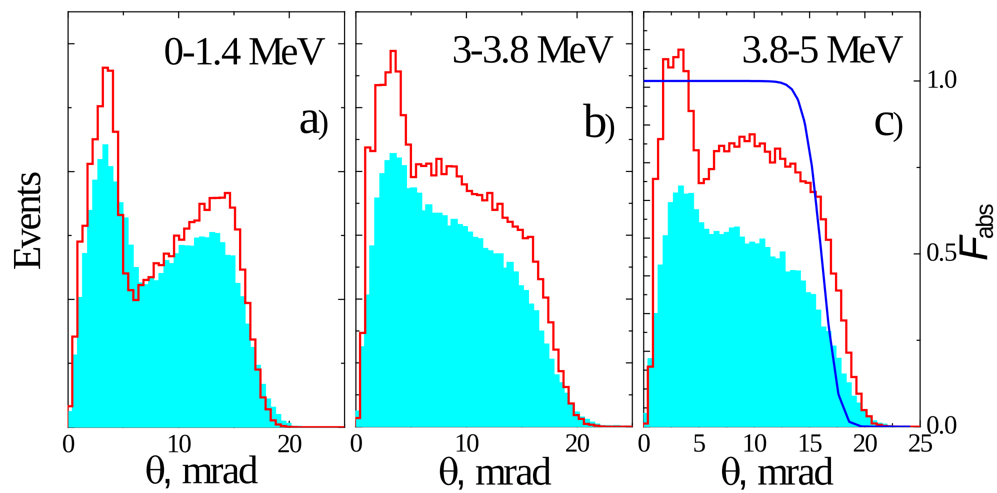


Three-body angular distributions for the states 5/2- and 1/2+ for the energy range 0 - 1.4 MeV in T-system; (a) is theoretical input separately for the state 5/2- and 1/2+; (b) results of the theoretical calculations (red line) obtained with dominant 5/2+ contribution, MC simulations (shaded histogram) taking into account the experimental bias of the experimental setup.

Example how the close states can be disentangled:

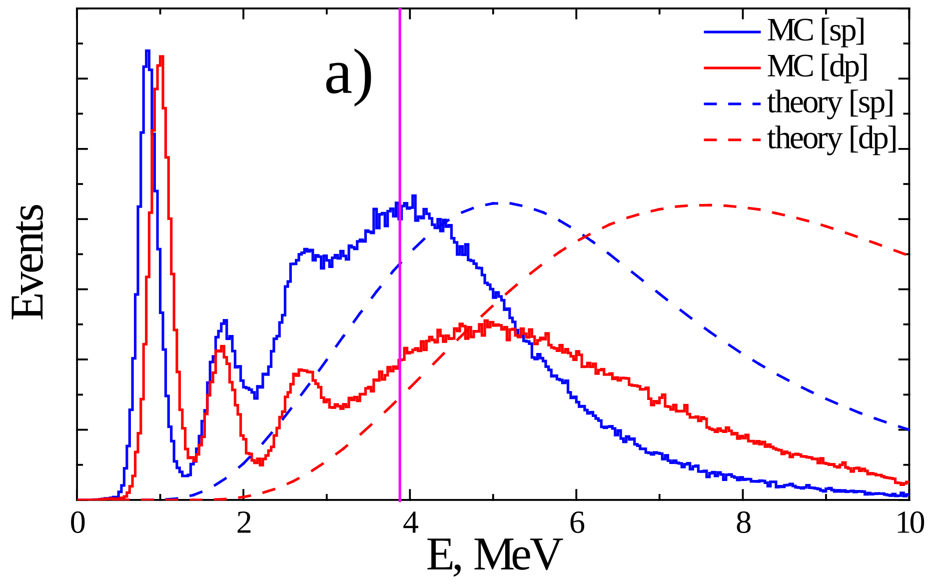
5/2-(0.831) 1/2+(0.975)

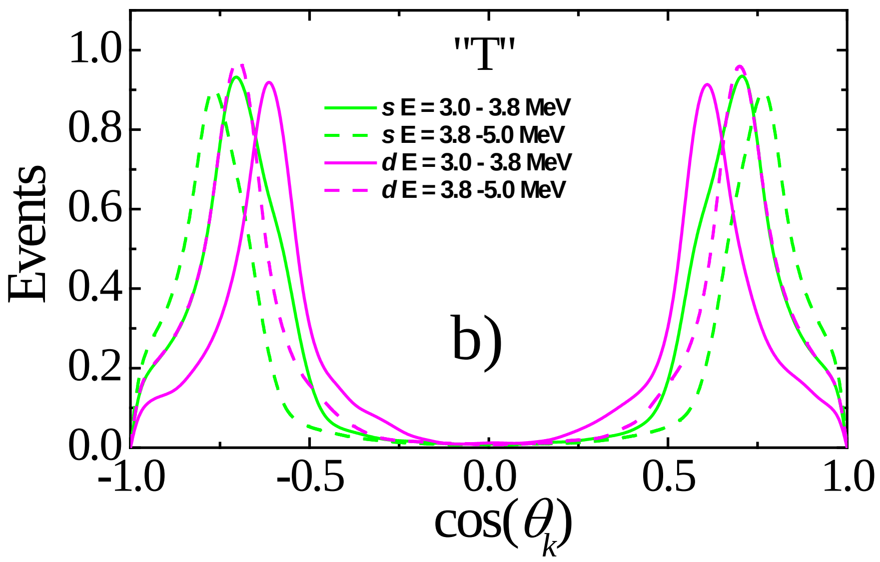




Angular distribution of ^{17}Ne in energy ranges: (a) 0- 1.4 MeV, (c) 3 - 3.8 MeV, and (d) 3.8 - 5 MeV. Blue line in (c) is the absorption function for ^{17}Ne beam on the lead target.

Results





Solid and dashed lines in (a) give the MC result and theoretical input obtained for population of the [sp] (blue line) and [dp] (red line) configurations; (b) are the correlations on the left slope of the SDM peak, and (c) on the right slope. The calculations are done with the ^{17}Ne ground state wave function with 48% of the [s2] configuration.

Conclusions

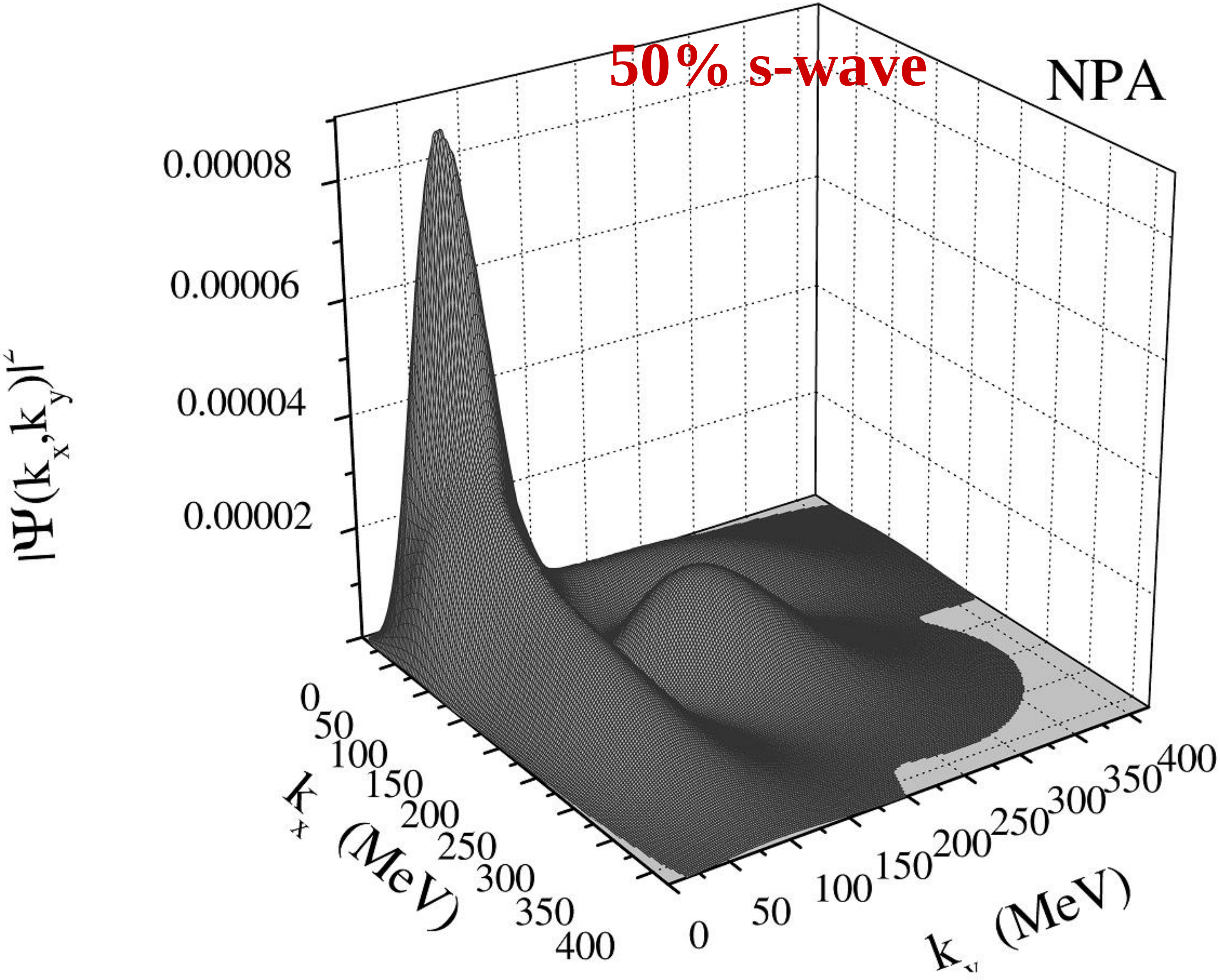
• We suggested **a simplified approach**, allowing qualitative and quantitative self-consistent description of spectral and correlation characteristics measured in modern experiments. We combined the theoretical calculations with the Code for **MC simulations**, taking into account the apparatus bias and resolution, allowing comparison between theory and experiment, and applied this code for calculations of the Coulomb dissociation of ^{17}Ne.

•The excitation spectrum in the soft E1 excitation of ^{17}Ne has maximum between 4 and 5.7 MeV, with the energy weighted sum rule 1.5 fm^2.

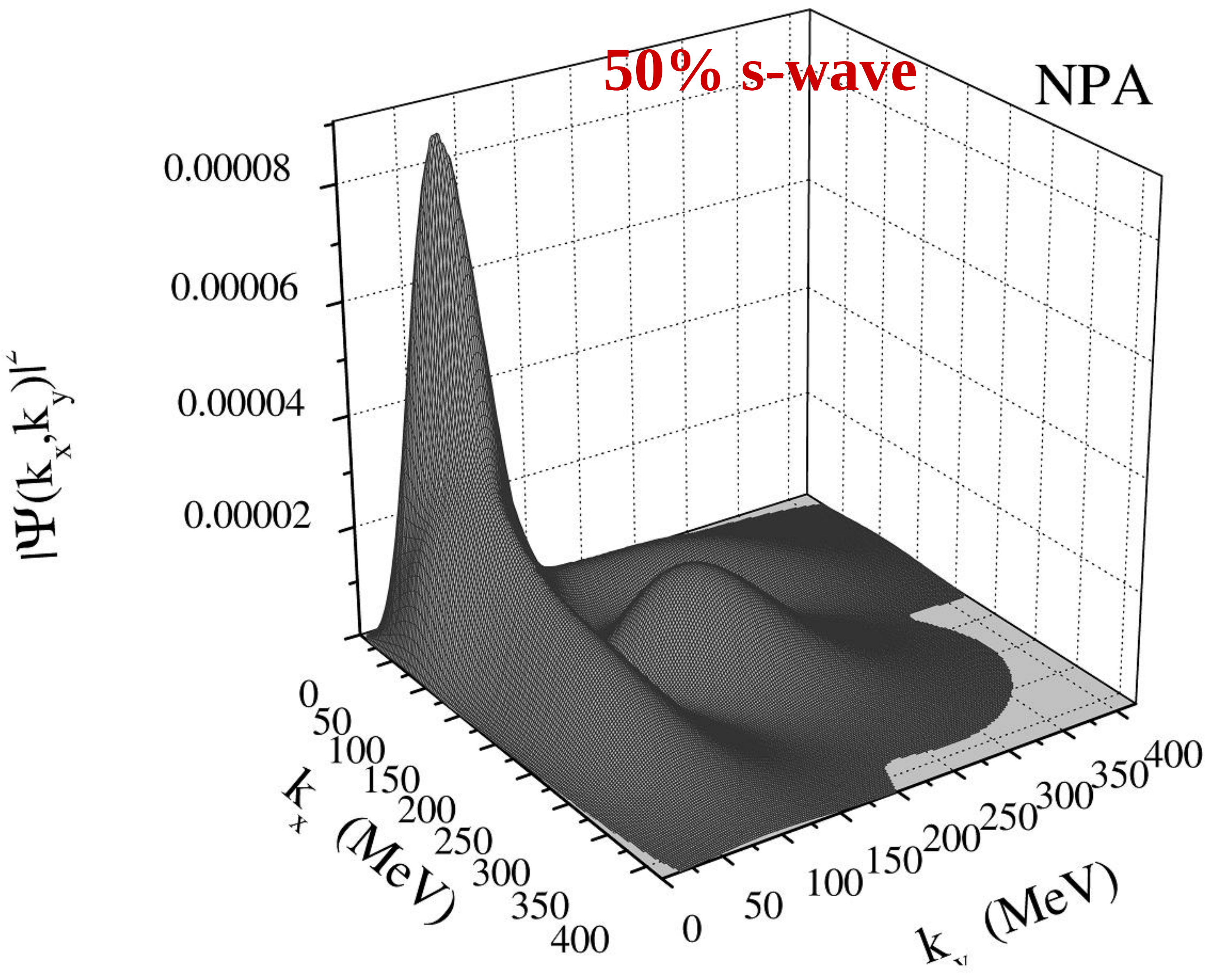
• 2p- halo nucleus exhibits **"Soft E1" mode of excitation**, and the peak position is higher than that for the 2n- halo nuclei (GLOBAL conclusion).

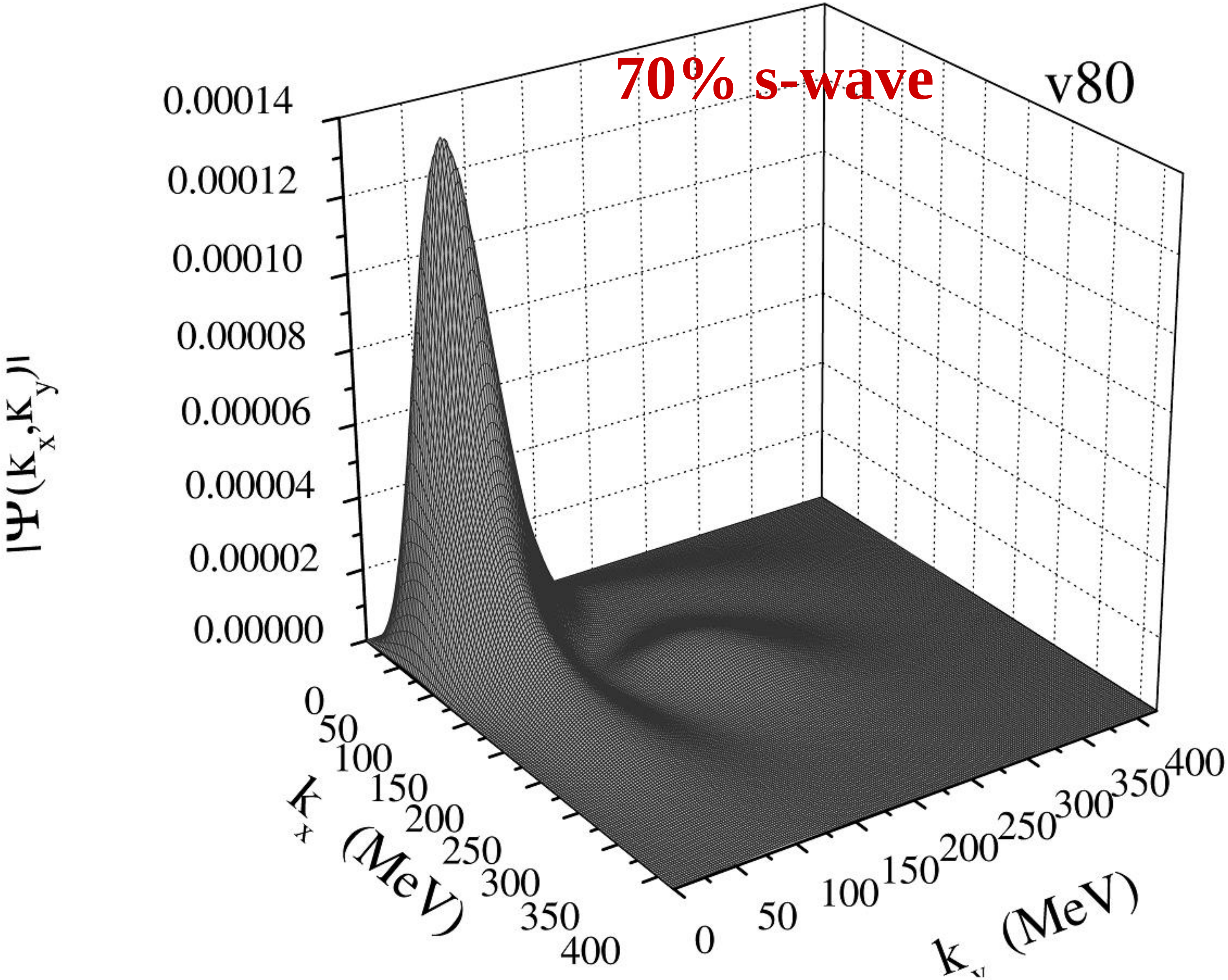
• In the Coulomb Soft E1 excitation, the s-wave states population dominates (by an order of magnitude) that for d-wave states. In the nuclear one, the s/d ratio is about **unity**.


Thank
You !!!



50% s-wave
NPA
0.00008
0.00006
0.00004
0.00002
$|\Psi(k_x,k_y)|^2$
0
50
100
150
200
250
300
350
400
k_x (MeV)
k_y (MeV)


50% s-wave
NPA
$|\Psi(k_x,k_y)|^2$
0.00008
0.00006
0.00004
0.00002
0 50 100 150 200 250 300 350 400
k_x (MeV)
0 50 100 150 200 250 300 350 400
k_y (MeV)



70% s-wave
v80
0.00014
0.00012
0.00010
0.00008
0.00006
0.00004
0.00002
0.00000
$|\Psi(k_x,k_y)|$
0
50
100
150
200
250
300
350
400
k_x (MeV)
k_y (MeV)

Dipole excitation: Soft E1, pigmy and giant dipole resonances

Resonance is described by

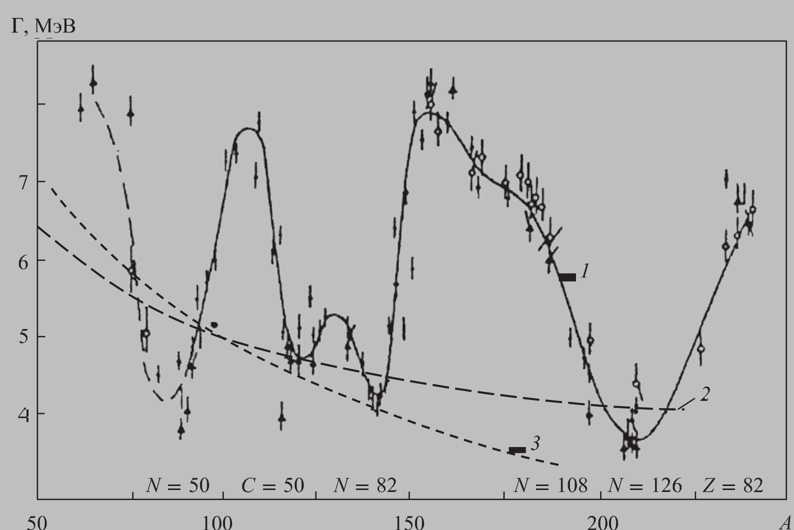
- Er – position of the resonance
- σr - cross section at maximum
- σ tot – integral cross section
- Γr – width of the maximum
- Main channels of the resonance decay

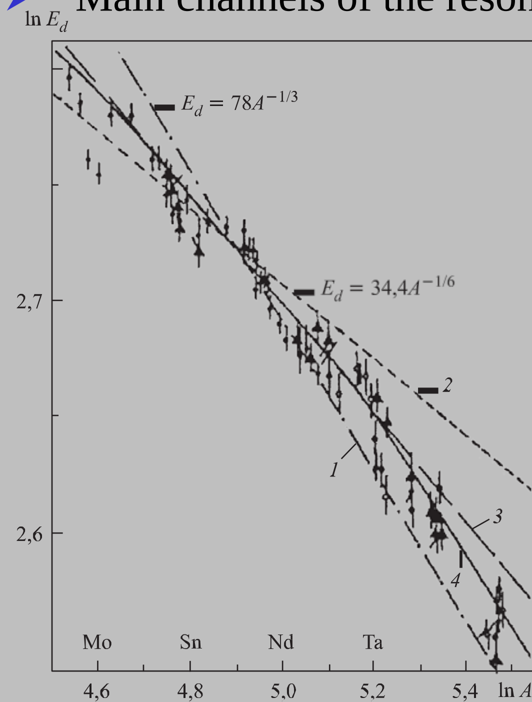
Giant Dipole Resonance -GDR

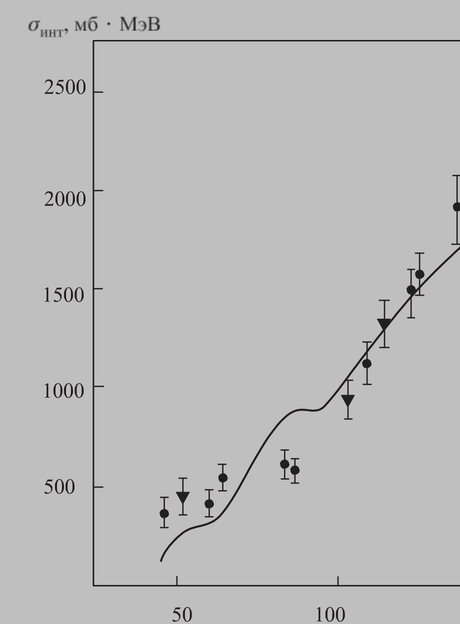
- Er – position of the resonance
- σr - cross section at maximum
- σ tot – integral cross section
- Γr – width of the maximum
- Main channels of the resonance decay

Pigmy Dipole R

- Er – positio
- σr - cross s
- σ tot – integ
- Γr – width o
- Main chann







Principally new experimental technique for exotic nucleus studies: LAND-R^{3}B, ALADIN (GSI)

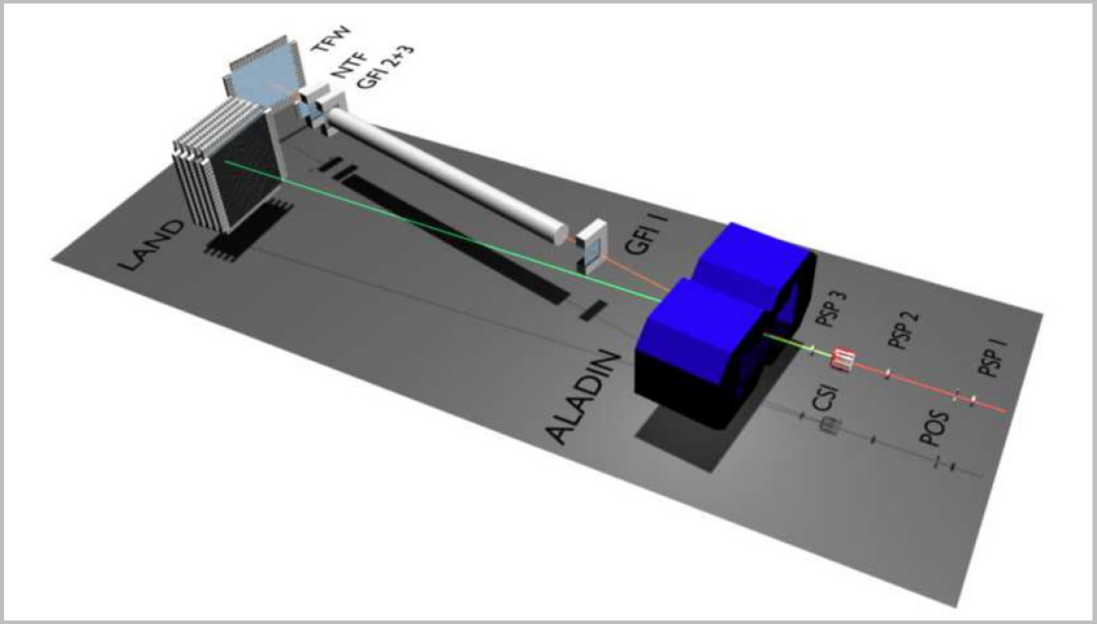
The experimental setup allows kinematically complete measurements. The excitation energy is reconstructed using the invariant mass method.

Low energy spectra in the Coulomb excitation of projectile is available.

It was applied to

- neutron-rich nuclei (^{68}Ni)
- proton-rich nuclei (^{17}Ne)

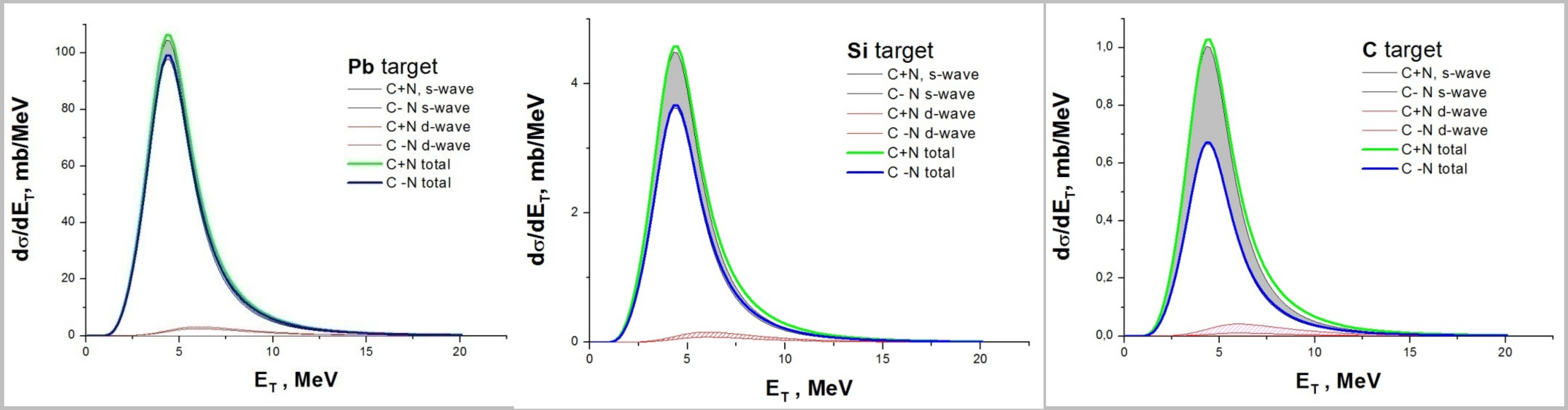
500 A MeV.



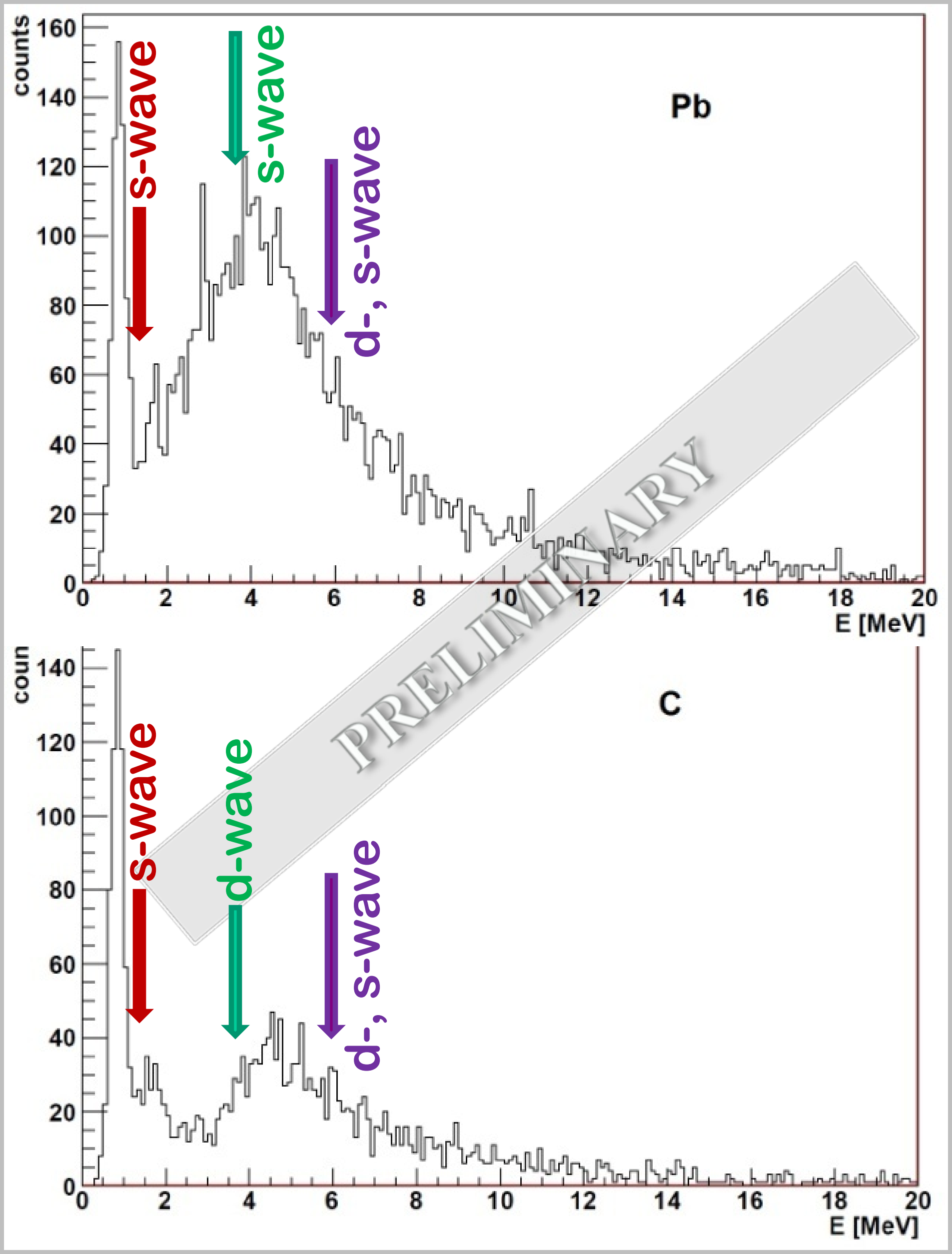
In such experiment an actual problem is how to separate the Coulomb and nuclear contributions, and whether there is the Coulomb/nuclear interference.

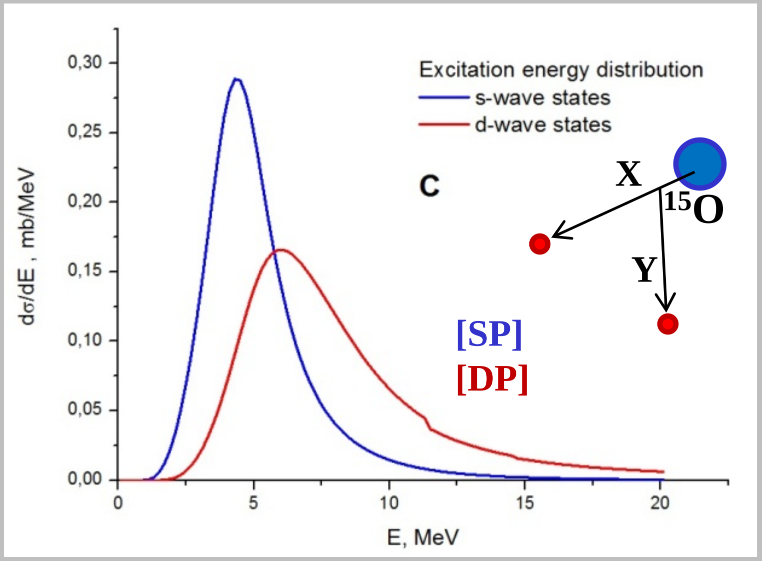
Nuclear & Coulomb SDM in ^{17}Ne: cross sections σ, mb (max at 4.0 MeV)

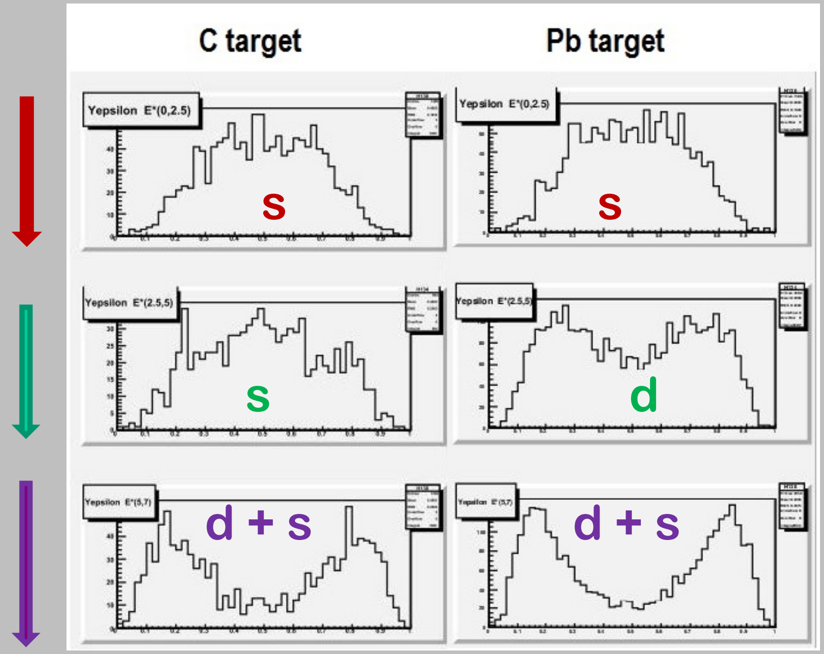
value	Pb target	Si target	C target
Coulomb total	415	17	3.2
Coulomb Soft E1	386	15	3.0
Coulomb s-wave	368	14.3	2.86
Coulomb d-wave	18	0.71	0.14
Nuclear total	35	13	12
Nuclear Soft N1	1.2	0.5	0.4
Nuclear s-wave	0.1	0.04	0.03
Nuclear d-wave	0.05	0.02	0.016



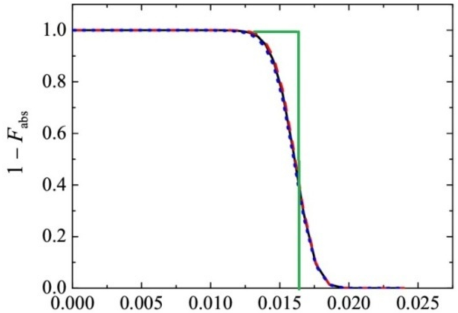
Coulomb SDM in ^{17}Ne: energy spectrum

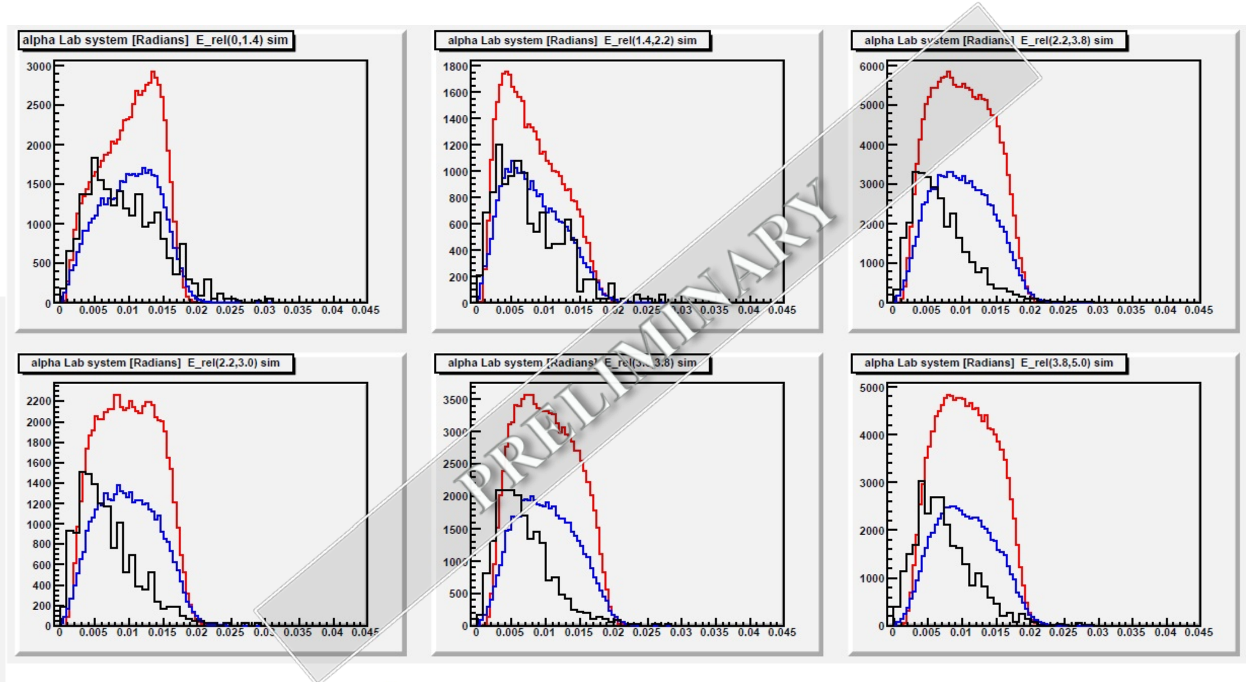


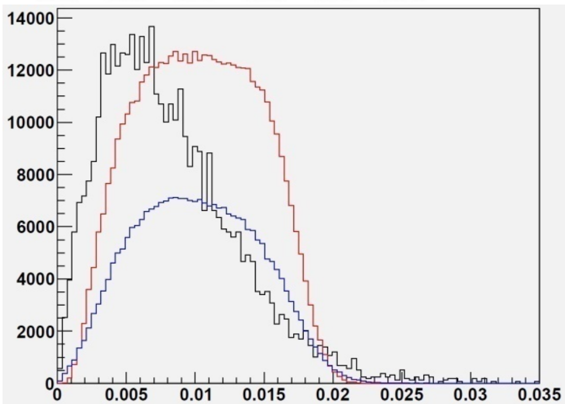


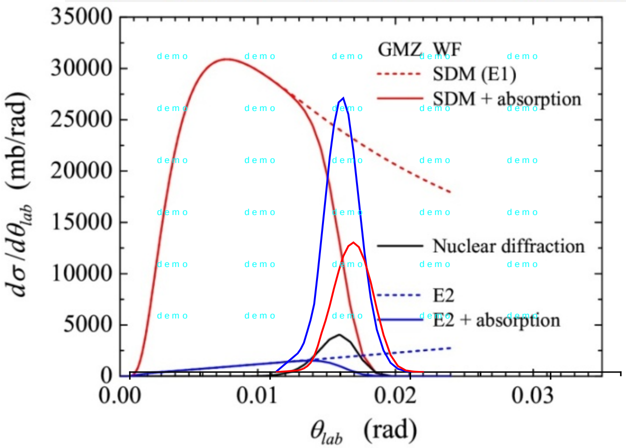


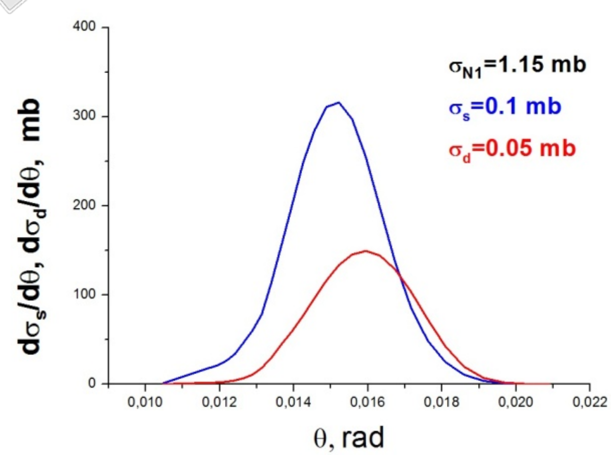
Nuclear & Coulomb SDM in ^{17}Ne: angular distribution



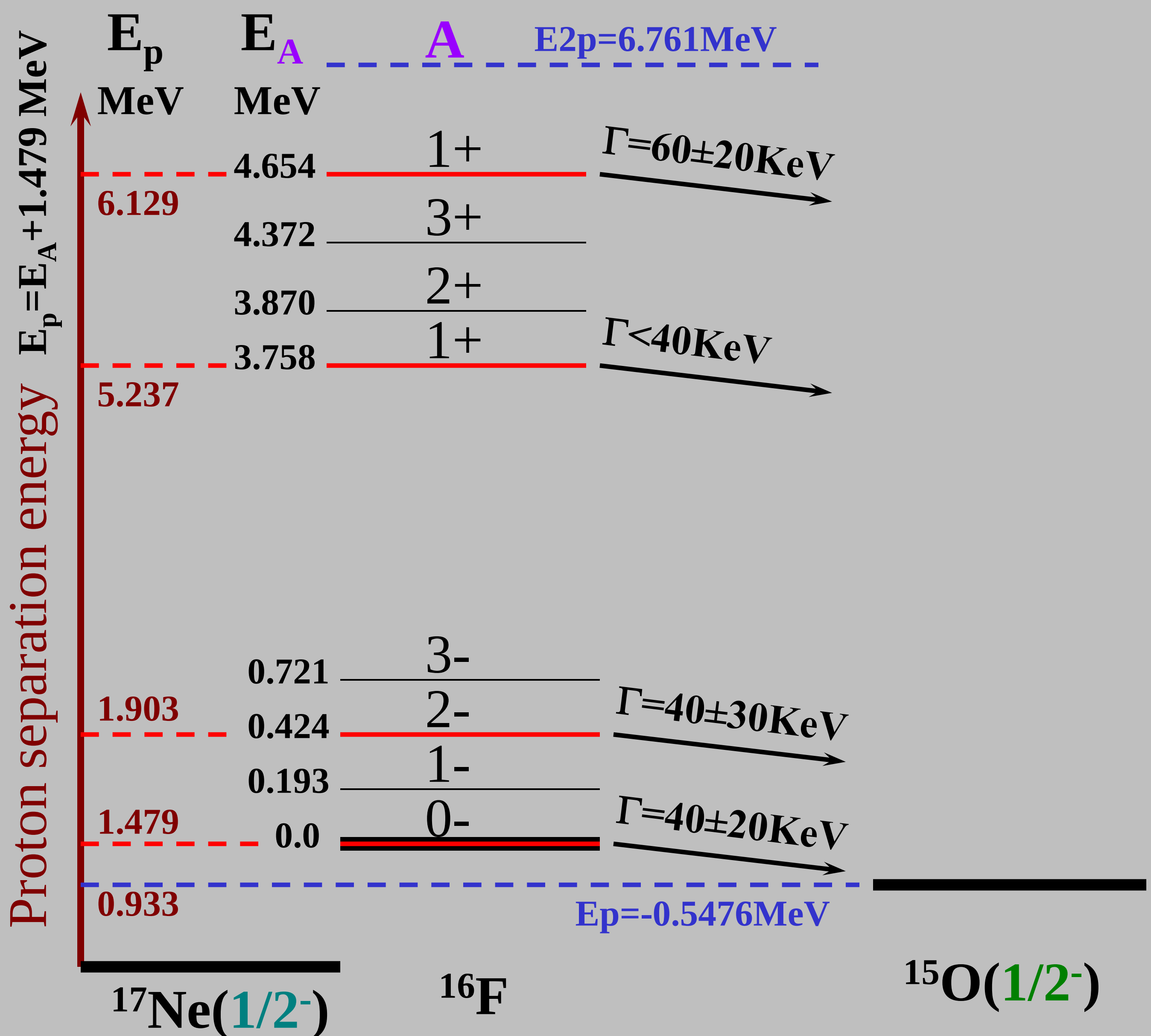








2-body model of ^{17}Ne



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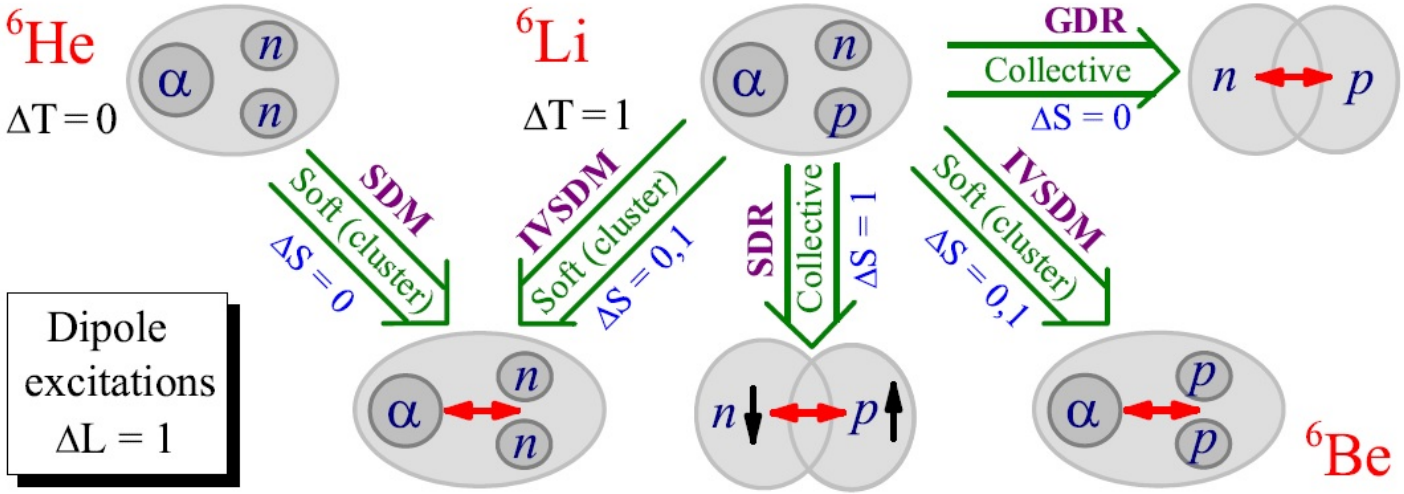

Figure 1: *Classification scheme of dipole excitations in ^{6}He and ^{6}Be prodused in charge-exchange reactions with ^{6}Li [1]. The appearance of the soft dipole mode in the electromagnetic excitation of ^{6}He is shown for comparison. Given is the illustration of difference between the cluster excitations (modes), i.e. the soft dipole mode (SDM) and isovector soft dipole mode (IVSDM), and the collective excitations (resonances), i.e. the giant dipole resonance (GDR) and spin-dipole resonance (SDR).*