# Study of $^{17}$Ne in Coulomb/nuclear induced reactions

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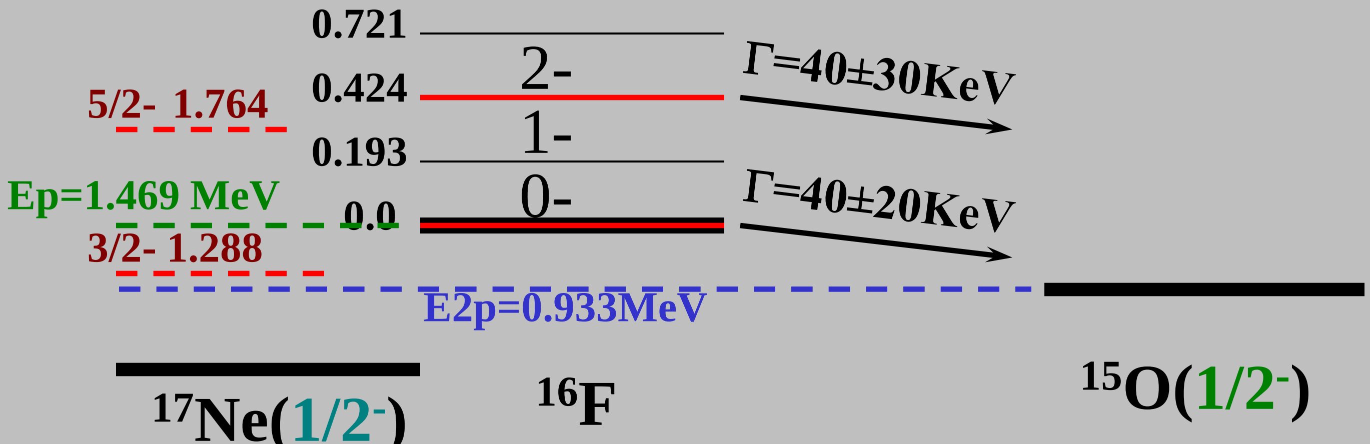
- Introduction: why do we study $^{17}$**Ne**
- Combined **model 2012**
- Results of calculations;
- Conclusions
- Outlook

# INTRODUCTION: why do we study $^{17}$Ne

## •History of $^{17}$Ne study

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.



# Why do we study $^{17}$Ne?

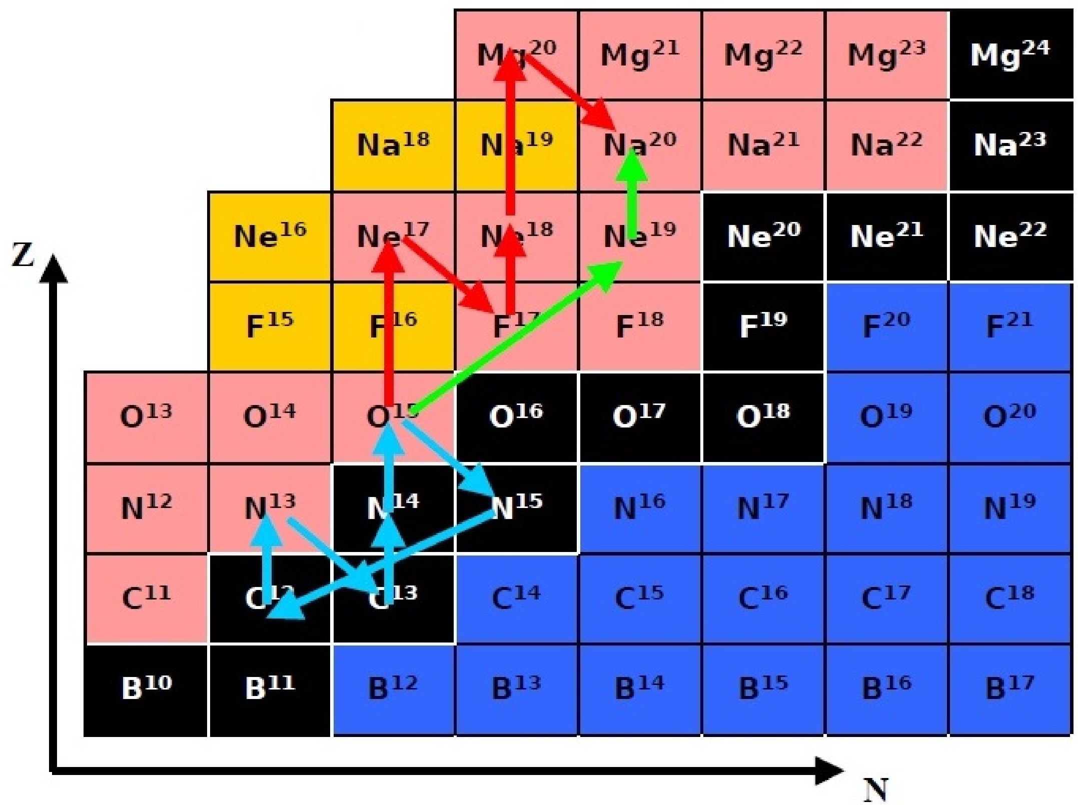
CNO cycle: $^{12}C(p,\gamma)^{13}N(e,\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(e,\nu)^{15}N(p,\alpha)^{12}C$

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

COMPETITION OF

$^{15}O(\alpha,\gamma)^{19}Ne(p,\gamma)^{20}Na$

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

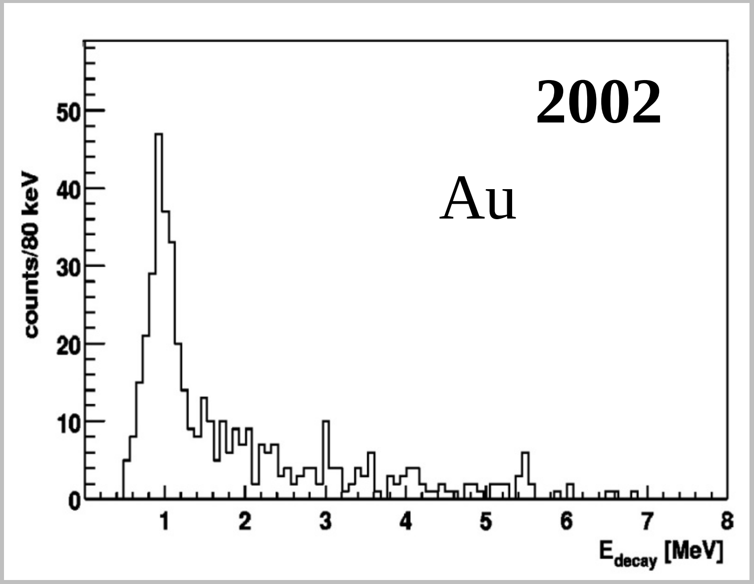



According to the **detailed balance theorem,** this reaction can be accessed as time-reversal one for E1 Coulomb dissociation of $^{17}$Ne in lead target.

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

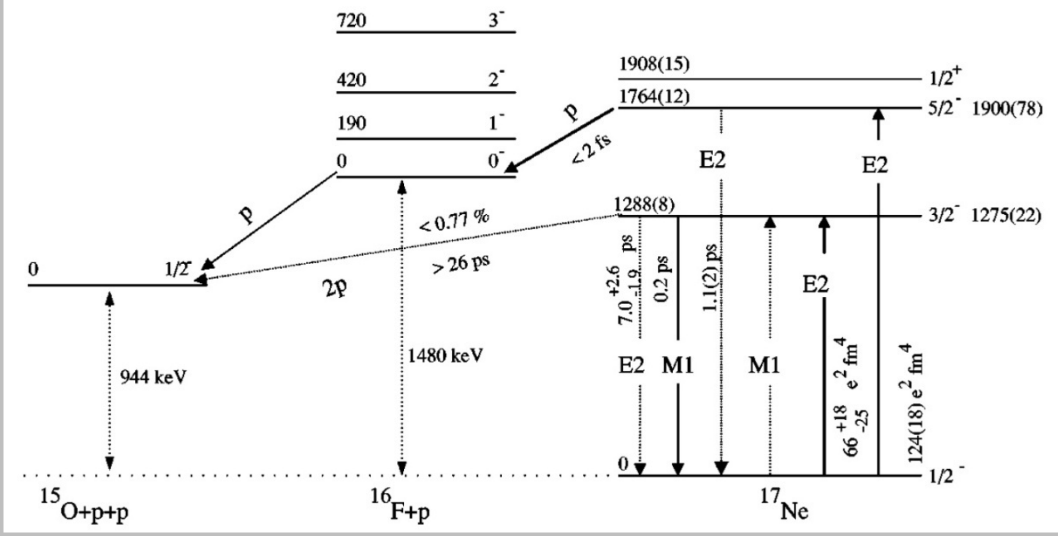
# Where the "Soft E1" mode is supposed to be?

M.J. Chromik, et al., PRC **66** (2002) 024313.




The peak corresponds to transitions to the first excited states of $^{17}$Ne. There is no structure above 2 MeV.

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.



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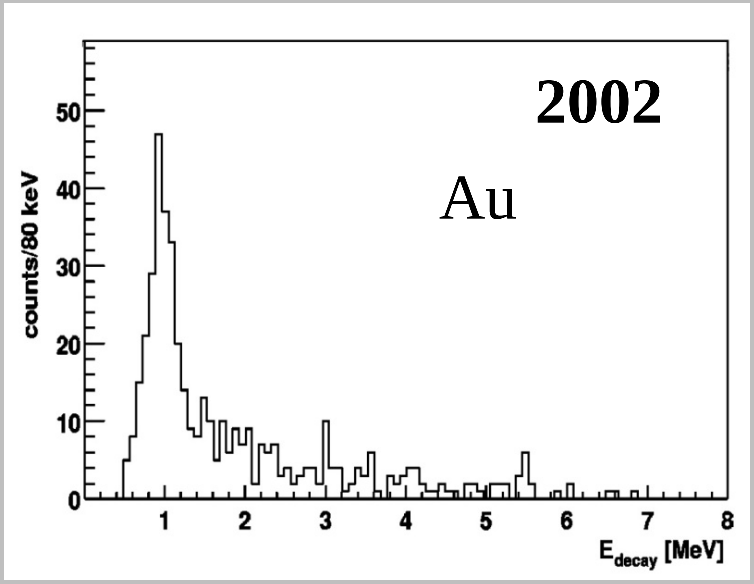


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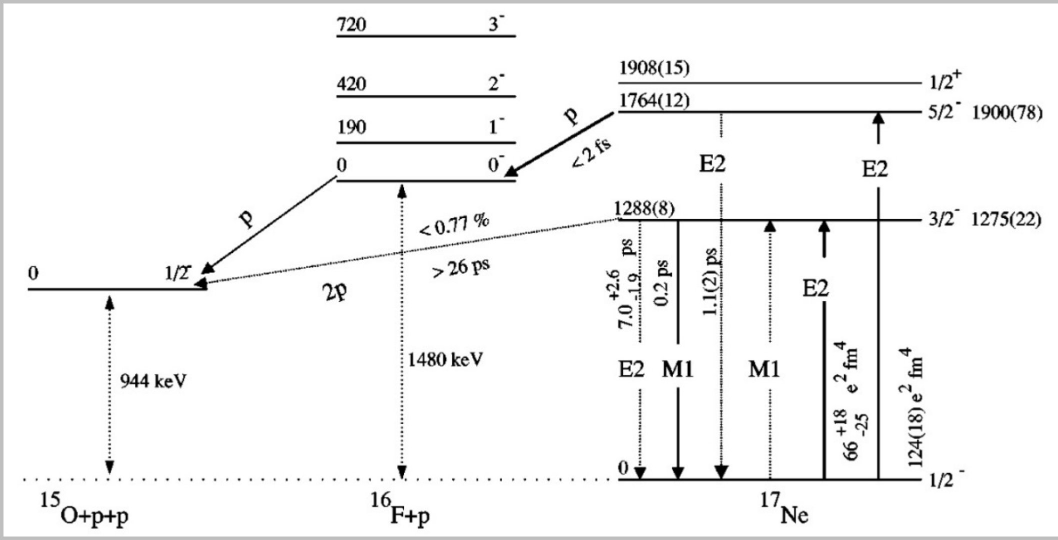


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**CLOSED**

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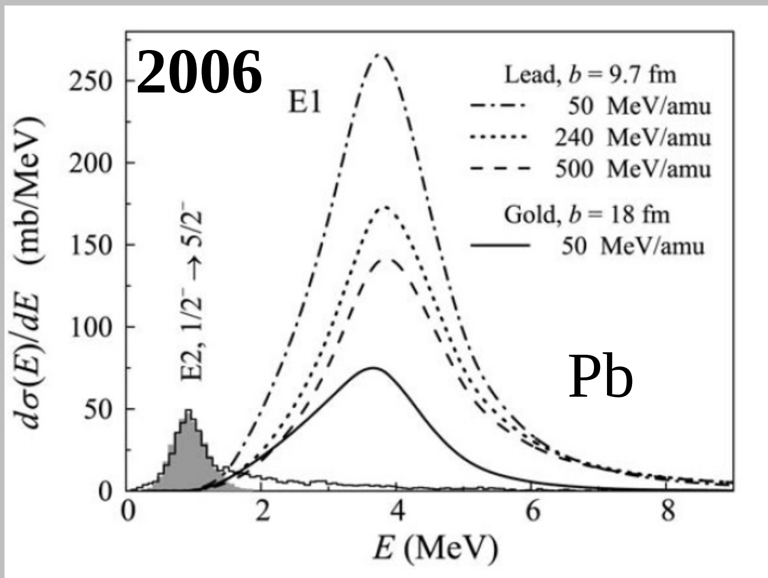


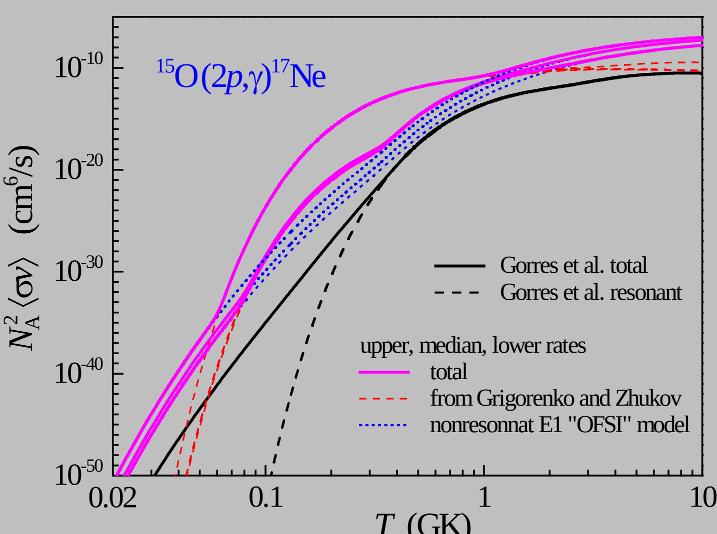


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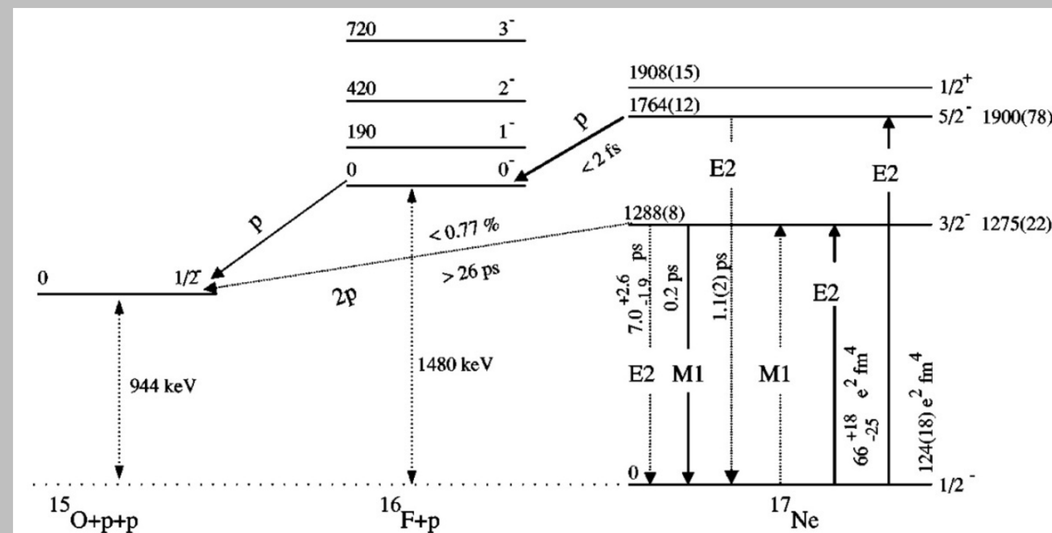
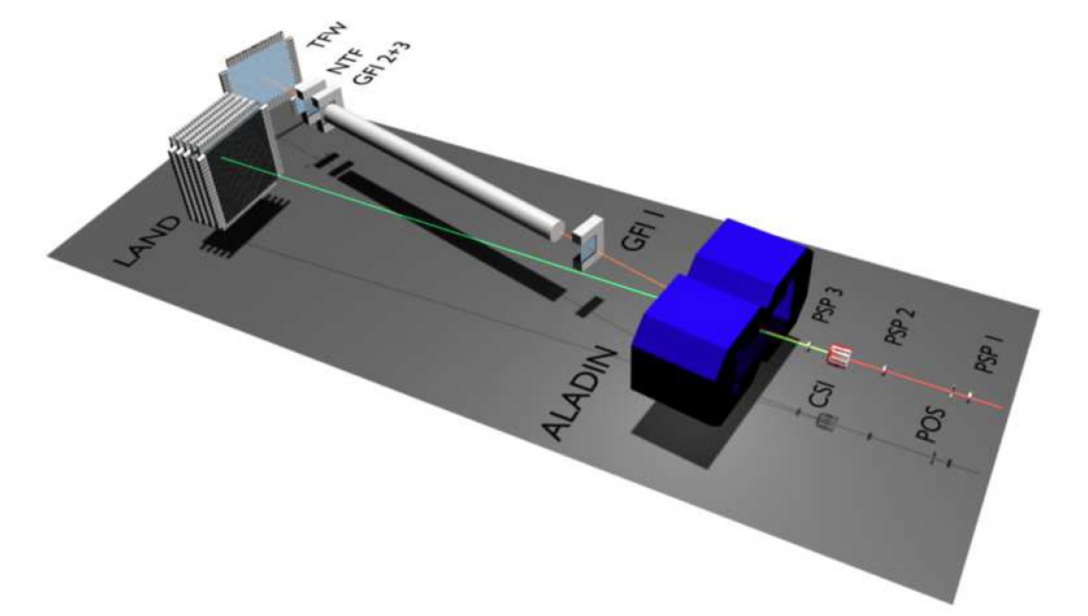



The astrophysical reaction rate can be enhanced by few orders of magnitude due to contributions of the non-resonant radiative 2p capture from continuum, for temperatures

**T < 0.05–0.08 GK and T > 0.4–1.0 GK**

# 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.

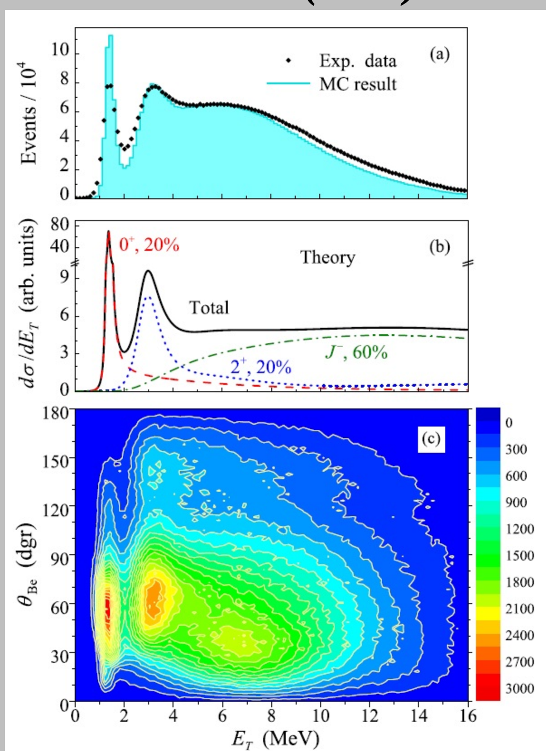



Low energy spectra in the Coulomb excitation of projectile is available.
It was applied to
•neutron-rich nuclei ($^{68}$Ni)
•proton-rich nuclei ($^{17}$Ne)
500 A MeV.

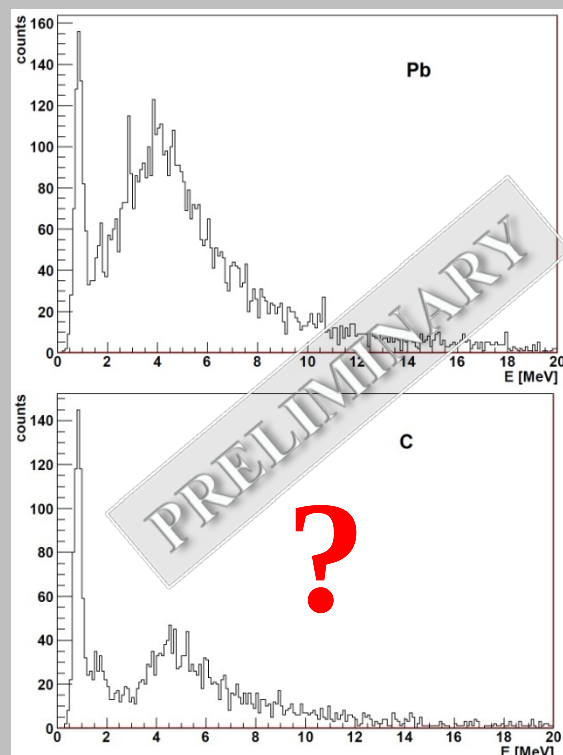
In such experiment an actual problem is how to separate the Coulomb and nuclear contributions, and whether there is the Coulomb/nuclear interference.

It is necessary to take into account some exotic features of unstable nuclei that cannot be observed in their stable counterparts. In neutron-rich nuclei, one of these features is the appearance of electric-dipole strength at energies near the neutron separation threshold, located below the well-known Giant Dipole Resonance (GDR), well known in stable species. This new low-lying E1 strength distribution is called Soft E1 mode of excitation, referring to much smaller photoabsorption strength compared to that of the GDR.

**PLB *708 (2012) 6***

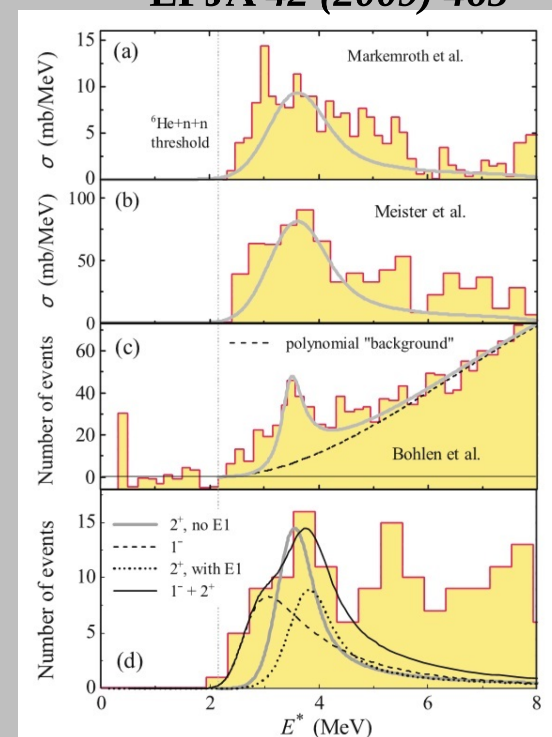



$^6$Be IVSDM




$^{17}$Ne

**EPJA *42 (2009) 465***




$^8$He SDM

# INTRODUCTION: why do we study $^{17}$Ne?

- History of study of time reverse reaction $^{17}Ne+\gamma \rightarrow {}^{15}O+2p$. Correlation patterns reveals structure.
- Astrophysical aspect of Soft E1 mode studies
- Principally new experimental technique for exotic nucleus studies: LAND-R$^3$B, ALADIN (GSI) and data.
- Absence of appropriate model for description of reaction where both Coulomb and nuclear mechanisms acts.

## Combined MODEL 2012

- main ingredients
- free parameters are fixed

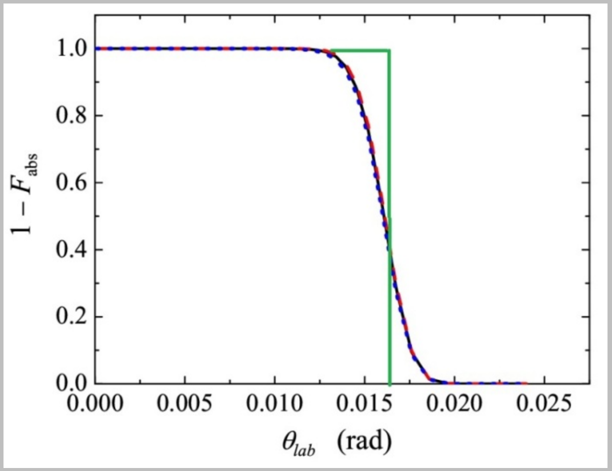
# Model 2012

| Quantity | $\sigma_{-p}$ | $\sigma_I$ | dσ/dE | dσ/dθ | dσ/dE/dθ | 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
[2] 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 corresponding to nuclaer absorption is replaced by smooth absorption function (no free parameter any more) from the Glauber model.
- strength function for the Coulomb and nuclear excitation is supposed to be similar
- angular distribution in nuclear interaction corresponds to the Coulomb trajectories

## ***In use***

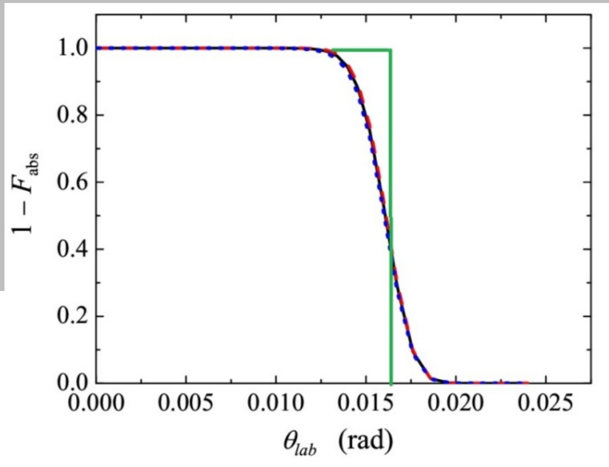
- 3-body wave function of $^{17}$Ne obtined with hyperspherical harmonics method
- Glauber model parameters are fitted [4] using available experimental data

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

# Model: Eikonal approximation of the Glauber Model

## *Assumptions*

- $a_V k_{proj} >> 1$ , $a_V$ is the range of the potential V, $k_{proj}$ is the momentum of projectile
- $|V| << E_{proj}$
- **Frozen Limit** (stright-line trajectories)




## *Cross sections*

$$\sigma^{n}_{str} = \int d^2b \, \langle (1 - |S_{n_1}|^2) \, |S_C|^2 |S_{n_2}|^2 \rangle$$

$$\sigma^{2n}_{str} = \int d^2b \, \langle (1 - |S_{n_1}|^2)(1 - |S_{n_2}|^2) \, |S_C|^2 \rangle$$

$$\sigma_{dif} = \int d^2b \, \{ \langle | 1 - S_{n_1} S_{n_2} S_C |^2 \rangle - | \langle 1 - S_{n_1} S_{n_2} S_C \rangle |^2 \}$$

$$\sigma_{abs} = \int d^2b \, \langle (1 - |S_{n_1}|^2 |S_{n_2}|^2 |S_C|^2) \rangle = \int d^2b \, (1 - \mathcal{F}_{abs}(b))$$

# Eikonal Approximation of the Glauber model

transition from the ground state with its total angular momentum $J$ to the excited state $J'$ is found as

$$\sigma_{JJ'} = \int d^2\mathbf{b}\,(\hat{J})^{-2} \sum_{PQ} \sum_{L'l'_x l'_y S S_x} \int X^2\,dX \int Y^2\,dY \tag{9}$$

$$\Bigg| \sum_{KLl_xl_y} R^J_{Ll_xl_ySS_x}(X,Y) \sum_{\lambda\omega} B^{PQ}_{\lambda\omega}(X,Y,b) C^{l'_x 0}_{l_x 0\,\lambda 0} C^{l'_y 0}_{l_y 0\,\omega 0}$$

$$\hat{l}_x \hat{l}_y \hat{\lambda}\hat{\omega}\hat{J}'\hat{L}\hat{L}'\hat{S}'\hat{P} \left\{ \begin{array}{ccc} L & S & J \\ P & 0 & P \\ L' & S' & J' \end{array} \right\} \left\{ \begin{array}{ccc} l_x & l_y & L \\ \lambda & \omega & P \\ l'_x & l'_y & L' \end{array} \right\} \Bigg|^2 - \delta(J,J')\delta(\pi,\pi')\sigma_{JJ}$$

where the final state quantum numbers are denoted by prime. $B^{PQ}_{\lambda\omega} = \sum_{\omega\nu} C^{PQ}_{\lambda u\,\omega\nu} [Y_\lambda Y_\omega]_{PQ}$ are coefficinents of expansion of profile functions in (...) into spherical harmonics.

$$S_\nu(b_\nu) = \exp\left[ \frac{-i}{\hbar v} \int_{-\infty}^{\infty} dz'\; V_{\nu T}\left(\sqrt{b_\nu^2 + z'^2}\right) \right]$$

$$\overline{V_{nT}}\,(r) = -\frac{i}{2}\hbar v\; A_T\;\rho_T\,(|\vec{r}|)\;\overline{\sigma_{NN}}.$$

$$V_{CT}(r) = \int d^3\,\vec{t}\;A_C\;\rho_C(|\vec{t}|) V_{\nu T}\left(|\vec{r} - \vec{t}|\right)$$

***NN interaction potential***

10<E<2000 MeV

S.K.Charagi et al PRC41(1990)1610

L.Ray PRC20(1979)1857

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$$\hat{l}_x \hat{l}_y \hat{\lambda}\hat{\omega}\hat{J}'\hat{L}\hat{L}'\hat{S}'\hat{P} \begin{Bmatrix} L & S & J \\ P & 0 & P \\ L' & S' & J' \end{Bmatrix} \begin{Bmatrix} l_x & l_y & L \\ \lambda & \omega & P \\ l'_x & l'_y & L' \end{Bmatrix} \Bigg|^2 - \delta(J,J')\delta(\pi,\pi')\sigma_{JJ}$$

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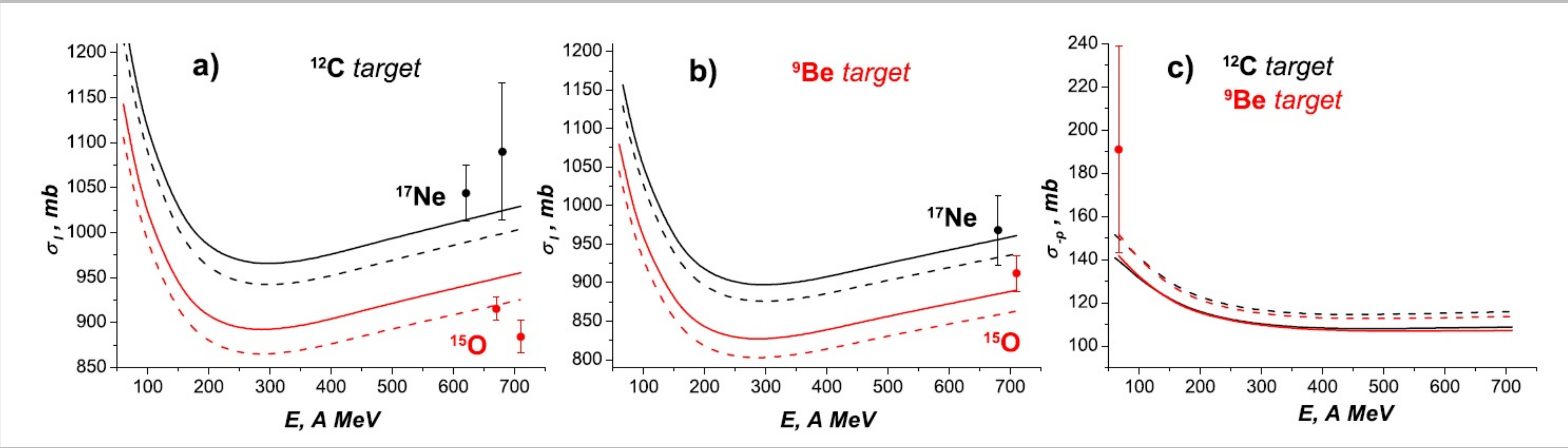
# Eikonal Approximation of the Glauber model PARAMETERS

Data of Ozawa, R. Kanungo etc.




# $^{17}$Ne wave function

***3-cluster wave function*** ($^{15}$O+p+p)

(obtained with Schrödinger equation with nucleon-cluster potential)

Reproduce the rms of $^{17}$Ne, magnetic moment, quadrupole model

Reproduce the binding energy of $^{17}$Ne 0.963 MeV

**Problems**: what is the s/d ratio in the partial waves?

(we used 3 wave functions with s/d 7%,50%,70%)

# Bertulani & Bauer Model of Coulomb excitation

Double-differential cross section

$$\frac{d\sigma_{E\lambda}}{dEd\Omega} = dE_\gamma \sigma_\gamma^{E\lambda} \frac{dn_{E\lambda}}{d\Omega} \mathcal{F}_{abs}(\theta)$$

*Photodissociation cross section*

$$\sigma_\gamma^{E\lambda} = 20\pi\hbar c \frac{(2\pi)^3(\lambda+1)}{\lambda((2\lambda+1)!!)^2}\left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda-1}\frac{dB}{dE}$$

$$\theta = \pi - \frac{2}{\sqrt{1-a^2/L^2c^2}}\arccos\left\{\frac{\varepsilon a}{\sqrt{(Lc\varepsilon)^2 - m^2c^4(L^2c^2-a)}}\right\}$$

*Equivalent photon number*

$$\frac{n_{E1}}{d\Omega} = \frac{Z_t^2\alpha}{4\pi^2}\xi^2\epsilon^4\left(\frac{c}{\gamma v}\right)^2\left[K_1^2(x) + \frac{1}{\gamma^2}K_0^2(x)\right]$$

$$\frac{n_{E2}}{d\Omega} = \frac{Z_t^2\alpha}{4\pi^2}\epsilon^2 e^{-\pi\eta}\left(\frac{c}{\gamma v}\right)^4\left\{\frac{4}{\gamma^2}[K_1^2(\chi) + yK_0(\chi)K_1(\chi) + y^2K_0^2(\chi)] + \chi^2\left(2-\frac{v^2}{c^2}\right)^2K_1^2(\chi)\right\}$$

$$\frac{n_{M1}}{d\Omega} = \frac{Z_t^2\alpha}{4\pi^2}\eta^2\epsilon^2e^{-\pi\eta}K_1^2(\chi)$$

$$L = |\mathbf{r}\times\mathbf{p}| + 1/2.$$

Comparison with experimental data

M.J. Chromik, et al., PRC **66** (2002) 024313.

Table 2: Population of the states $3/2^-$ ($E_T$=1.228 MeV) and $5/2^-$ ($E_T$=1.764 MeV) in the reaction $^{17}$Ne+$^{197}$Au at the $^{17}$Ne energy 48.4 A MeV, and theoretical estimates of the population in the reaction $^{17}$Ne+$^{208}$Pb at the $^{17}$Ne energy 500 A MeV.

| | Energy of $^{17}$Ne A MeV | $1/2^- \to 3/2^-$ E2, $E_\gamma$=1.288 MeV $\sigma$ mb | $1/2^- \to 3/2^-$ M1, $E_\gamma$=1.288 MeV $\sigma$ mb | $1/2^- \to 5/2^-$ E2, $E_\gamma$=1.764 MeV $\sigma$ mb |
|---|---|---|---|---|
| Our calc. | 48.4 | 15.68 | 0.25 | 29.7 |
| Chromik et al [13] | 48.4 | $11.9^{3.3}_{-4.5}$ | $0.24 \pm 0.1$ | $29.9 \pm 4$ |

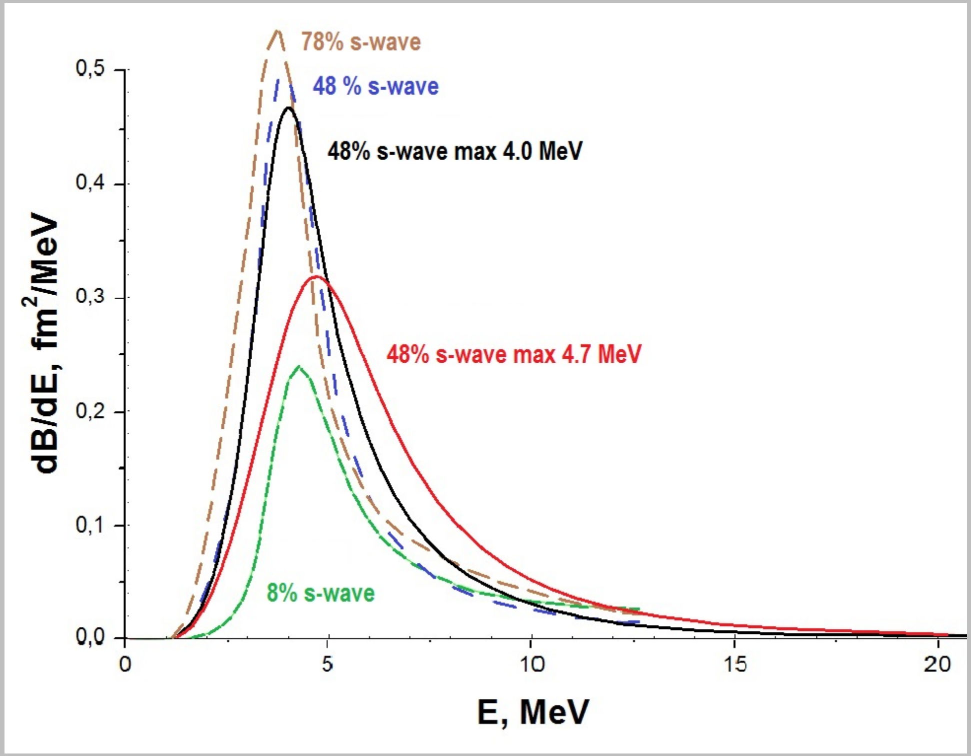
# Strength function in PWIA using Green Function method

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

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

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

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




Strength functions [sp] and [dp] in $^{17}$Ne

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

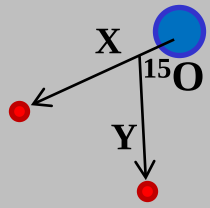
0.535 MeV $0^-$

0.738 MeV $1^-$

0.959 MeV $2^-$

1.256 MeV $3^-$

5.856 MeV $2^-$

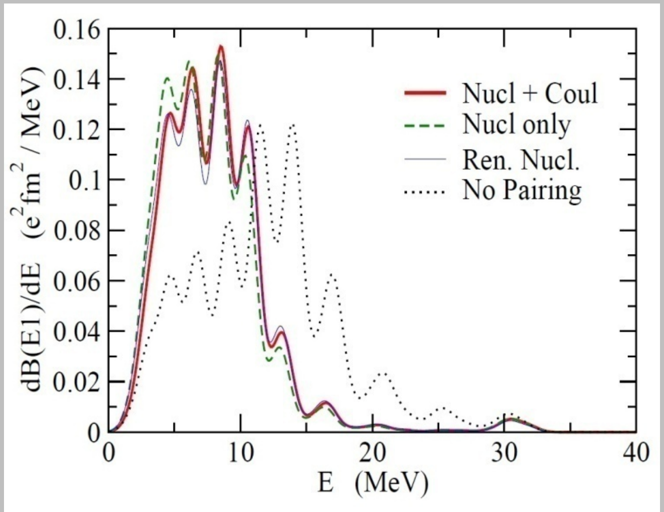


# Comparison with other calculations
# Strength function

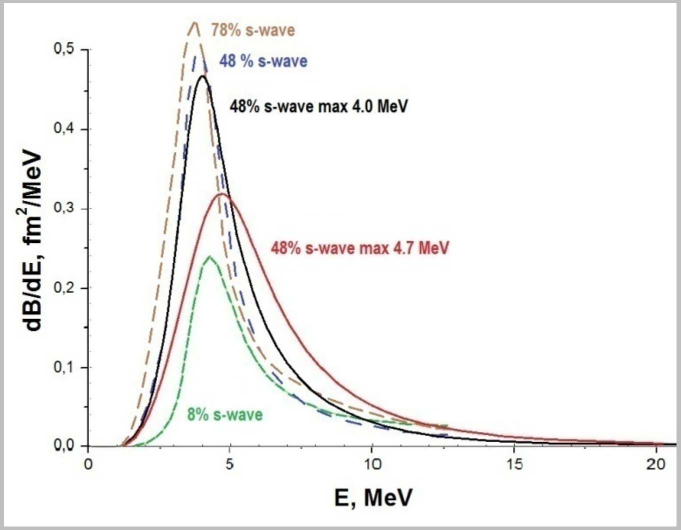
T.Oishi, et al PRC 84(2011) 057301

**Collective model calculations**

$^{17}$**Ne**




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




**Sum rule**

$S_0$**=1.206**

**Sum rule:**

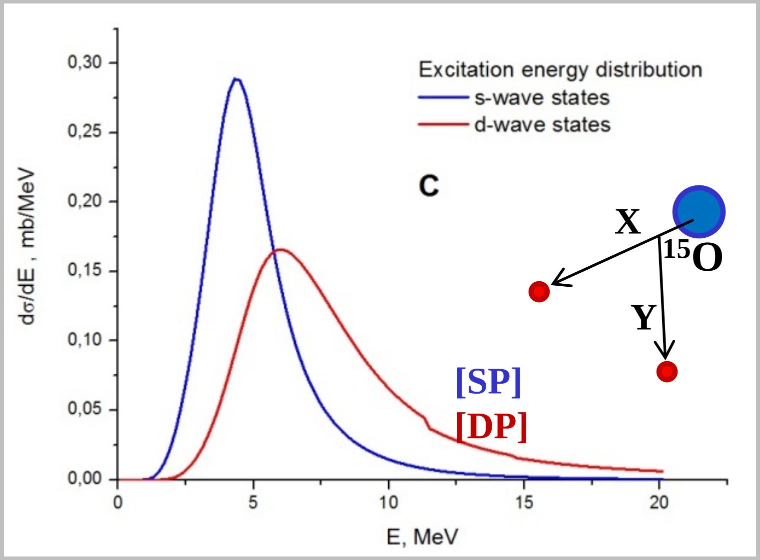
**WF08** $S_0$**=0.822 fm$^2$**

**WF48** $S_0$**=1.42 fm$^2$**

**WF70** $S_0$**=1.62 fm$^2$**

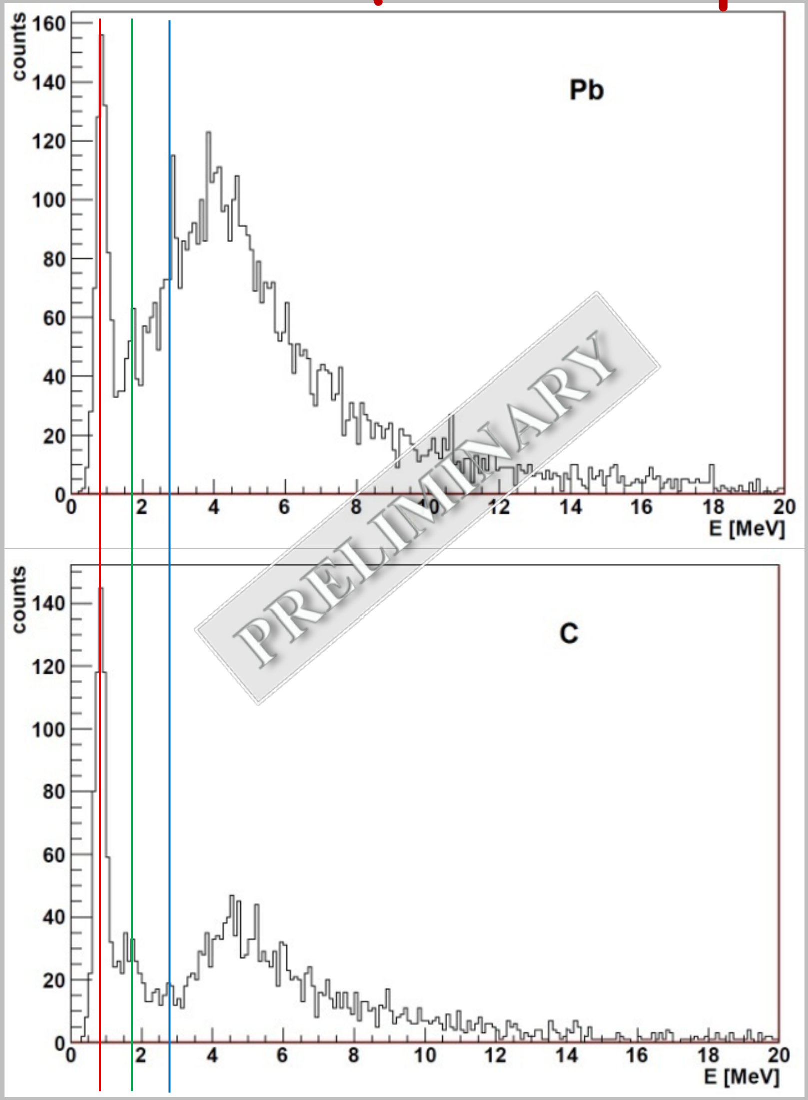
# RESULTS: excitation spectrum of $^{17}$Ne and correlations

- There is a bump at 4-5 MeV
- Energy spectra in different targets are not similar **due to difference in s- and d- wave contributions (?)**



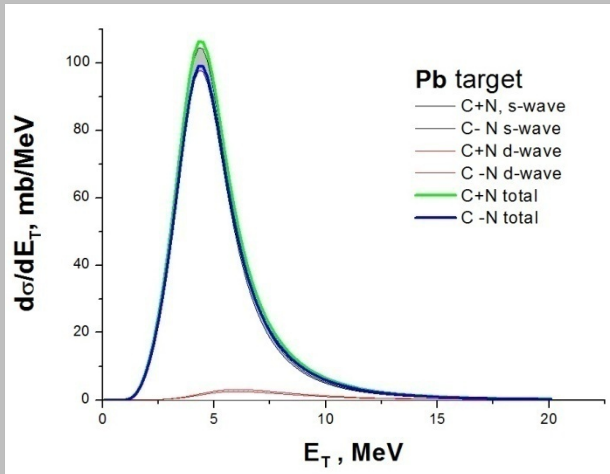

**Coulomb s/d** 20
**Nuclear s/d** 1

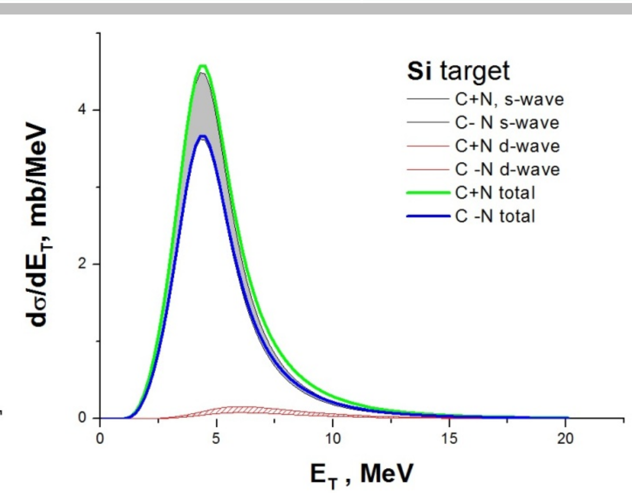
$^{17}Ne+\gamma \rightarrow {}^{15}O+2p$

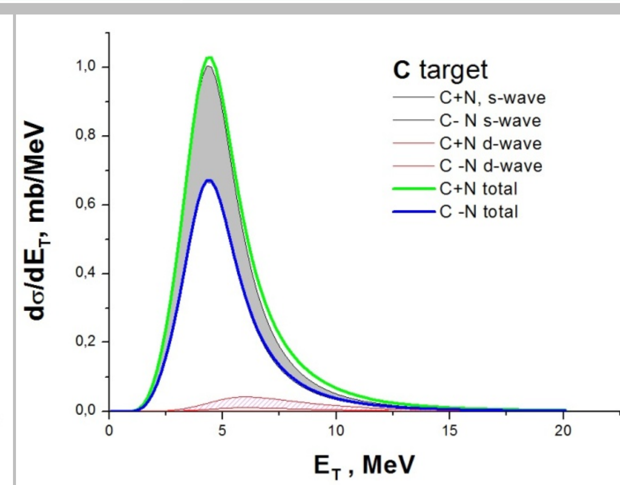


# Nuclear & Coulomb SDM in $^{17}$Ne: cross sections $\sigma$, mb (max at 4.0 MeV)

| 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 |



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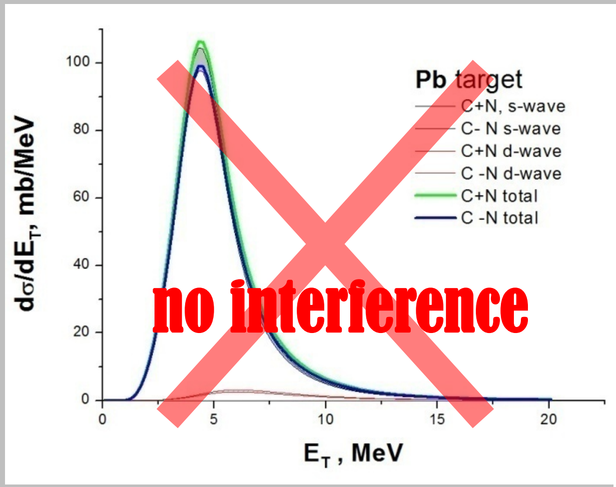
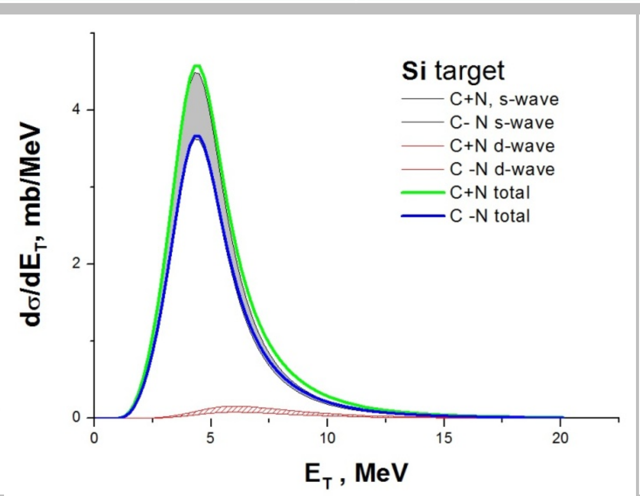
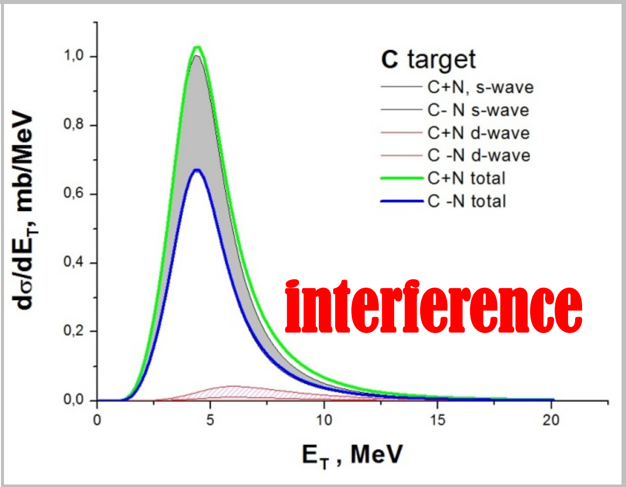
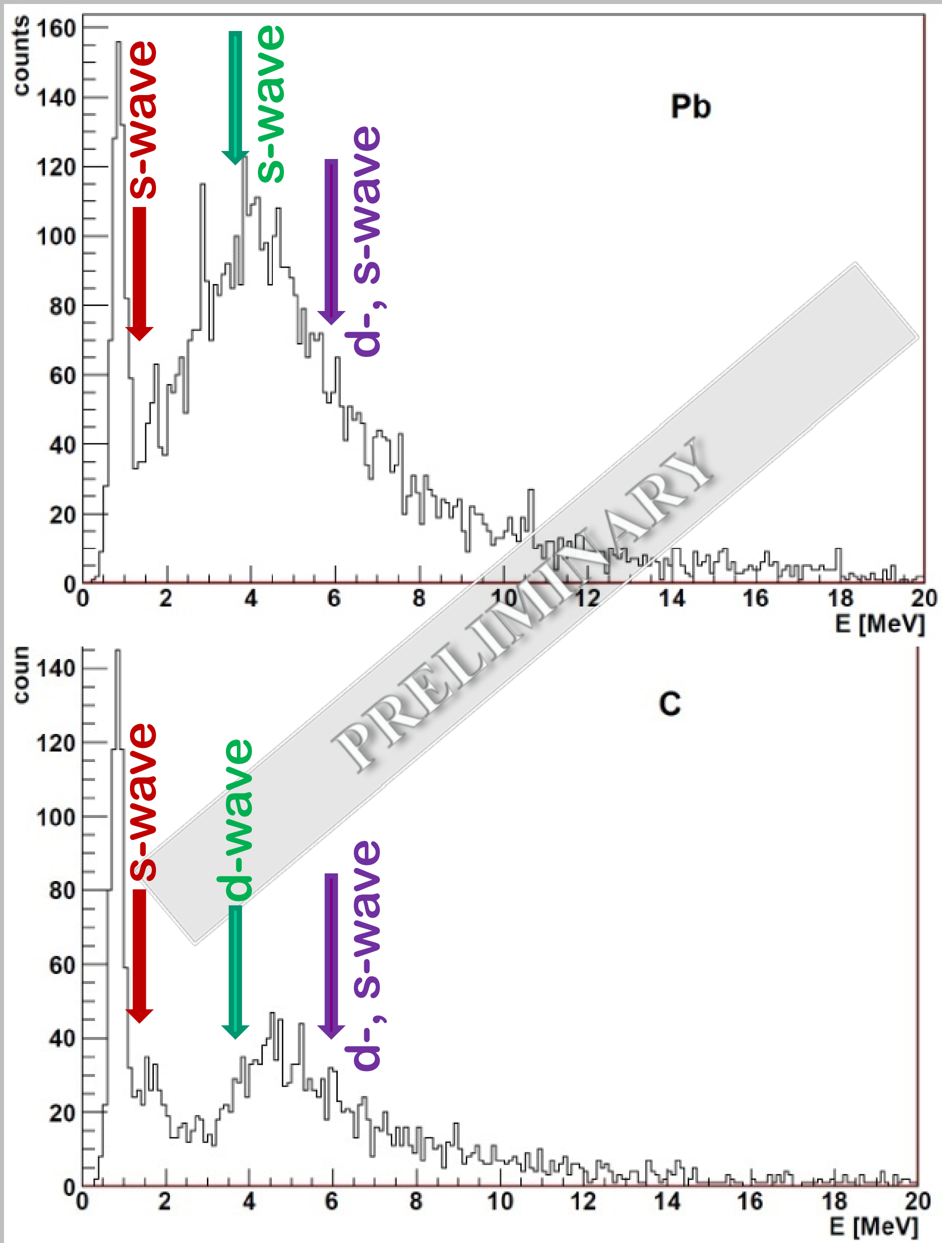
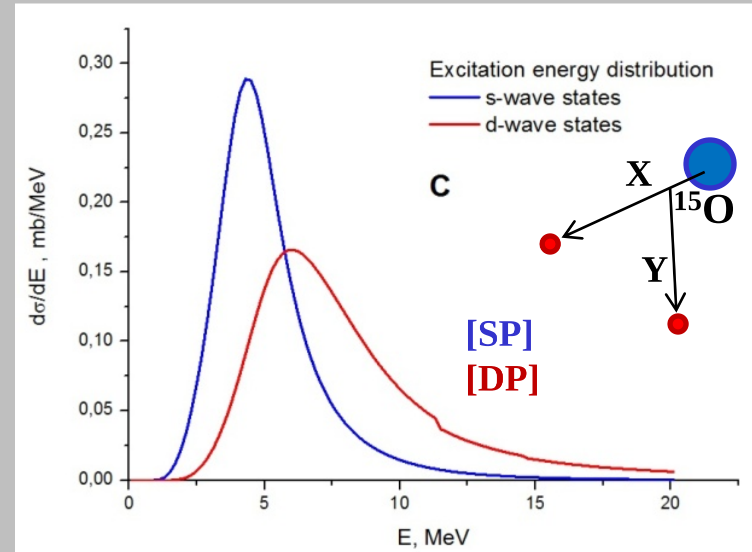


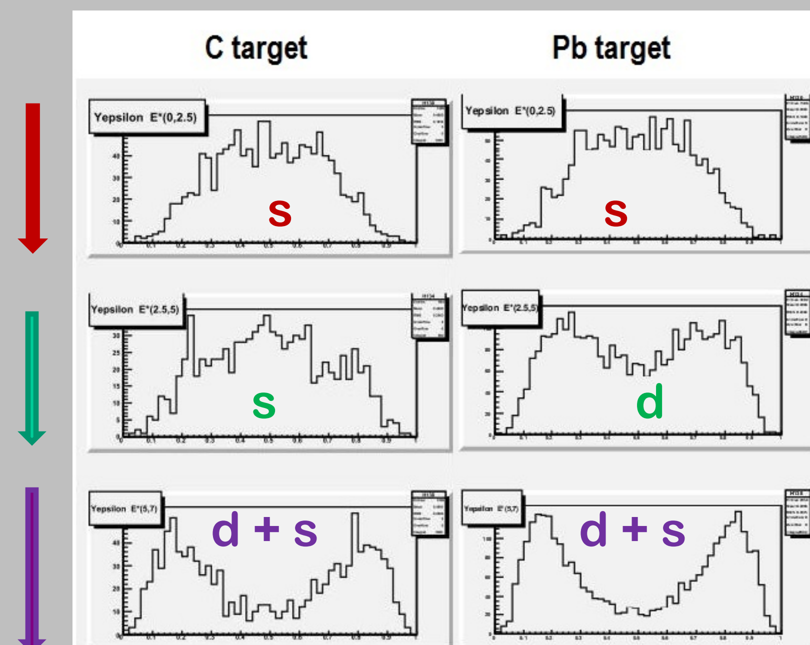



# Coulomb SDM in $^{17}$Ne: energy spectrum



# Excitation spectrum of $^{17}$Ne and correlations

- There is a bump at 4-5 MeV
- Energy spectra in different targets are not similar **due to difference in the Coulomb population of continuum with its γ decay to lower states**

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


TABLE I. Nuclear levels in $^{17}$Ne identified.

| Ex. energy (MeV) | $J^{\pi}$ adopted |
|---|---|
| 0.0 | $\frac{1}{2}-$ a |
| 1.288 | $\frac{3}{2}-$ |
| 1.764 | $\frac{5}{2}-$ |
| 1.908 | $\frac{1}{2}+$ |
| 2.651 | $\frac{5}{2}+$ |
| 2.997 | $\frac{7}{2}-$ |
| 3.548 | $\frac{9}{2}-$ |
| 4.010 | $\frac{3}{2}+$ |

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[dp] hypotetic

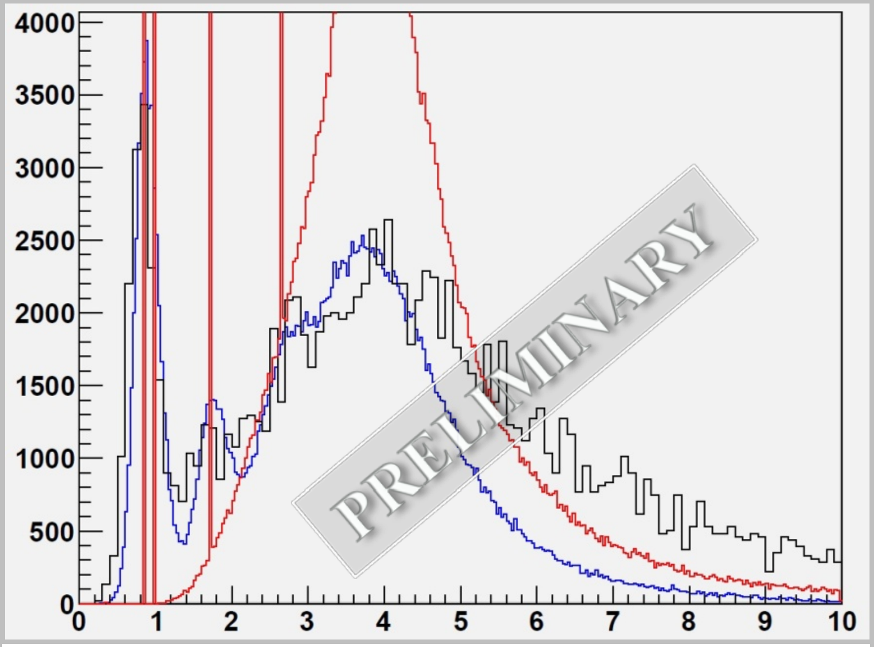
# Results and discussion

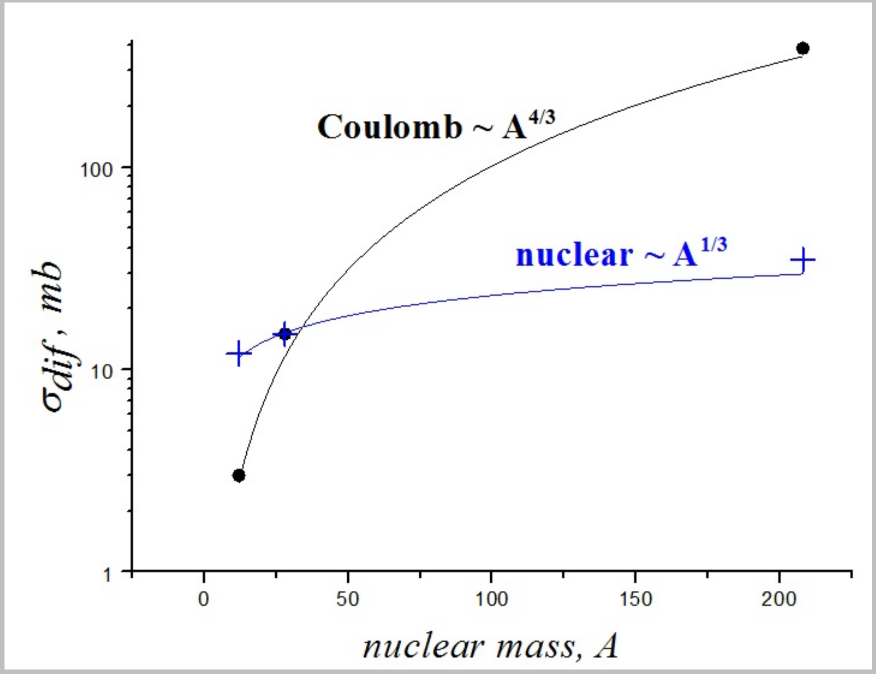
***Important results***

**• The "Soft E1" mode shows to have maximum at 4 MeV. Here the result of theoretical calculaions  and that after the MC simulation procedure.**

**• The excitation energy spectrum of $^{17}$Ne is well reproduced with d-wave contribution of the state at the energy 2.987 MeV.**

**• Mass number dependences of nuclear- and Coulomb dissociation is essentially different, that should be taken into account when separation their contribution.**



# Conclusions

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

• Contribution of the Coulomb **Soft E1** excitation in $^{17}$Ne in C target **dominates.**

• Due to negligibly small contribution of nuclear Soft N1 excitation the **Coulomb/nuclear interference** (if it is) in the Pb target is less than experimental errors (few percent). The interference is probable in the C target.

• 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**.

• To reproduce the internal energy-angular correlation we need to suppose the excited $^{17}$Ne states with [dp] structure.

• The energy spectra of $^{17}$Ne excitation in C and Pb targets are not similar.

# What is done

- We suggest a self-consistent approach for calculations of Coulomb/nuclear –induced dissociation of clustered nuclei for reactions at the nuclear surface.

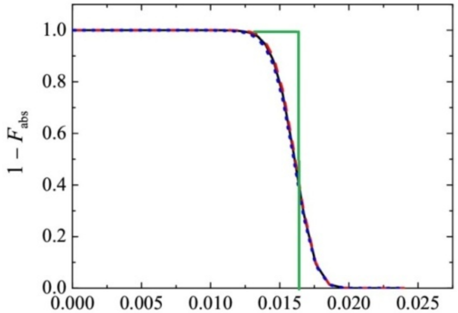
- Mass number dependence of nuclear and Coulomb dissociation is essentially different, that should be taken into account when separation their contribution.

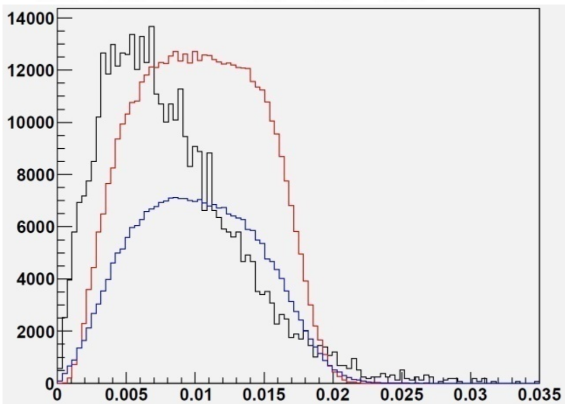
# Nearest plans

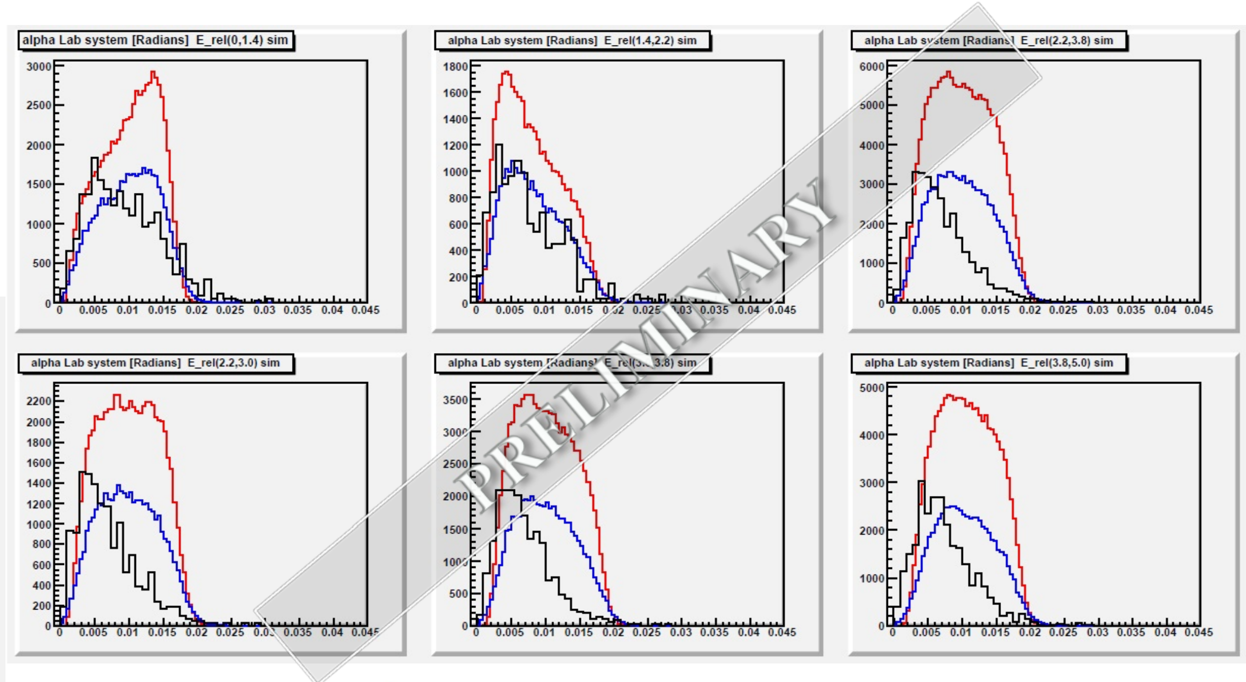
- to analyze the angular distributions of fragments (we are working on now)
- to clarify the origin of the hypothetic states, we need for best description;
- to take into account for p-removal in 15O diffraction dissociation (estimated to be up to 30%  of nuclear dissociation cross section)
- to calculate the strength function for nuclear- induced excitation of $^{17}Ne$

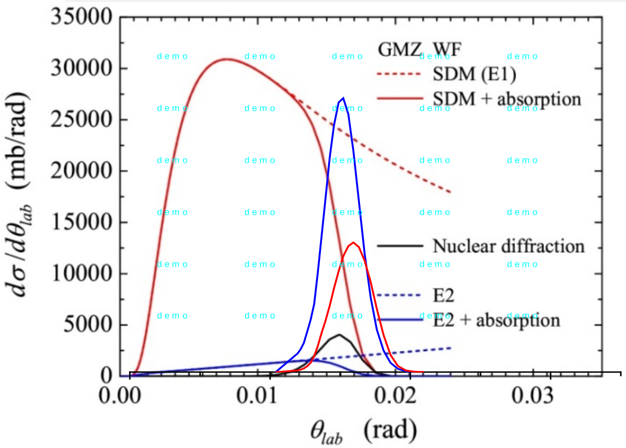

Дубна-Блюз

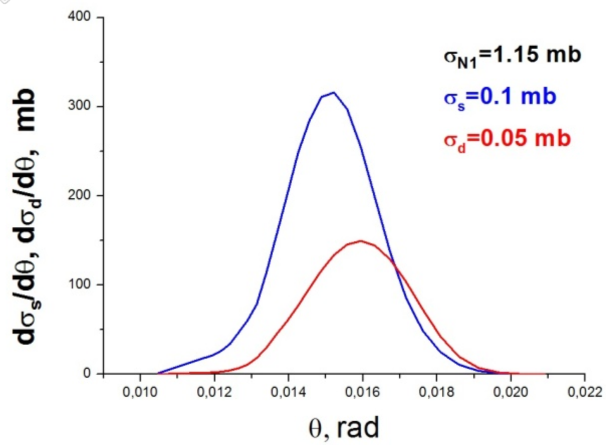
# Nuclear & Coulomb SDM in $^{17}$Ne: angular distribution



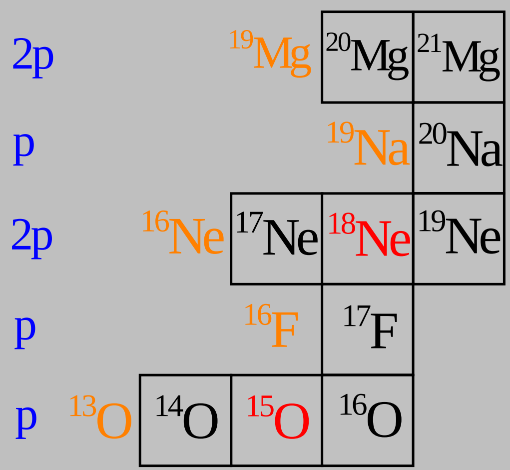



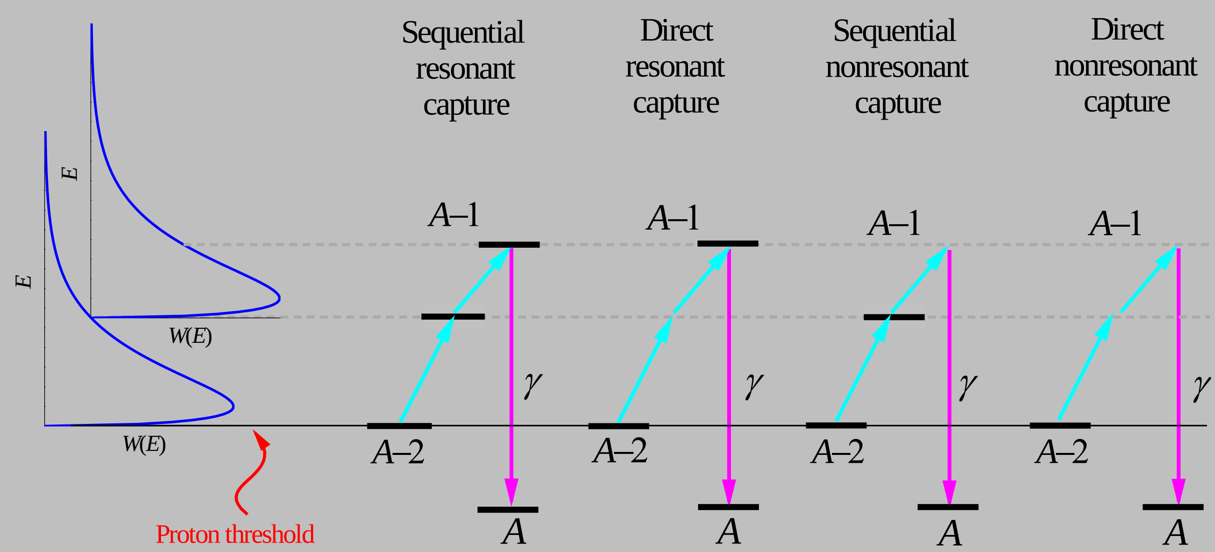



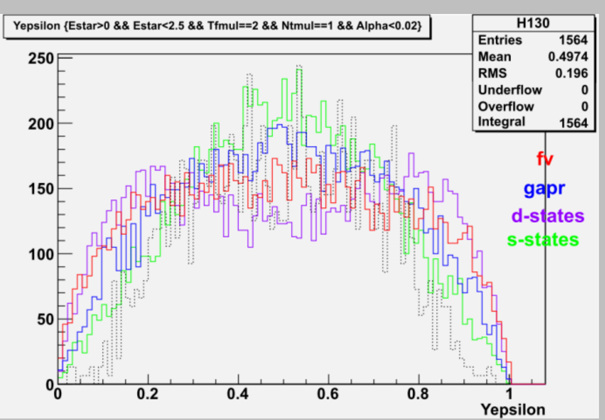



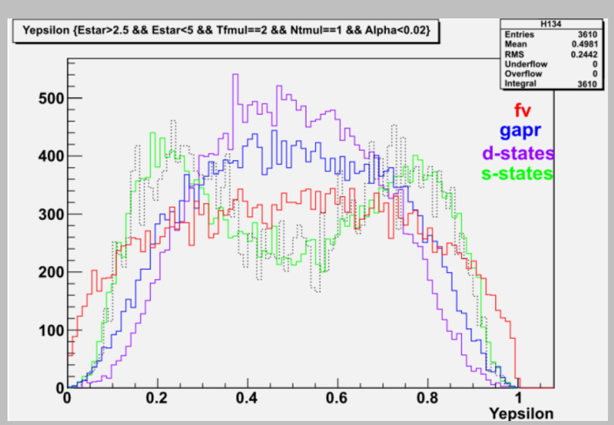



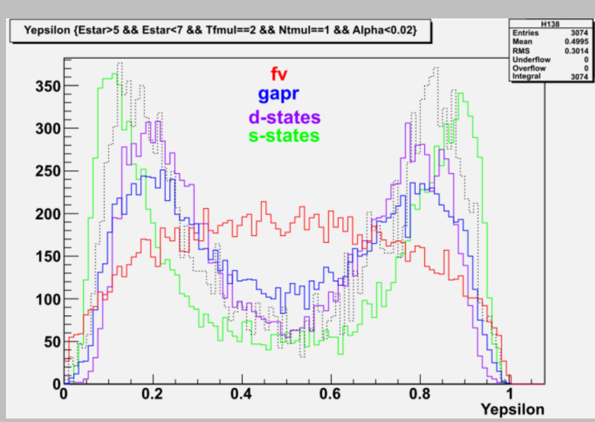
# Modes of two-proton radiative capture



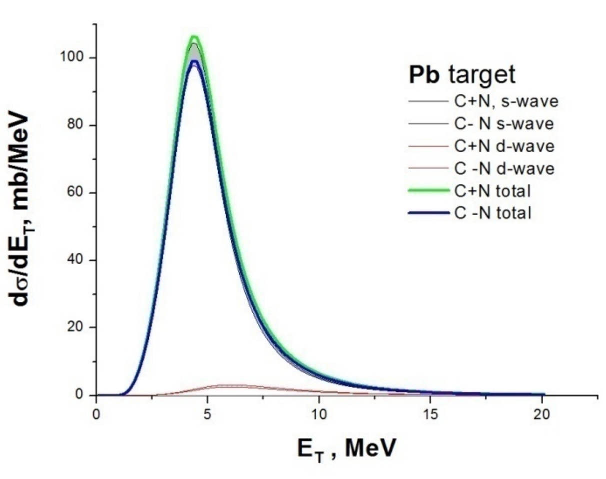



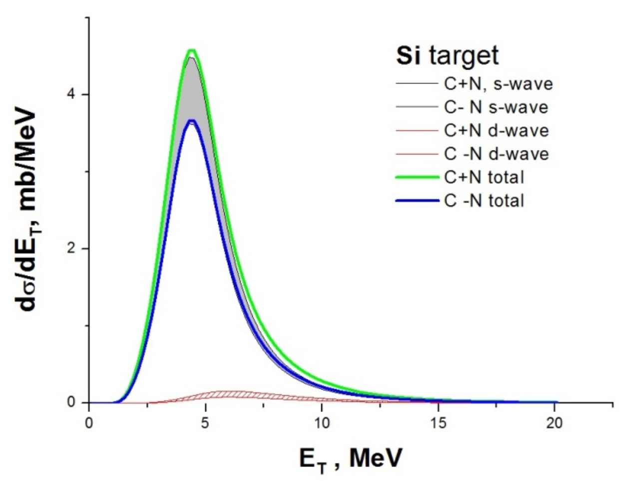



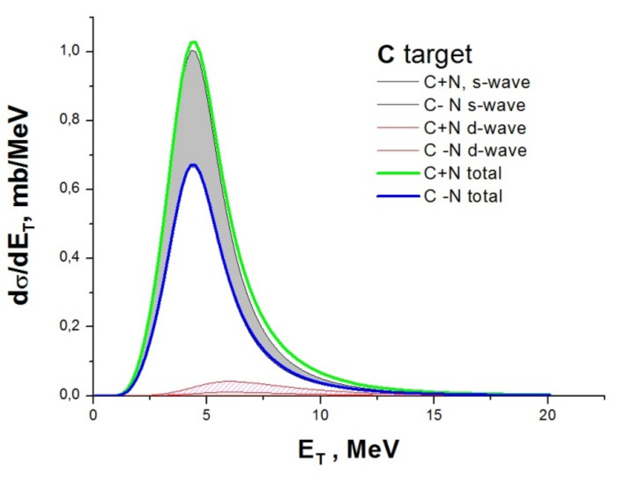



# Nuclear & Coulomb SDM in $^{17}$Ne: cross sections σ, mb

| value | Pb target | Si target | C target |
|---|---|---|---|
| Coulomb total | 415 / 380 | 17 /16 | 3.2 |
| Coulomb Soft E1 | 386 /342 | 15 /14 | 3.0 |
| Coulomb s-wave | 368/326 | 14.3/13.3 | 2.86 |
| Coulomb d-wave | 18/16 | 0.71/0.67 | 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 |



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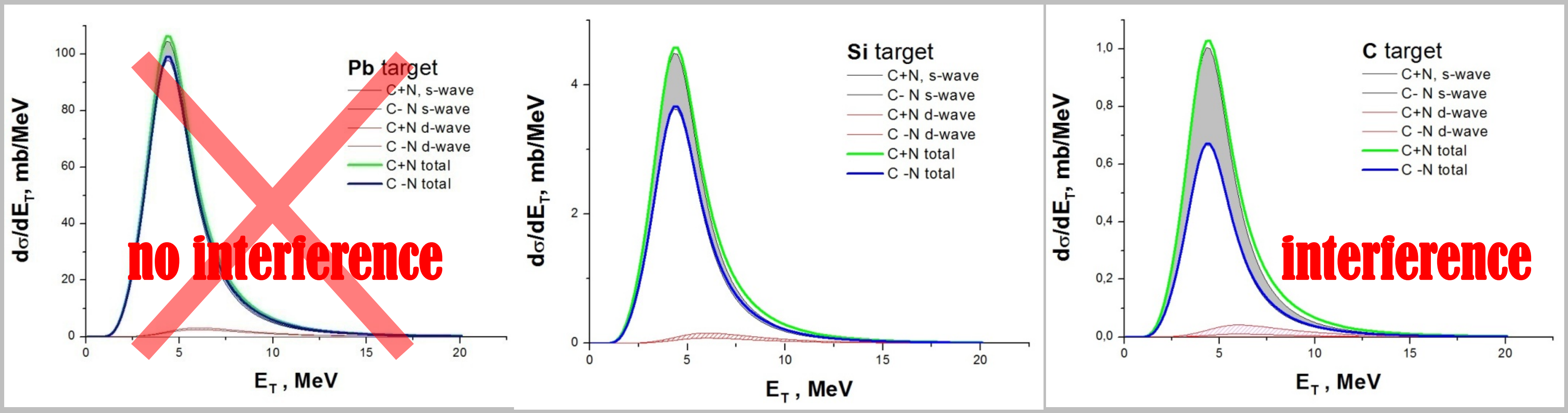
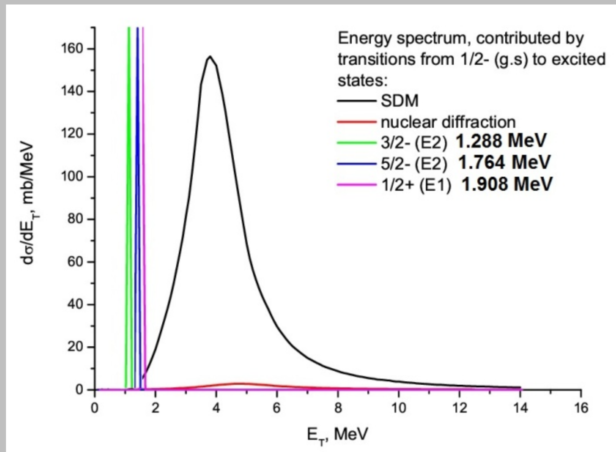
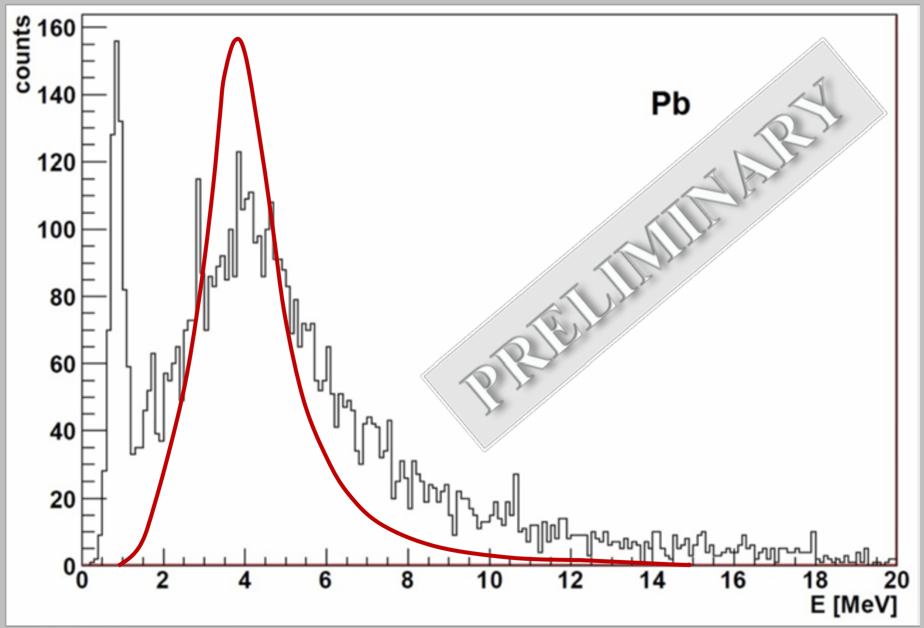
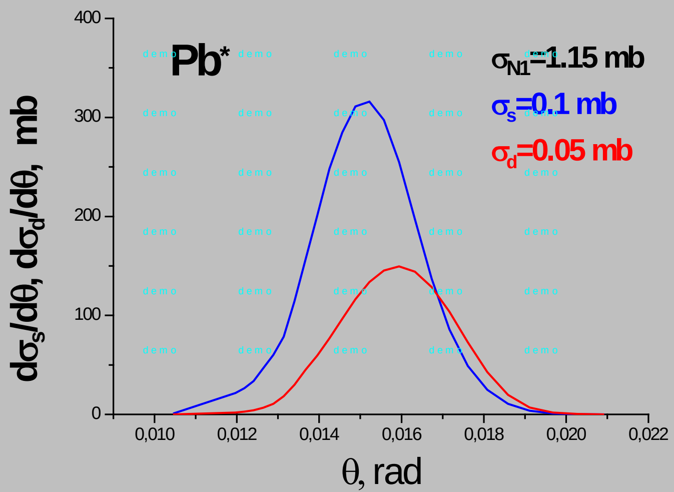
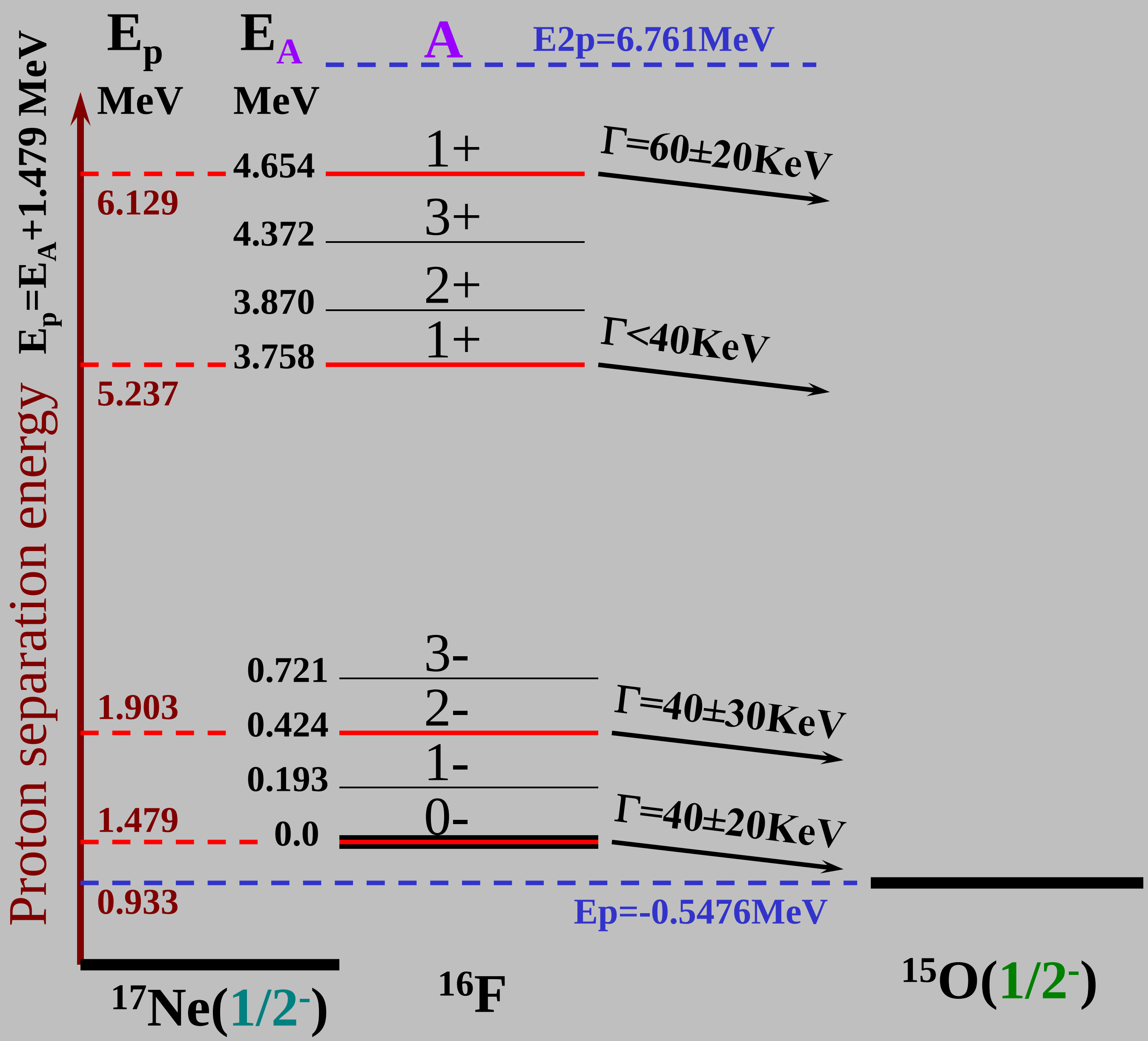



Energy spectrum, contributed by transitions from 1/2- (g.s) to excited states:
SDM
nuclear diffraction
3/2- (E2) 1.288 MeV
5/2- (E2) 1.764 MeV
1/2+ (E1) 1.908 MeV
dσ/dE_T, mb/MeV
E_T, MeV
0 2 4 6 8 10 12 14 16
0 20 40 60 80 100 120 140 160


counts
Pb
PRELIMINARY
E [MeV]
0 2 4 6 8 10 12 14 16 18 20
0 20 40 60 80 100 120 140 160


Pb*
σN1=1.15 mb
σs=0.1 mb
σd=0.05 mb
dσs/dθ, dσd/dθ, mb
θ, rad
0,010 0,012 0,014 0,016 0,018 0,020 0,022
0 100 200 300 400

# 2-body model of $^{17}$Ne



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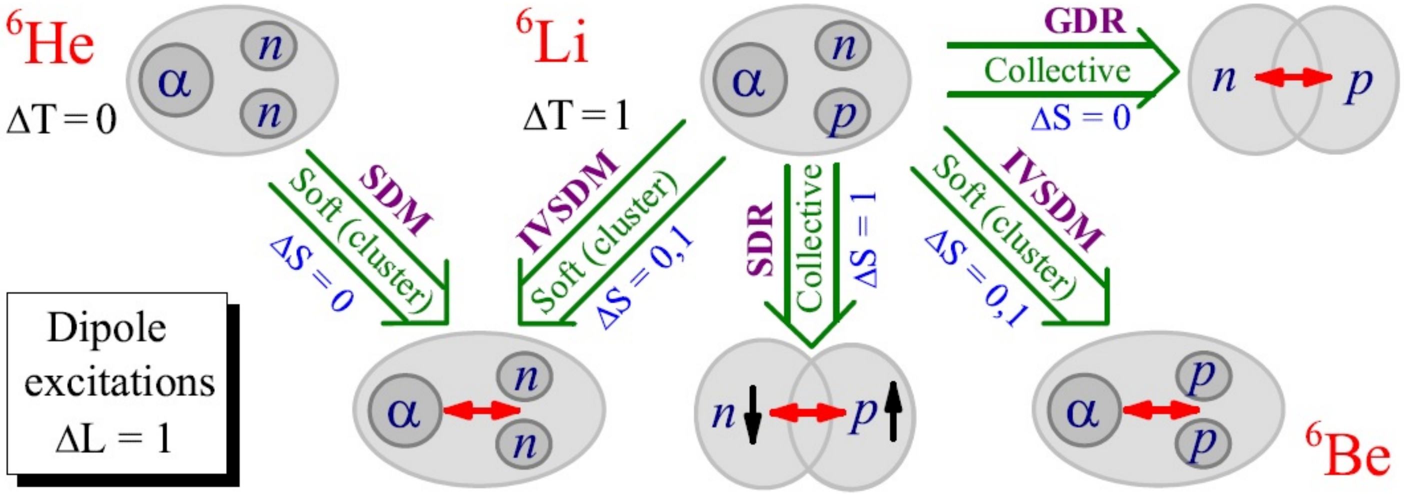



Figure 1: *Classification scheme of dipole excitations in $^{6}$He and $^{6}$Be prodused in charge-exchange reactions with $^{6}$Li [1]. The appearance of the soft dipole mode in the electromagnetic excitation of $^{6}$He is shown for comparison. Given is the illustration of difference between the cluster 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).*

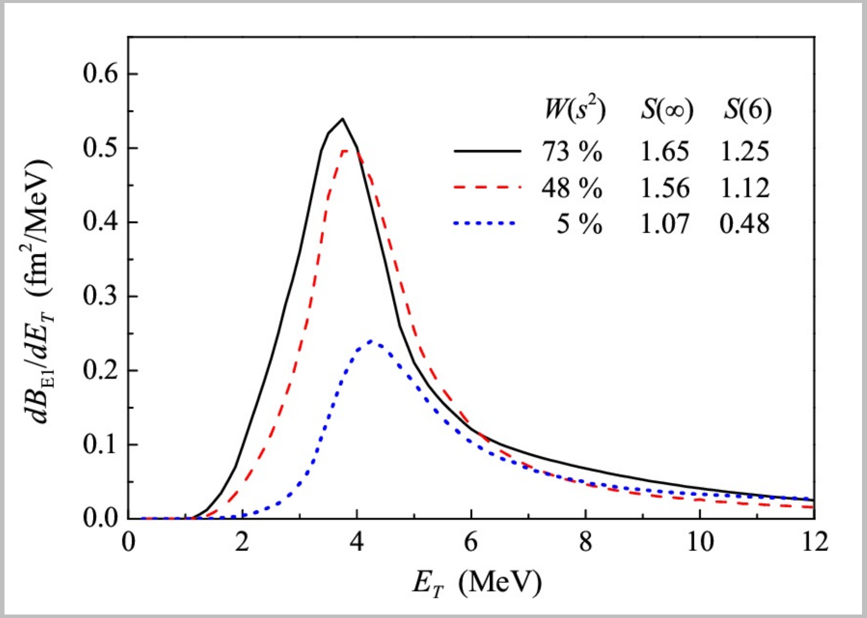
# THANK YOU!!!

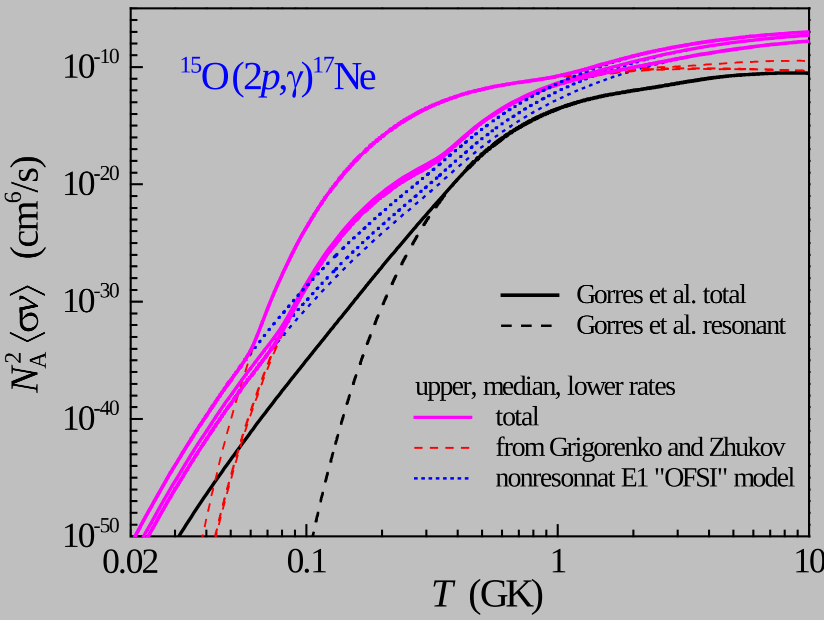
# "Soft E1" mode in proton dripline nuclei

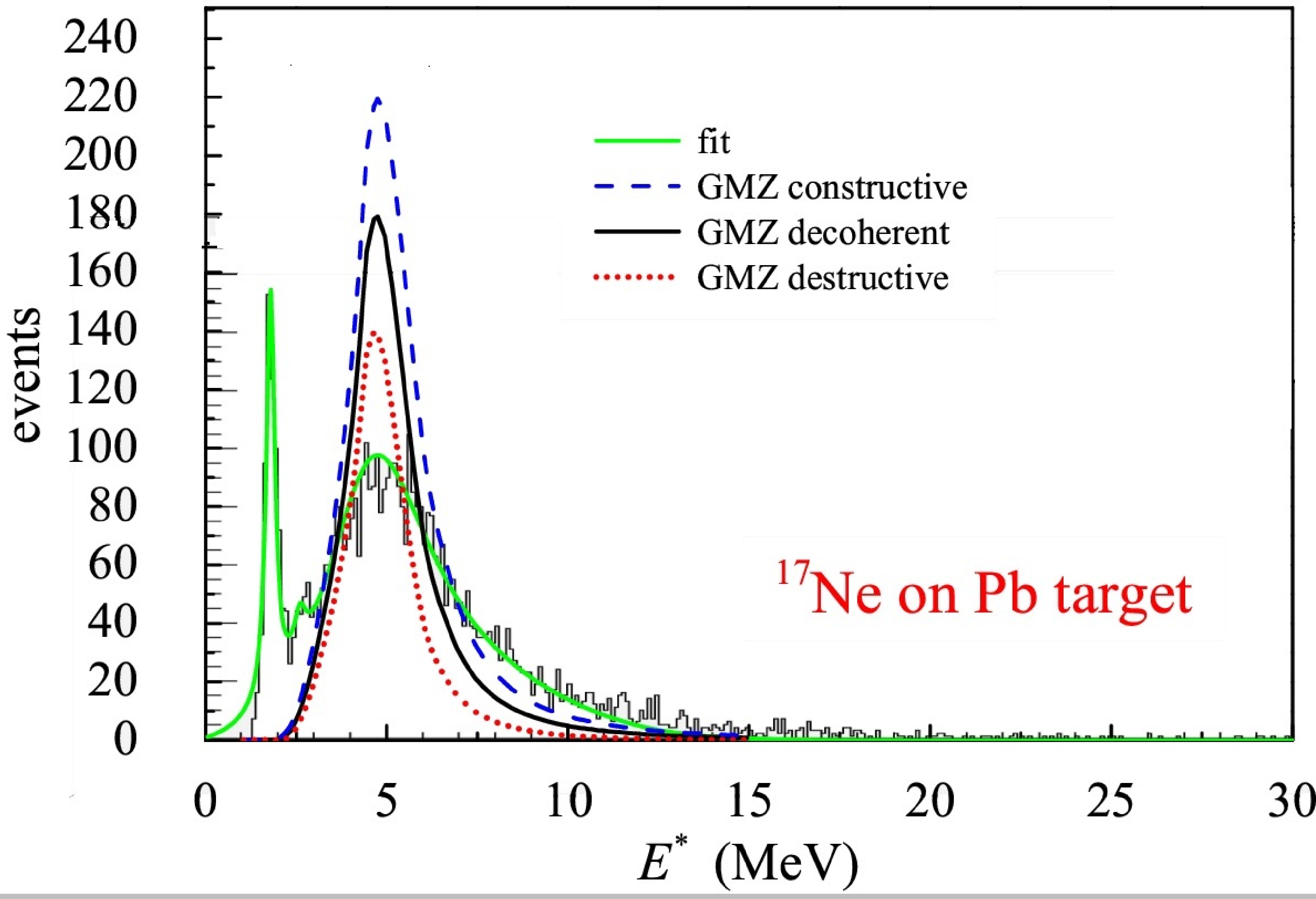
- Existence of "soft E1" mode now established in neutron-rich nuclei ($^{6}$He, $^{11}$Li).
- Cluster sum rule exhausted within several MeV above 2p threshold.
- **Possibility of "soft E1" in proton-dripline nuclei**.
- Calculations predict a strong and narrow E1 peak in $^{17}$Ne.
- **The 2p capture rate is dominated by the nonresonant E1 for**

**T < 0.05–0.08 GK and T > 0.4–1.0 GK**

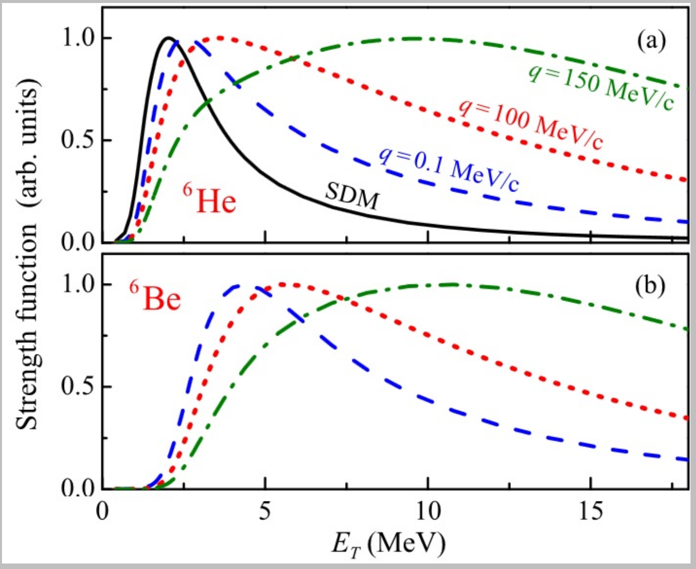
- In 2p halo nuclei, the "soft E1" peak is placed higher in that in 2n halo nuclei (analogy with $^{6}$Be $^{6}$He and $^{6}$Be **A.S. Fomichev et al PLB 708 (2012) 6**





events
240
220
200
180
160
140
120
100
80
60
40
20
0
0
5
10
15
20
25
30
$E^*$ (MeV)
fit
GMZ constructive
GMZ decoherent
GMZ destructive
$^{17}$Ne on Pb target


Strength function (arb. units)
$E_T$ (MeV)
(a)
(b)
$^6$He
$^6$Be
$q = 150$ MeV/c
$q = 100$ MeV/c
$q = 0.1$ MeV/c
SDM
0.0
0.5
1.0
0
5
10
15

# 2-body model of $^{17}$Ne