Dynamical Dipole Resonance (DDR)

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DDR: what is it?

- Suppose that we have an isospin asymmetric reaction (i.e. N/Z of projectile and target are different) at low energy, where the formation of the compound nucleus CN is expected
- In the early stages of the reaction before the formation of the equilibrated CN, a collective dipole oscillation (DDR, dynamical dipole resonance) develops
- The DDR gives rise to a prompt γ emission in the region 10-25 MeV, i.e. the same region of the GDR
- The GDR has a statistical origin and it comes from the equilibrated CN
- The DDR is a pre-equilibrium phenomenon
- The DDR emission takes place in the low density neck region in the early stages of the reaction, when the system is in a very deformed configuration (almost dinuclear)
- The DDR oscillation damps in 200-300 fm/c
- The angular distribution associated to the DDR emission is strongly anisotropic: it is dipolar like, but it is damped with respect to a pure dipolar emission because the dipole axis rotates during the emission

The DDR is expected in a limited window of beam energies and it is enhanced by the use of radioactive beams

- A rise and fall trend of the DDR strength with respect to the beam energy is expected
- The DDR emission should be negligible below 5-6 AMeV because the neck dynamics is too slow and the dipole acceleration is reduced
- The DDR emission should be negligible beyond 15AMeV because the pre-equilibrium emission of n and LCP and NN collisions tend to make the dynamical dipole disappear
- The DDR emission strongly depends on the isospin asymmetry in the entrance channel => the use of radioactive beams will enhance this phenomenon
- Both the anisotropy of the angular distribution and the dipole oscillation frequency depend on the stiffness of the symmetry energy

Theoretical framework (BNV model)

V.Baran et al., PRC79(2009)021603

- The yields of the γ of the DDR can be described by means of a transport model of BNV-type (Boltzmann-Nordheim-Vlasov) in the hypothesis that they are due to a bremssthralung mechanism

$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}|D''(\omega)|^2,$$

γ probability emission as a function of the energy

D(t) is the time dependent dipole amplitude

$$D(t) = D(t=0)e^{i(\omega_0 + i/\tau)t}$$

τ damping rate due to NN collisions and n pre-equilibrium emission

ω_0 oscillation frequency

D(t=0) static dipole depending on the isospin asymmetry of the entrance channel => importance of radioactive beams

$$D(t=0) = \frac{r_0\left(A_p{}^{1/3} + A_t{}^{1/3}\right)}{A} Z_p Z_t \left|\frac{N_t}{Z_t} - \frac{N_p}{Z_p}\right|$$

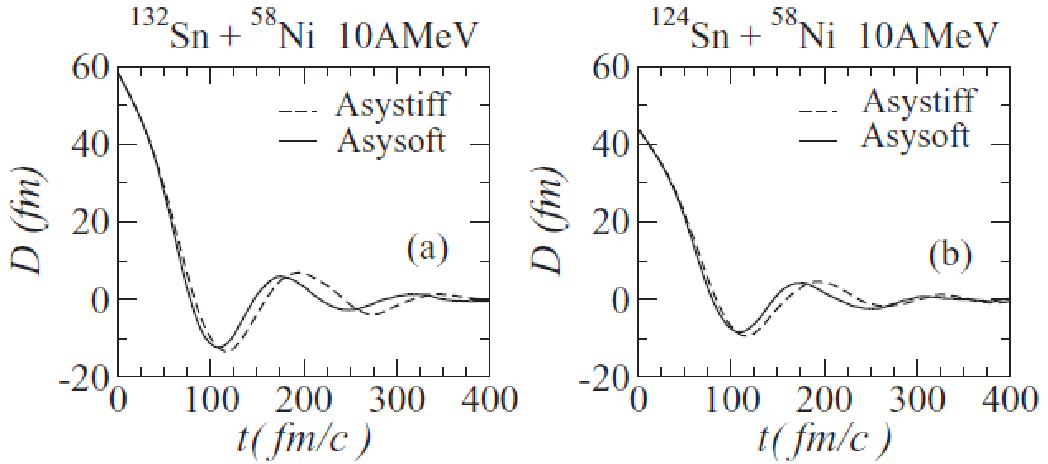
$\ddot{D}(t)$ Dipole acceleration

$\ddot{D}(\omega)$ Fourier transform of the dipole amplitude acceleration

$$|\ddot{D}(\omega)|^2 = \frac{\left(\omega_0{}^2 + 1/\tau\right)^2 D(t=0)^2}{(\omega-\omega_0)^2 + 1/\tau^2}$$

$\boldsymbol{Y \propto \omega_0{}^3 \tau D(t=0)}$ Total yields of γ = quantity experimentally measurable, obtained by integrating $\frac{dP}{dE_\gamma}$

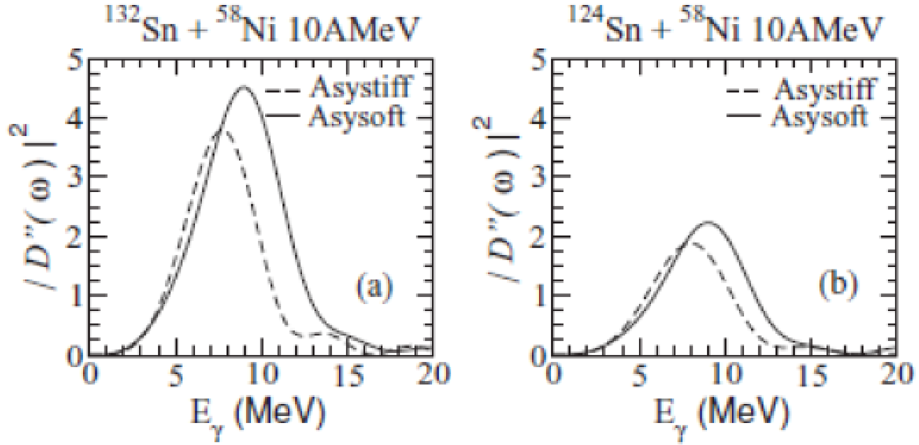
The oscillation frequency depends on the symmetry energy



D(t) for asystiff and asysoft

$$D(t) = D(t=0)e^{i(\omega_0 + i/\tau)t}$$

$$D(t=0) = \frac{r_0\left(A_p^{1/3} + A_t^{1/3}\right)}{A} Z_p Z_t \left|\frac{N_t}{Z_t} - \frac{N_p}{Z_p}\right|$$



$$\left|\ddot{D}(\omega)\right|^2 = \frac{\left(\omega_0^{\,2} + 1/\tau\right)^2 D(t=0)^2}{(\omega - \omega_0)^2 + 1/\tau^2}$$

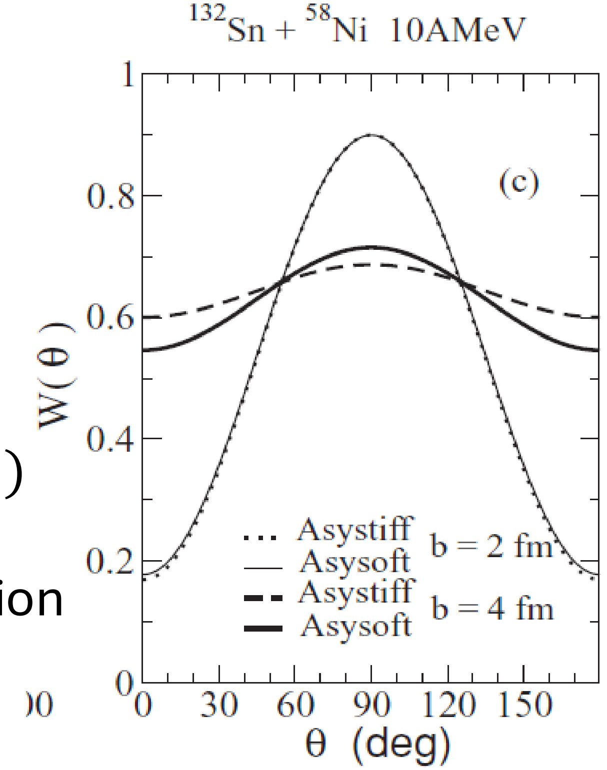
$\boldsymbol{Y \propto \omega_0^{\,3}\tau D(t=0)}$ Total yields

$\omega_0\tau$ depends on the symmetry energy of the EOS of the nuclear matter, acting as a recall term to restore the equilibration of N/Z => **from the γ yields it is possible to extract information on the behaviour at low density of the symmetry energy**

$$W(\theta) = 1 + a_2 P_2(\cos\theta)$$

For pure dipole a_2=-1

Also the angular distribution of the γ depends on the symmetry energy



Open points

- To my knowledge, the studies on the DDR performed up to now have been done with stable beams => small static dipole => small DDR emission => very big error bars
- Discrepancies among the experimental results on different systems and the predictions of the BNV model concerning the rise and fall trend with the beam energy, absent for some dataset, too steep for others with respect to the predictions
- The angular anisotropies experimentally observed are not in agreement with the model
- Even the trend of the γ yields as a function of the system isospin asymmetry is different from the predictions of the model: maybe also the mass asymmetry or the total mass of the system have a role in the DDR intensity

Some examples

There are mainly 2 methods to put into evidence the DDR emission:

1)Difference method

Which uses only experimental data collected in different reactions, in particular one isospin symmetric and one asymmetric giving the same CN

The contribution of the DDR is isolated by subtracting the γ spectrum of the symmetric reaction (supposed to be of pure statistical origin, i.e. due to the GDR) from that found for the asymmetric reaction.

Obviously we must be sure that the formed CN is exactly the same and therefore the contribution of the pre-equilibrium must be accurately evaluated

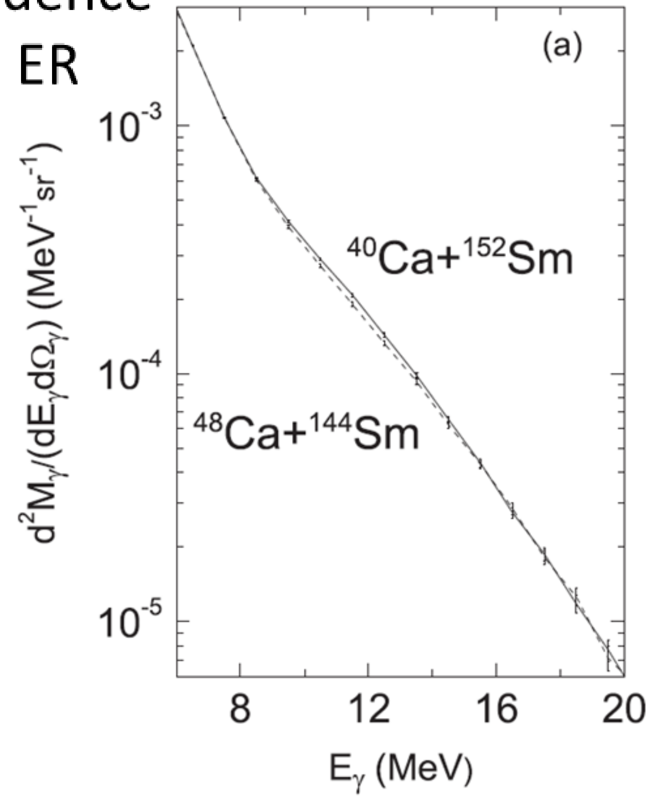
Example of use of the difference method

C.Parascandolo et al., PRC 93 (2016) 044619

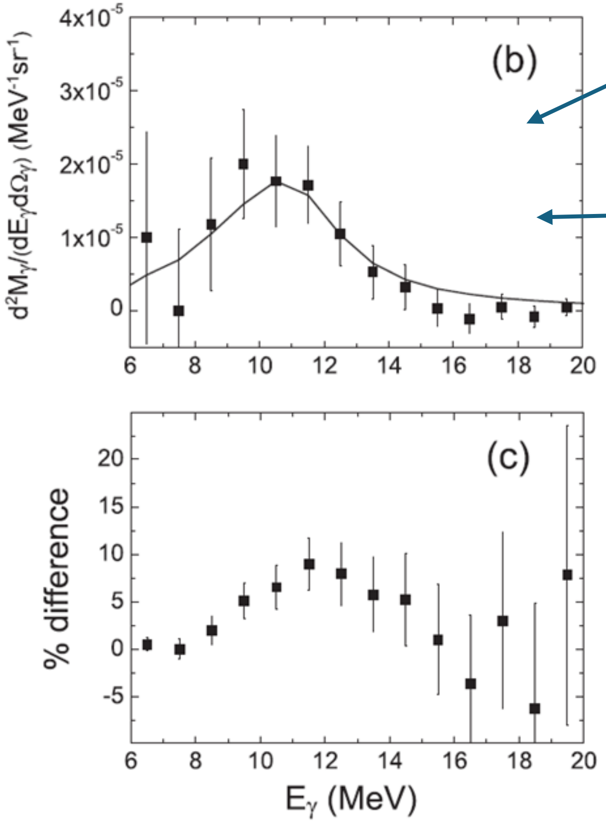
$^{48}Ca+^{144}Sm$ @10.1AMeV (reference)

$^{40}Ca+^{152}Sm$ @ 11AMeV

γ Spectra for the 2 reactions in coincidence with the ER



Spectrum obtained by subtracting the one obtained for 48Ca+144Sm from that obtained for 40Ca+152Sm



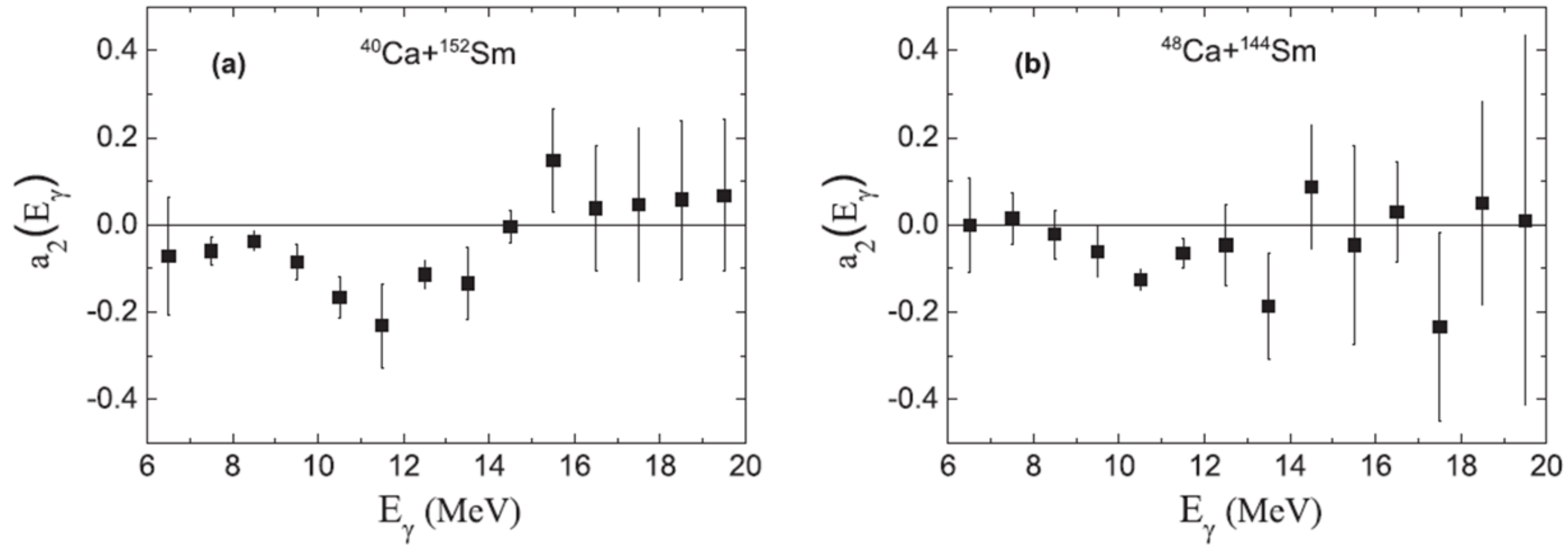
This would be the DDR

The angular distribution of the γ was fitted with the formula

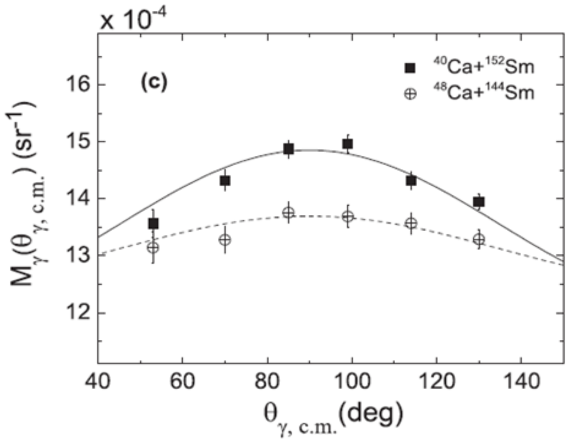
$$M_\gamma(E_\gamma,\theta_\gamma) = M_0(E_\gamma)\{1 + Q_2 a_2(E_\gamma) P_2[\cos(\theta_\gamma)]\},$$

a_2 anisotropy coefficient

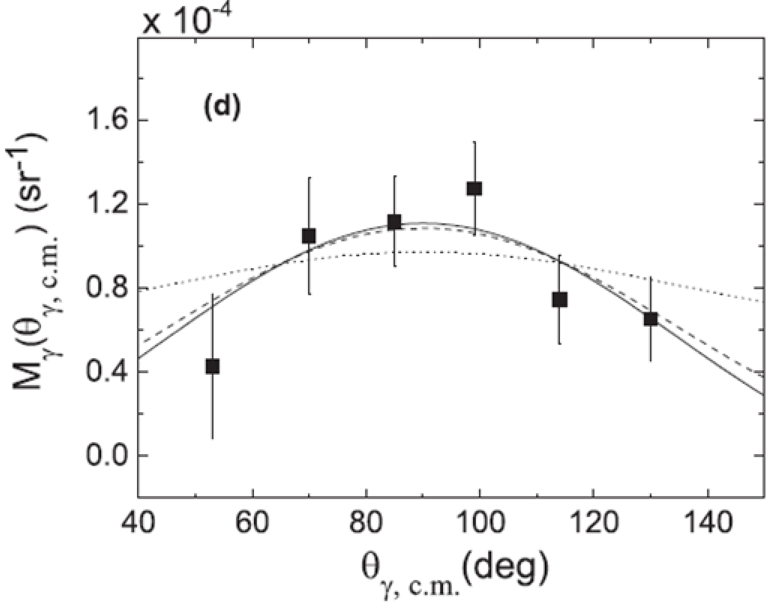
Q_2 attenuation factor



For the asymmetric reaction the a_2 coefficient is higher



Angular distribution integrated on energy



Angular distribution of the DDR (obtained by subtracting the distribution of the symmetric reaction from that of the asymmetric reaction)

Fit from BNV con a_2=0.84 (asystiff case)

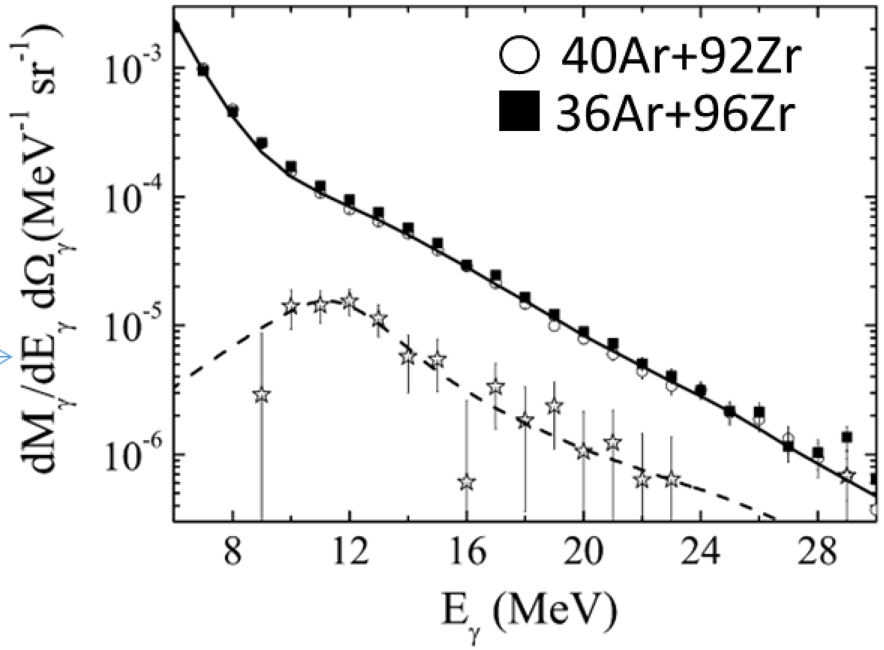
An other example of this technique can be found in

B.Martin et al., PLB 664 (2008) 47

$^{36}Ar+^{96}Zr$ @ 16AMeV

$^{40}Ar+^{92}Zr$ @ 15.1AMeV (reference)

Subtracted spectrum (DDR)



Some examples

There are mainly 2 methods to put into evidence the DDR emission:

2)Method using statistical model calculations

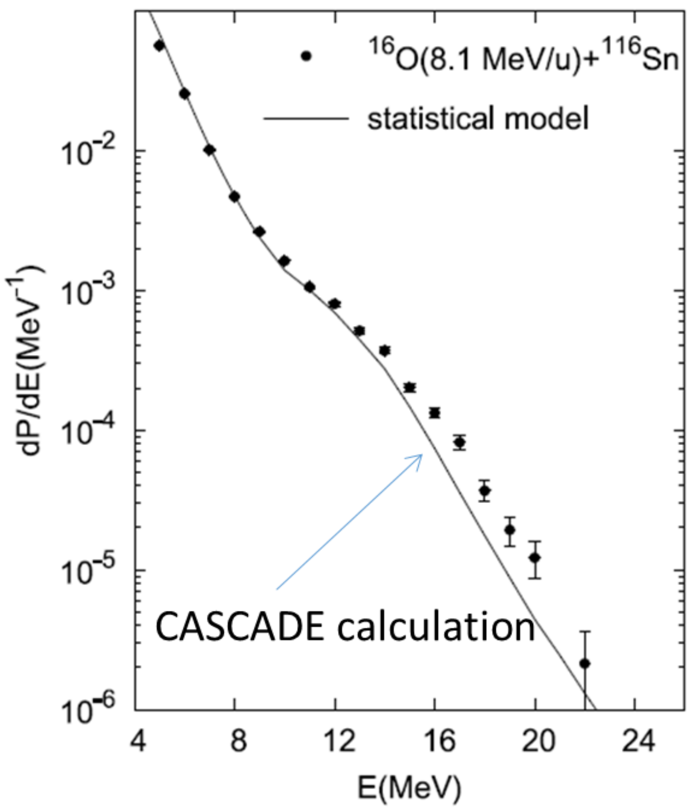
Even in this case we use 2 experimental reactions producing similar CN (this time it does not matter that they are equal), one isospin symmetric (used as reference) and one asymmetric.
It is important to carefully evaluate the pre-equilibrium contribution to find the E* of the CN in the 2 reactions.
The γ spectrum of the symmetric reaction which is supposed to be of statistical origin (GDR) is fitted by means of a statistical model (e.g. the CASCADE code), in order to fix all its parameters. At this point, keeping fixed the code parameters (with the possible exception of CN E* and of the GDR width) the spectrum of the statistical γ of the asymmetric reaction is simulated and then subtracted from the total spectrum in order to find the DDR

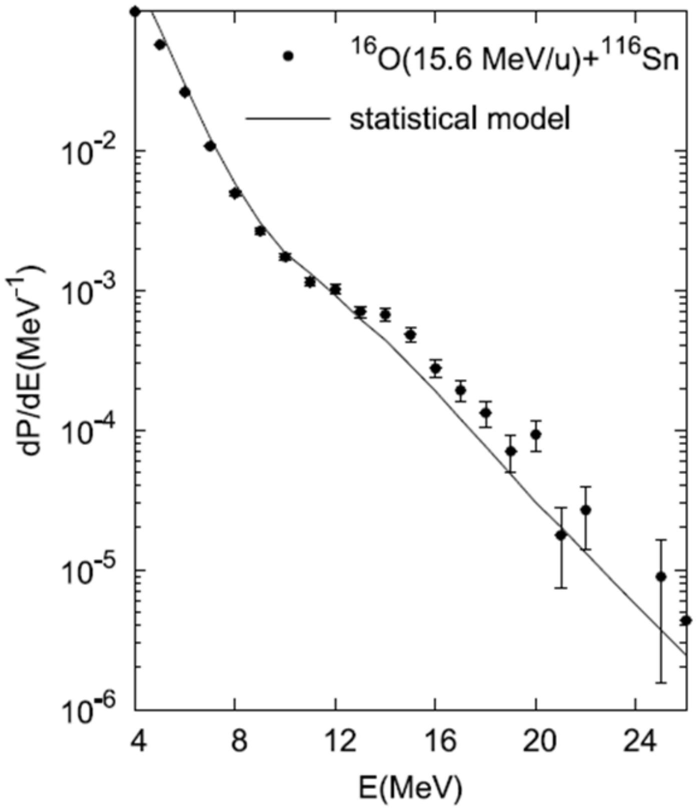
Example of use of the method employing the statistical model

A.Corsi et al., PLB 679 (2009) 197

$^{16}O+^{116}Sn$ @8.1, 15.6 AMeV

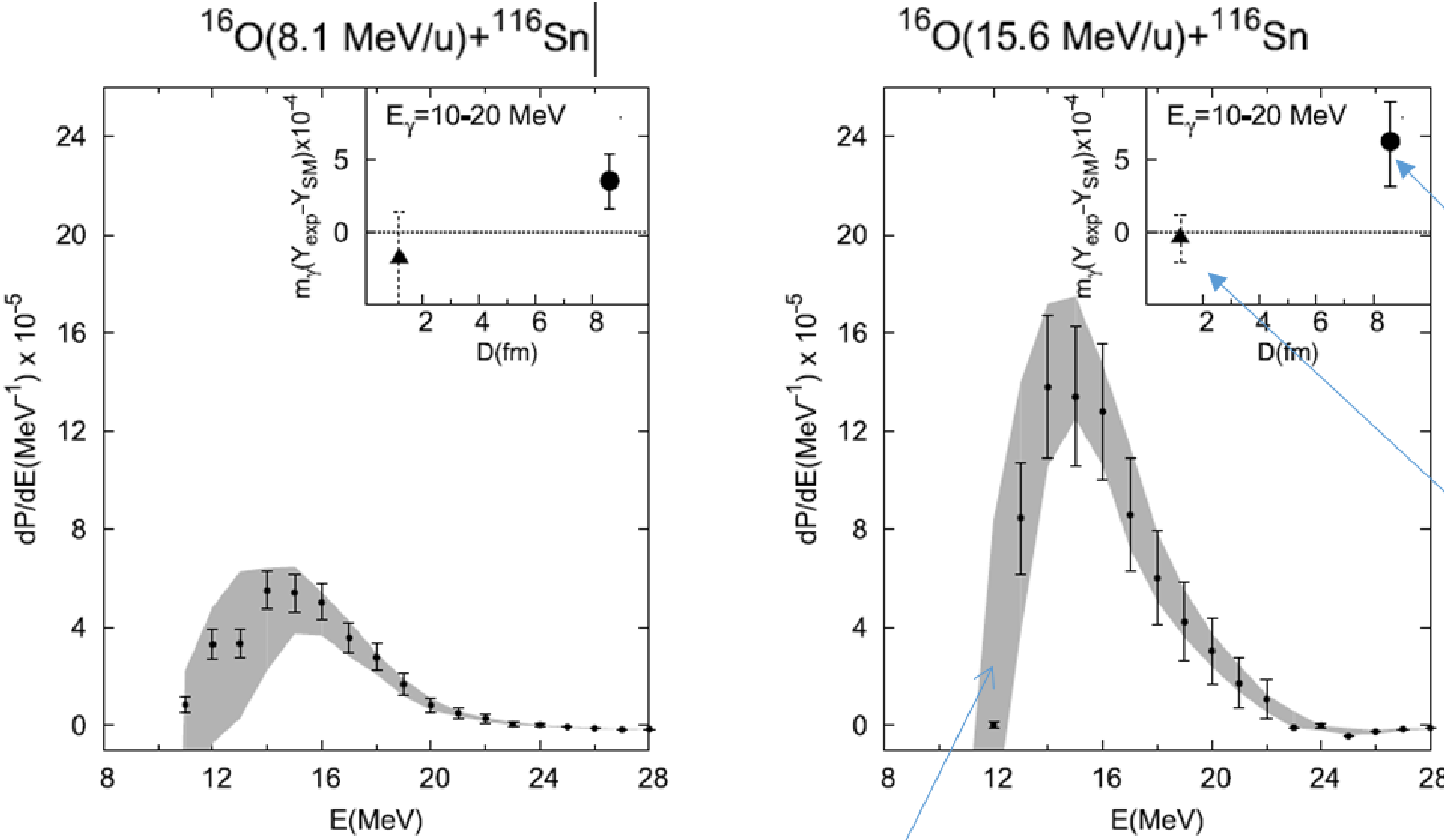
$^{64}Ni+^{68}Zn$ @ 4.7, 6.25, 7.8 AMeV (reference)





Evolution with the beam energy

Residual spectrum after subtracting the statistical contribution (DDR)



Integrated difference between data and model

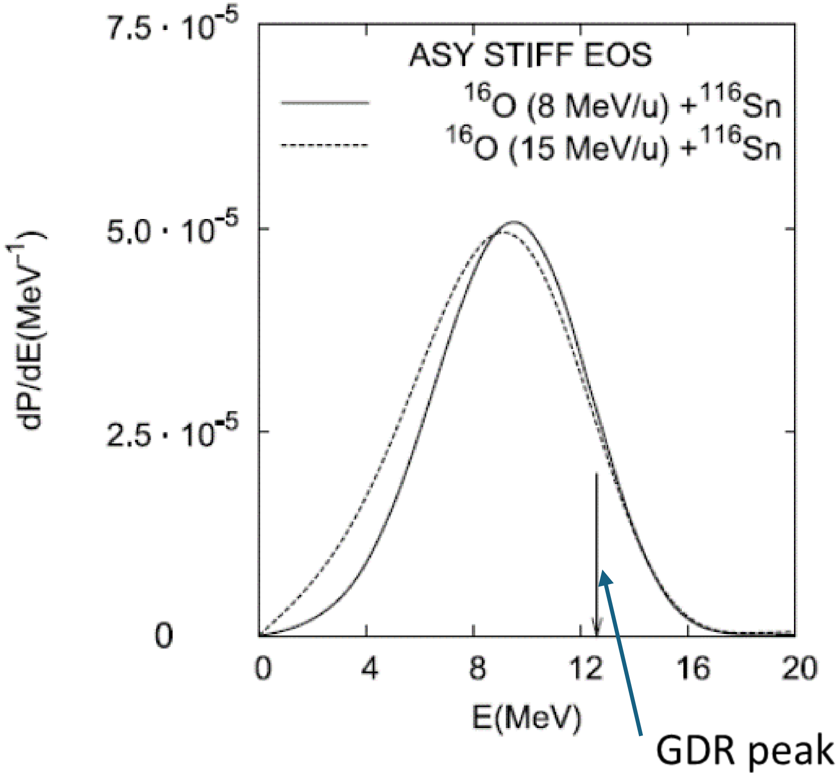
Reference (^{64}Ni+^{78}Zn reaction , with very small static dipole): difference ~ 0

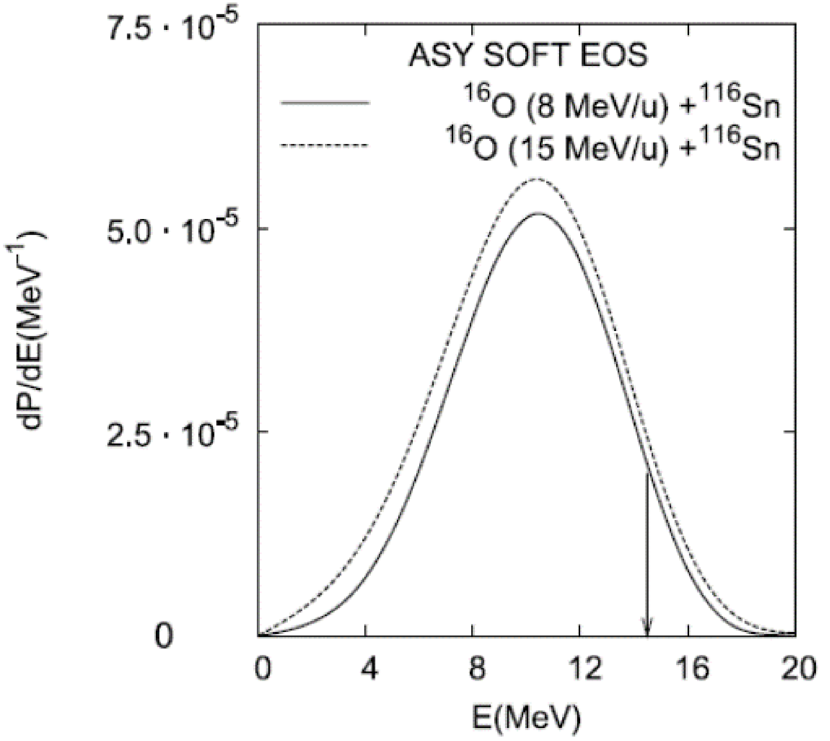
Uncertainty due to the preequilibrium estimate

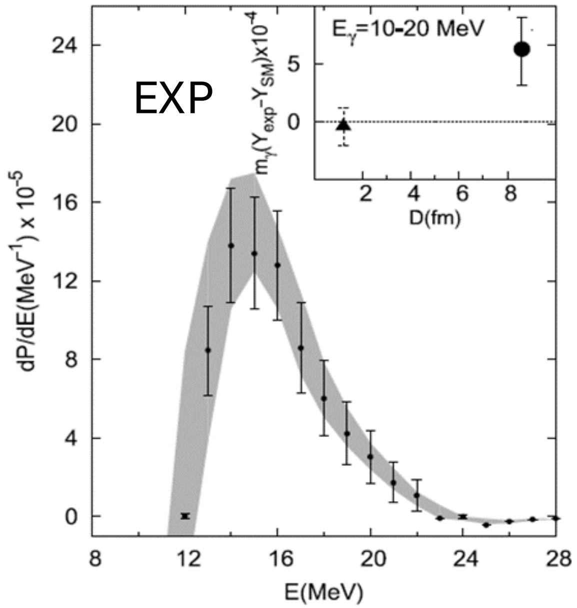
With respect to the BNV model the DDR peak in the data is at a shifted energy

Transport model calculations

bremsstrahlung spectra, obtained from the Fourier transform of the dipole acceleration







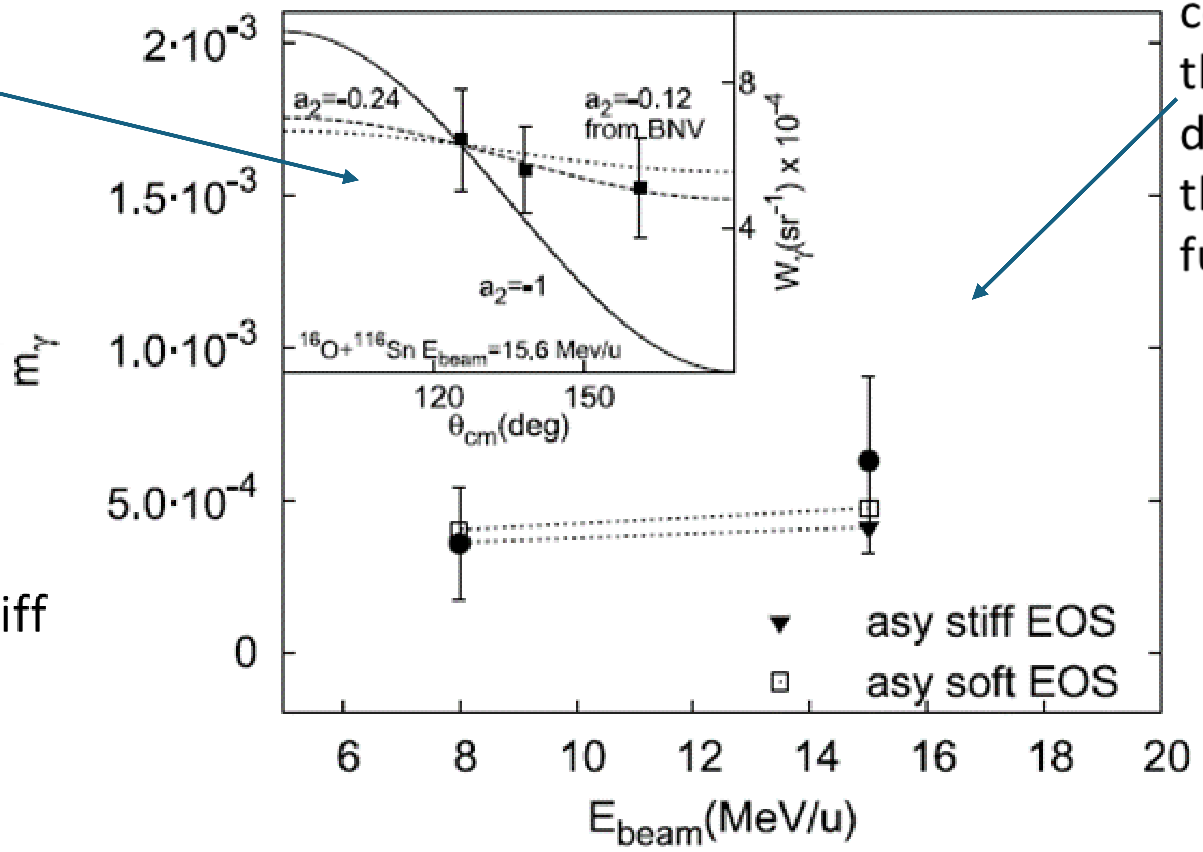
The peak is predicted at around 11 MeV , in the data it is at 14MeV

Angular distribution and γ multiplicities

γ Excess as a function of the angle (compared with BNV)

$$W(\theta) = W_0[1 + a_2 P_2(\cos\theta)]$$

a_2=0.12 corresponds to a BNV stiff



Experimental γ multiplicity compared with the results of the BNV simulation with 2 different parametrizations of the symmetry energy as a function of E_{beam}

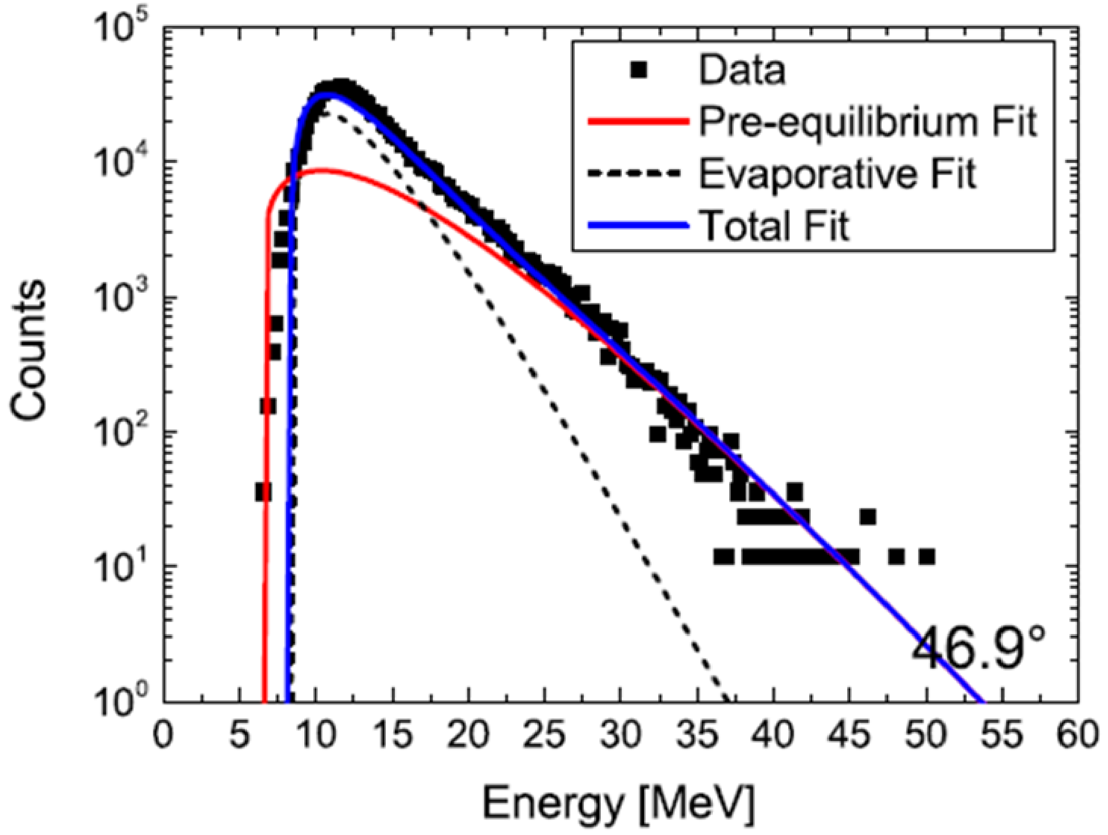
Other example:

A. Giaz et al., PRC 90 (2014) 014609

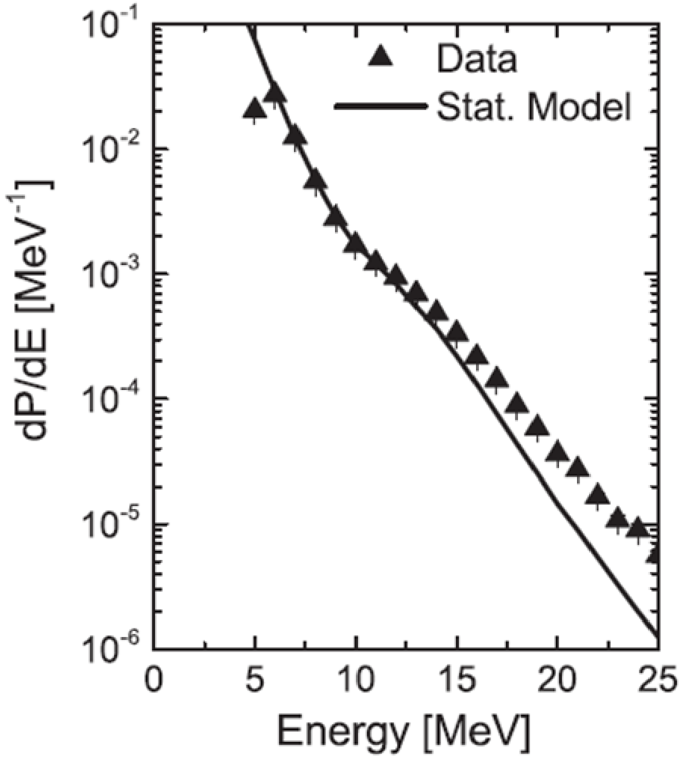
$^{16}O+^{116}Sn$ @ 12AMeV

Same reaction of the previous paper but at an intermediate beam energy

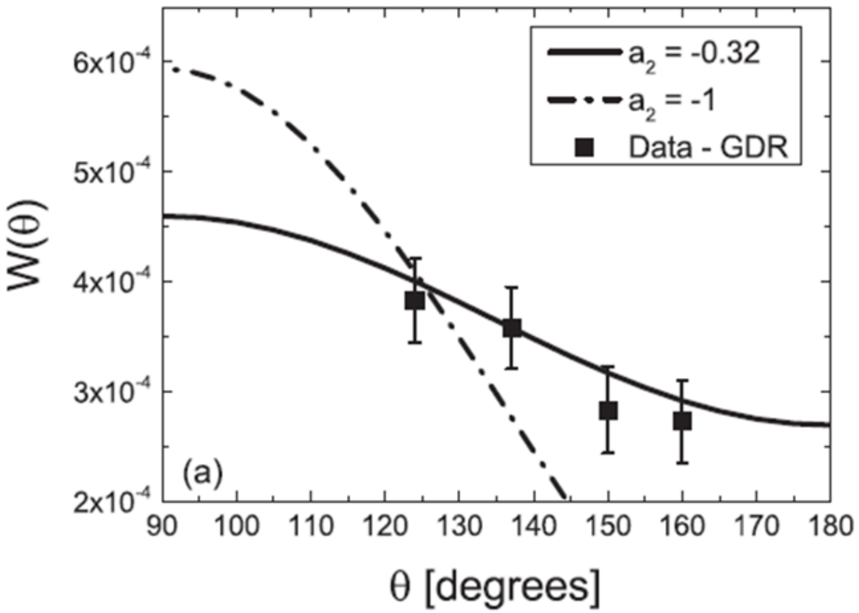
α spectrum to estimate pre-equilibrium



γ spectrum compared with the statistical model calculation



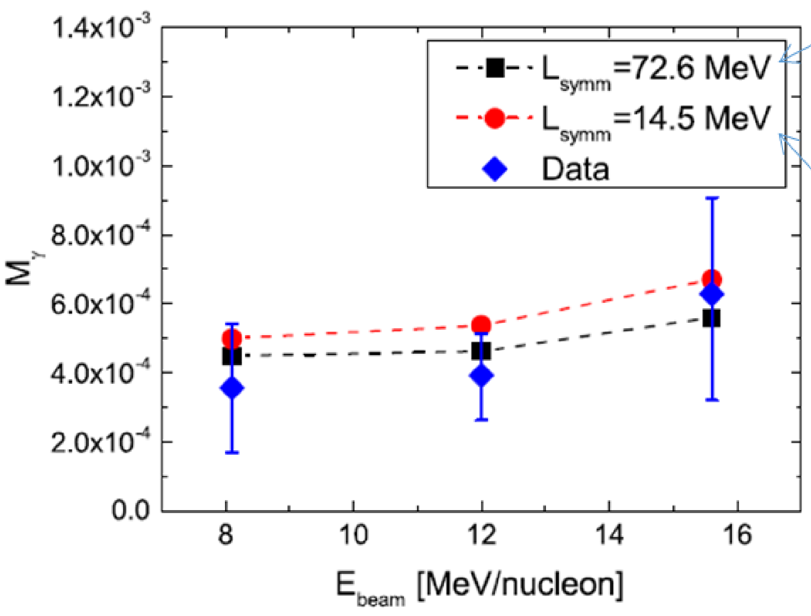
Angular distribution fitted by means of the function $W(\theta) \approx 1 + a_2 P_2(\cos\theta)$,



a_2 quenching factor with respect to the expected angular distribution for a dipole emission

a_2=-1 dipole without quenching

BNV predicts a quenching factor much stronger than the one observed in the experimental data

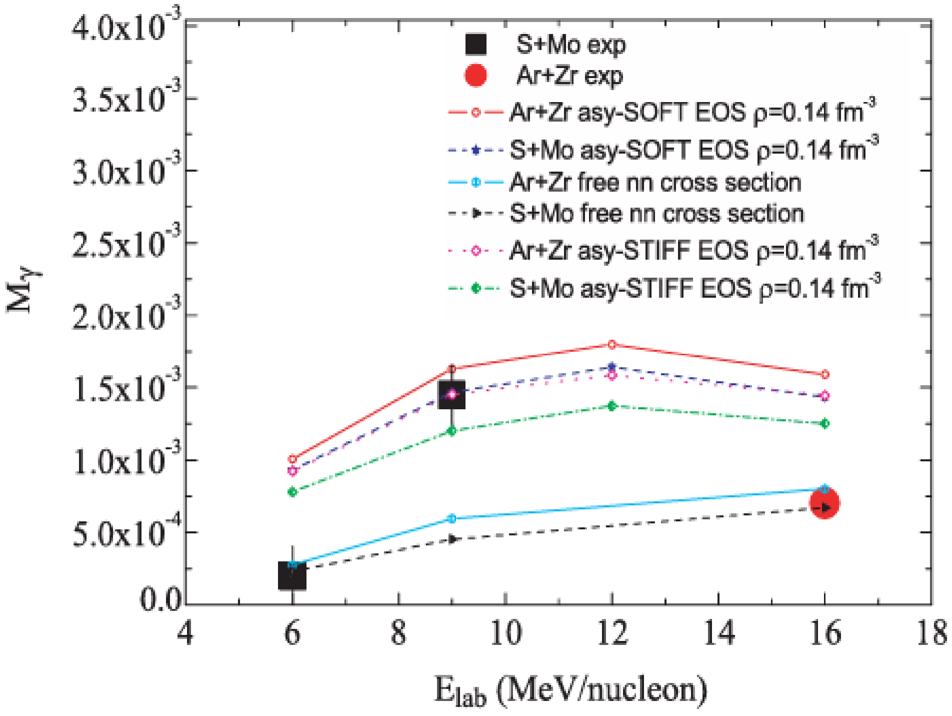


stiff

soft

DDR γ yields as a function of the beam energy.
Data compared with BNV calculations with stiff and soft parametrizations for the symmetry energy

No rise and fall of the DDR strength observed neither in the experimental data nor in the simulation



36Ar + 96Zr and 32S + 100Mo

For these data (different system) on the contrary the rise and fall is observed

D. Pierroutsakou et al., PRC80(2009)024612

Detector requirements

- **A device able to detect the evaporation residue** at low energies, possibly measuring Z and A
- **BaF_2 to detect high energy γ**
- The 4π detection of the LCP emitted by the CN
- neutron detection

It is important to evaluate the pre-equilibrium emission, therefore a calorimetric measurement would be useful

Some possible beam-target combinations

Proj.	Target	N/Z proj	N/Z targ.	D(t=0)	CN
^{133}Cs	^{48}Ca	1.42	1.40	1.2fm	^{181}Re
^{141}Cs	^{40}Ca	1.56	1.00	34fm	^{181}Re

Dependence on D(t=0): Same CN produced in 2 reactions with extremely different D(t=0)

Proj.	Target	N/Z proj	N/Z targ.	D(t=0)	CN
^{132}Sn	^{58}Ni	1.64	1.07	88fm	^{190}Pt
^{124}Sn	^{58}Ni	1.48	1.07	78fm	^{182}Pt
^{124}Sn	^{64}Ni	1.48	1.29	73fm	^{188}Pt
^{132}Sn	^{40}Ca	1.64	1.00	61fm	^{172}Yt
^{124}Sn	^{48}Ca	1.48	1.40	53fm	^{172}Yt

Similar CN produced in reactions with **decreasing D(t=0)** using always Sn projectile

Beam energy= 8-15AMeV

Proj.	Target	N/Z proj	N/Z targ.	D(t=0)	CN
^{124}Sn	^{56}Fe	1.48	1.15	25fm	^{180}Os
^{90}Kr	^{90}Zr	1.50	1.25	21.5fm	^{180}Os
^{90}Zr	**^{90}Zr**	1.25	1.25	**0fm**	^{180}Hg

Effect of the mass asymmetry in the entrance channel: similar D(t=0), different mass asymmetry

Reference (no DDR)