European Radioactive Ion Beam Conference 2012

Abano Terme (PD) Italy

Dynamical Dipole and EOS in N/Z asymmetric fusion reactions with stable and unstable beams

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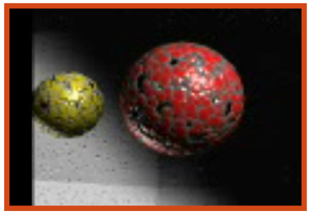
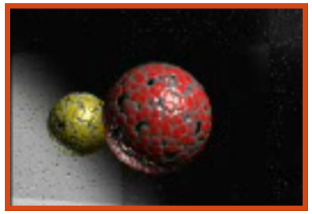
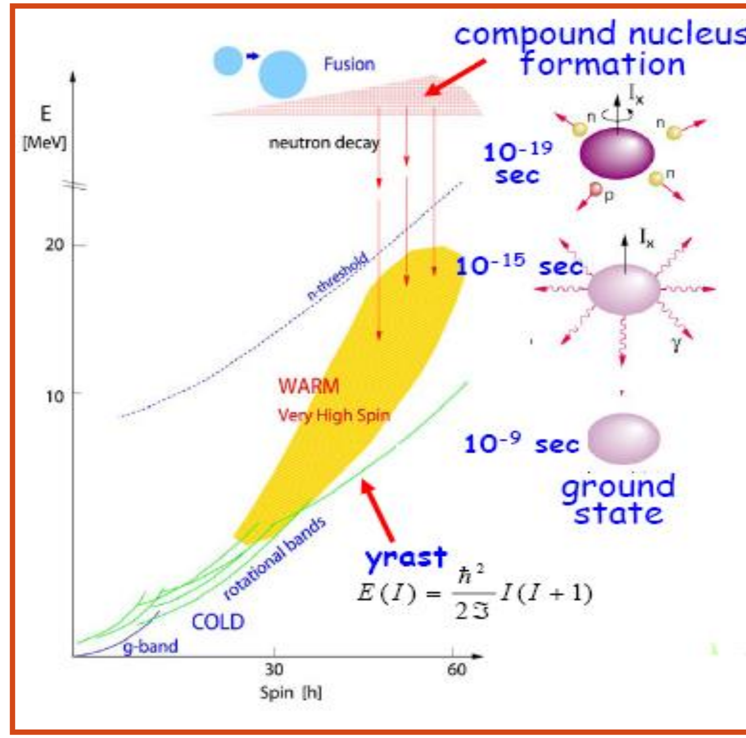
Dynamical Dipole in N/Z Asymmetric Reactions

t=0s | t=10^{-24}s CN formation | t=10^{-21}s CN statistical decay







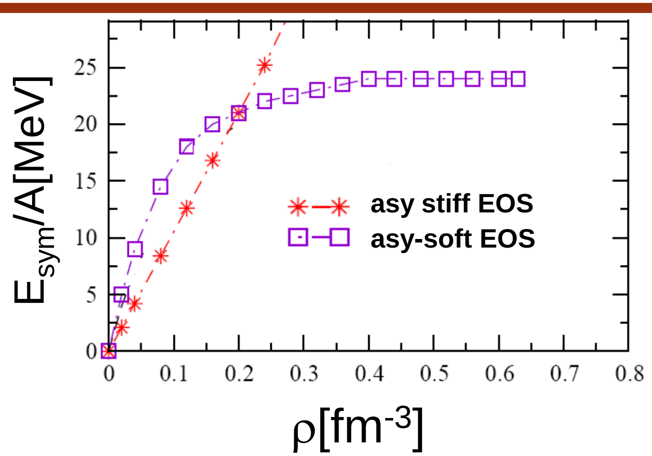
$10^{-24} < t < 10^{-21}$s **CN formation**: pre-equilibrium phase - energy and momentum equilibration

↓

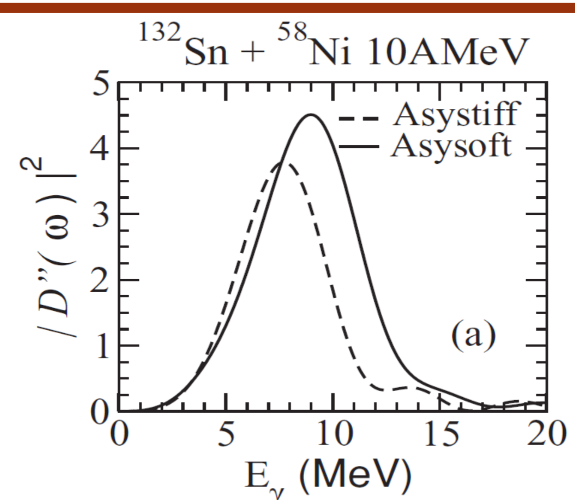
t $> 10^{-21}$s **CN statistical decay** - GDR decay

In a fusion reaction, if the colliding nuclei have a different N/Z ratio, a charge equilibration process takes place. The related neutron-proton motion has the features of a collective oscillation and it is associated to a γ emission, the so called **Dynamical Dipole (DD)** emission.

Physical Motivation



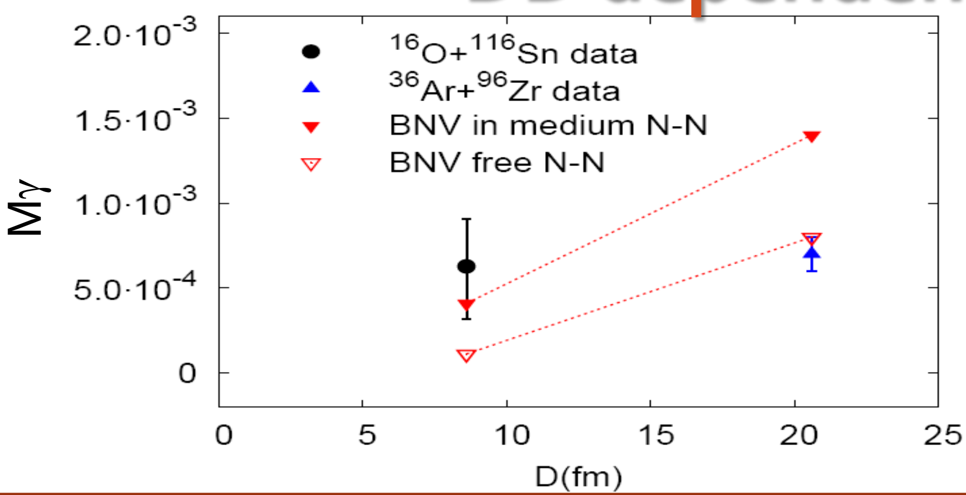
Sensitivity to **Nuclear Equation of State** (EOS), **symmetry term** (Asy-Stiff and Asy-Soft) and to **n-n cross section**



Necessity of exotic beam

V. Baran et al. PRC 79 (2009), 021603

DD dependence on N/Z

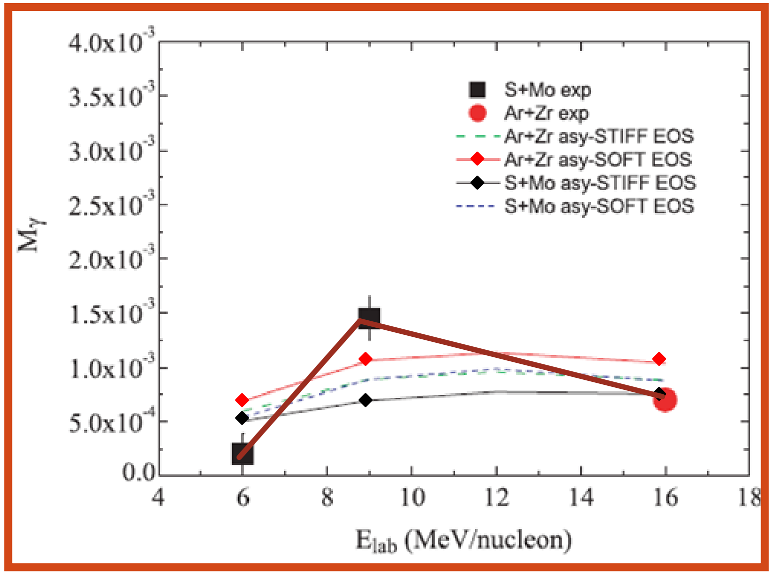


DD dependence on N/Z asymmetry at fixed beam energy per nucleon (15 MeV/u)
The experimental data don't seem to confirm the theoretical model

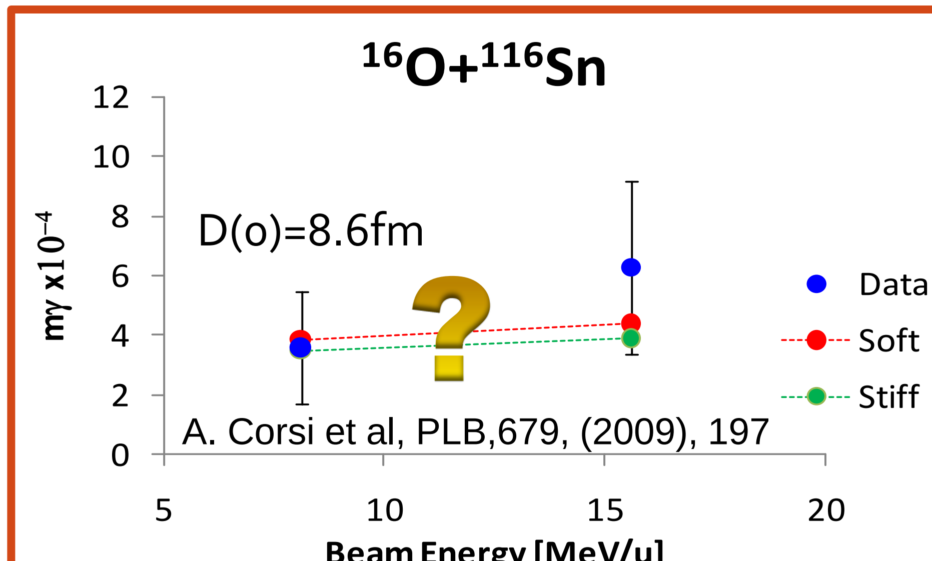
DD dependence on Beam Energy

The existing experimental data are still rather scarce.
Some systematic exists in A=132 mass region.

D. Pierroutsakou et al. , PRC, 80, 024612 (2009)

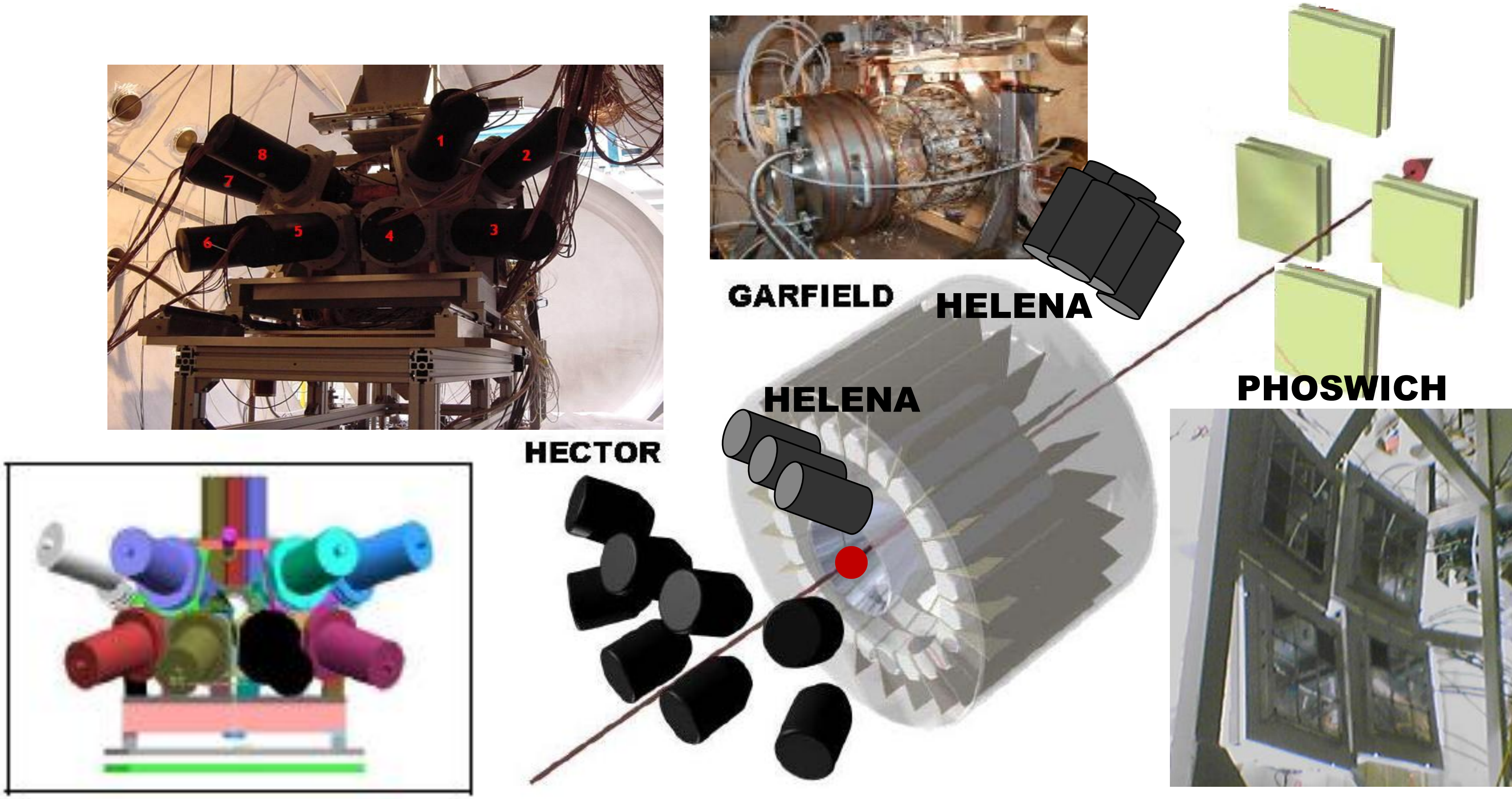


- Verify rise and fall in a similar system
- Refine theoretical calculations
- More exclusive experiment



My work: DD dependence on beam energy per nucleon in the $^{16}O+^{116}Sn$ system.

Experimental Set Up



- **Garfield** for light charge particle (LCP)
- **Phoswich** for evaporation residues
- **Hector** for high energy γ-rays
- **Helena** as time reference and for pre-equilibrium neutrons

Dynamical Dipole γ Emission

The **DD γ emission** and the **GDR** have the same dipolar nature and the same energy.

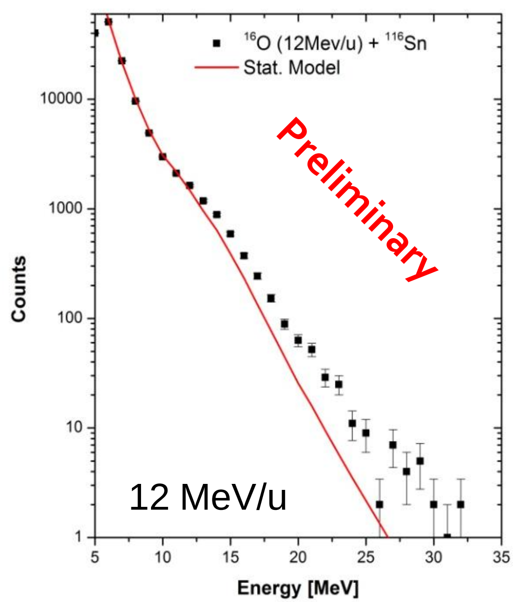
$N_p/Z_p = N_t/Z_t$ ($^{64}Ni+^{68}Zn$) $\longrightarrow$ Only GDR

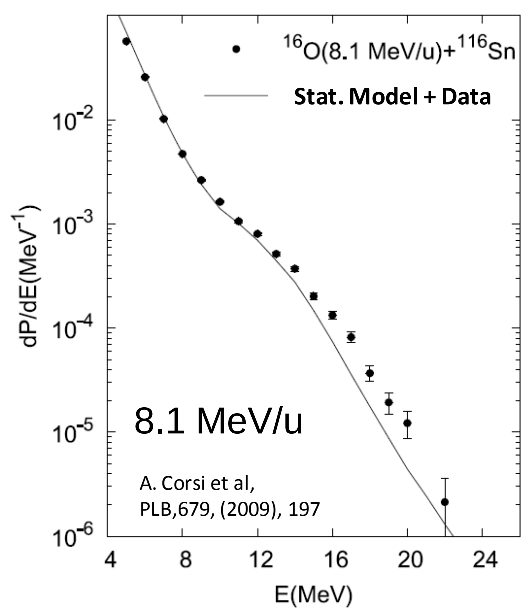
$N_p/Z_p \neq N_t/Z_t$ ($^{16}O+^{116}Sn$) $\longrightarrow$ DD + GDR

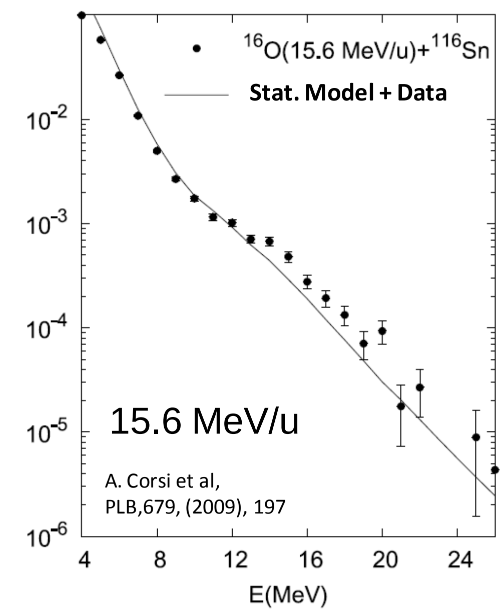
The experimental signature of pre-equilibrium emission is an **excess of counts** in energy range of **10-20MeV** with respect to the statistical decay.

DD excess of counts (between 10 and 22 MeV) at 12, 8.1 and 15.6MeV/u

The γ energy spectra: the coincidence between the high-energy γ rays and the evaporation residues







Dynamical Dipole γ Emission

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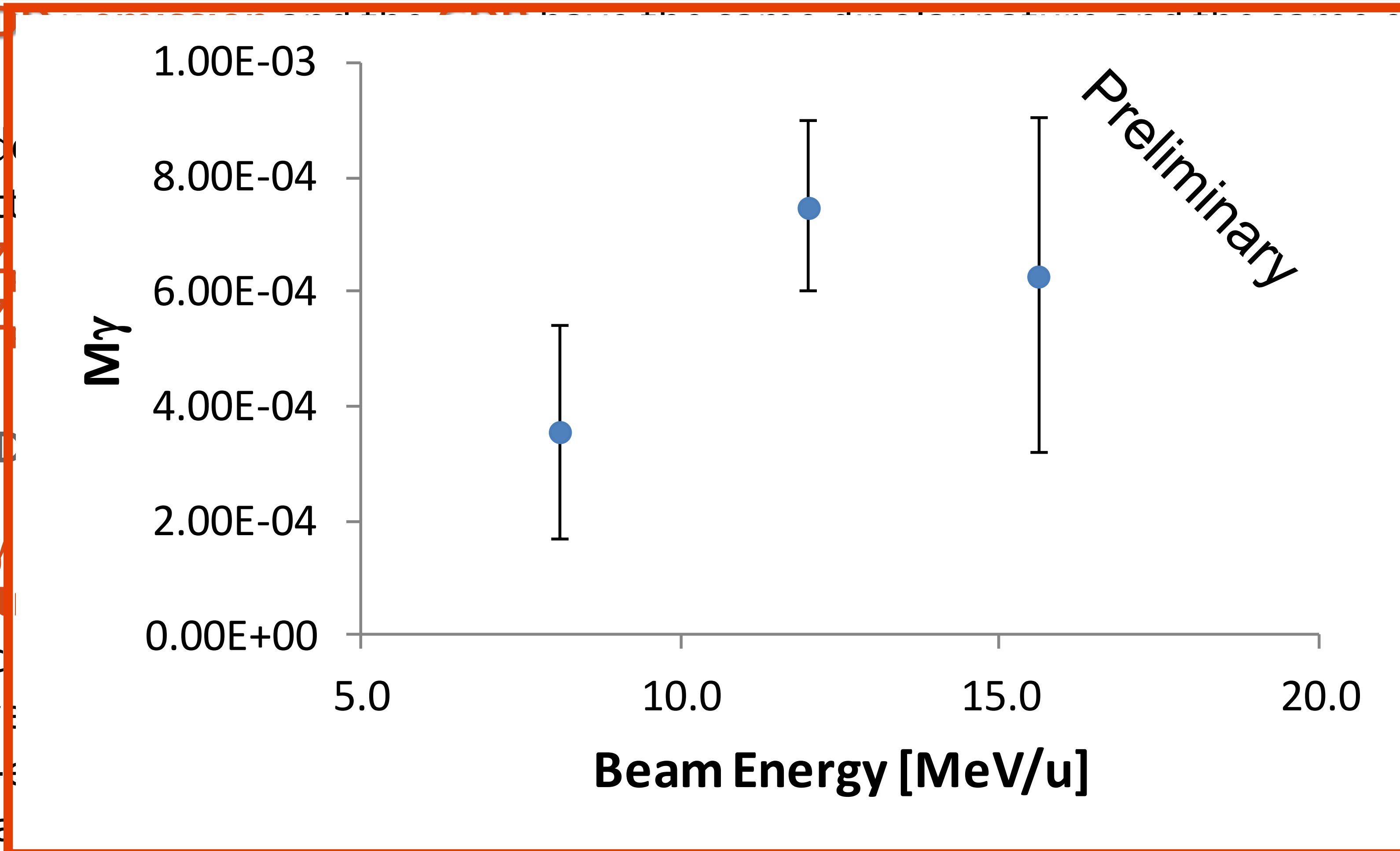

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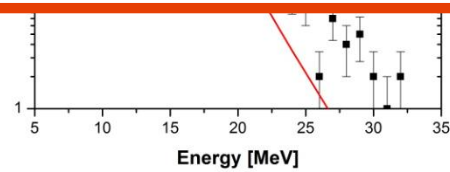
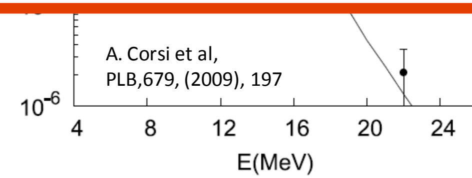
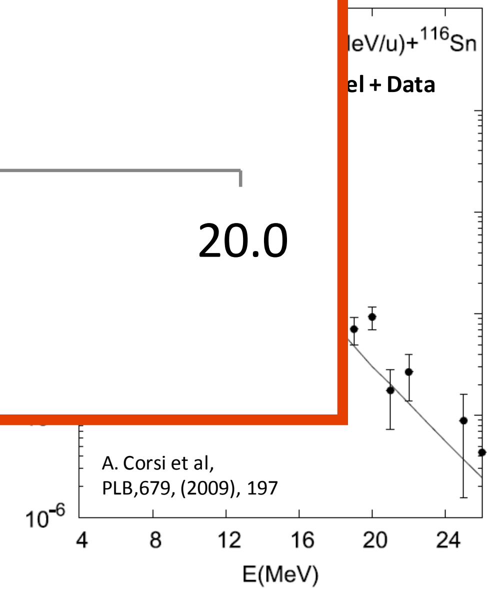
The γ spect coinc betw high- rays a evaporation residues







Angular Distribution

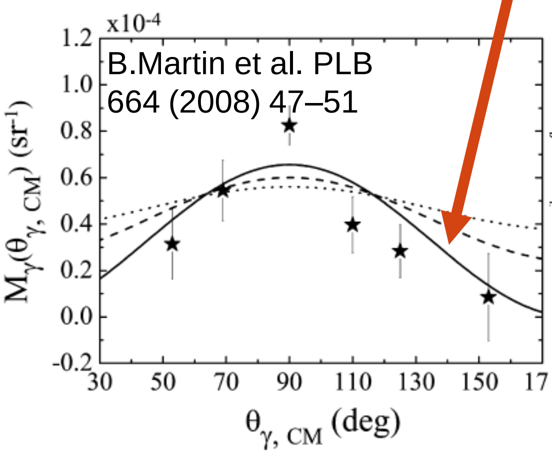
Angular distribution is expected to be **dipolar** but due to the rotation of dipolar axis is expected to be quenched.

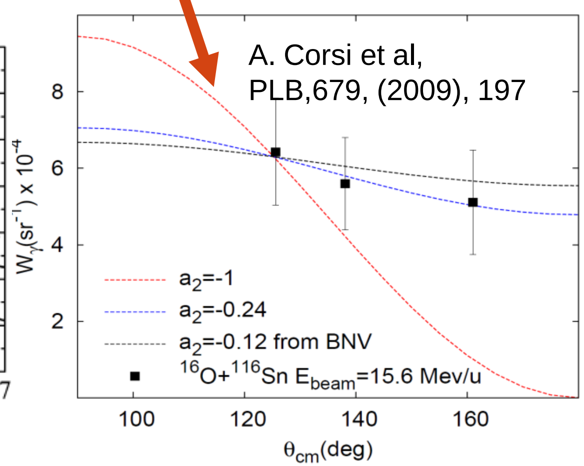
$$W(\vartheta) \approx 1 - a_2 P_2(\cos\vartheta)$$

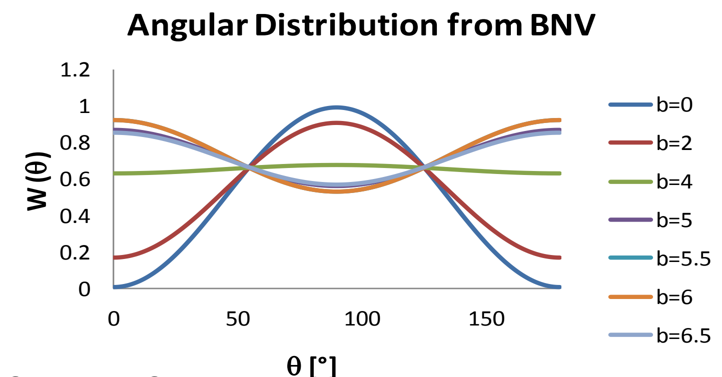
where $P_2(\cos\theta)$ is the Legendre Polynomial:

$$P_2(\cos\vartheta) = \frac{1}{2}\left(3\cos^2\vartheta - 1\right)$$

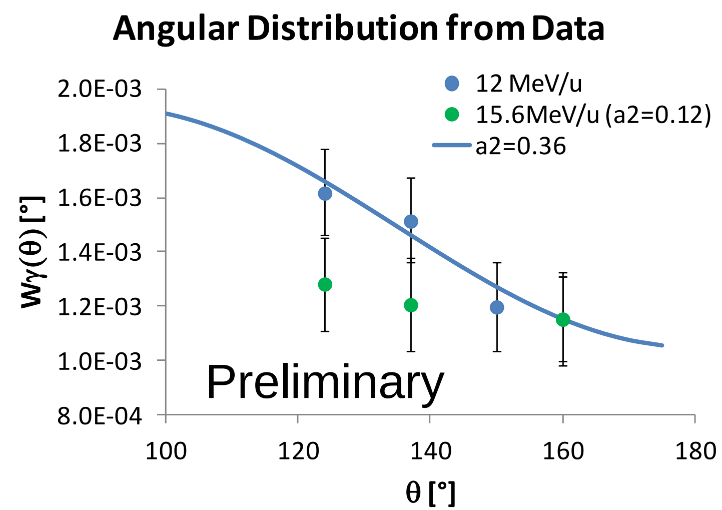
Pure Dipole (not quenched)







If b=0 fm the angular distribution is expected like a pure dipole, if b≠0 fm there is a rotation of the dipolar axis



The data (12 and 15.6 MeV/u) and the theoretical curve are normalized at 160°.

BNV (Bolzman Nordheim Vlasov) Model

V. Baran et al. PRL, 87 (2001) 18

Developed in LNS (Catania)

The BNV is based on nuclear EOS as function of ρ + n-n cross section in medium

Microscopic dynamics in fusion process and time evolution of Dipole Moment

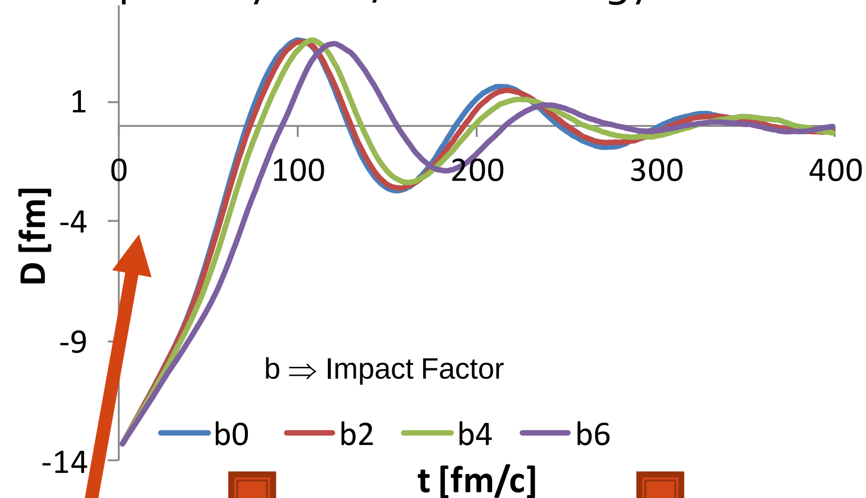
DD emission from bremsstrahlung :

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

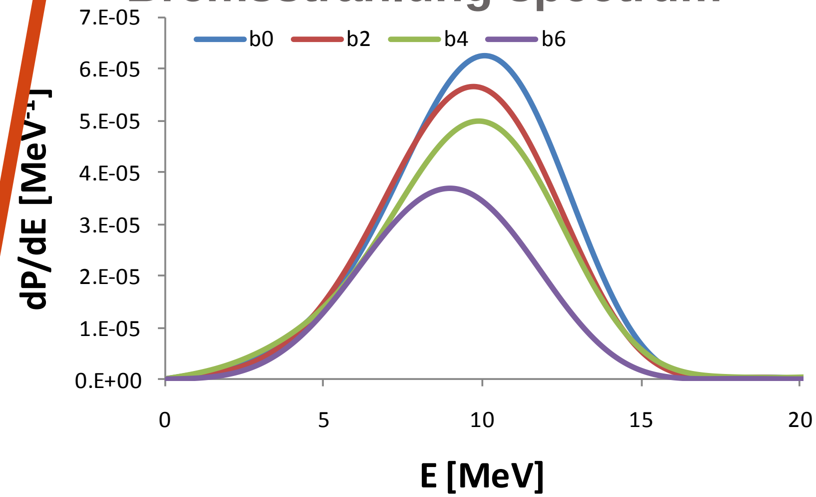
Theory predicts an oscillation of the Dipole Moment that is collective and coherent.

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

Example: Asy-Stiff, beam energy 12MeV/u



Bremsstrahlung spectrum



BNV model statistical fluctuations

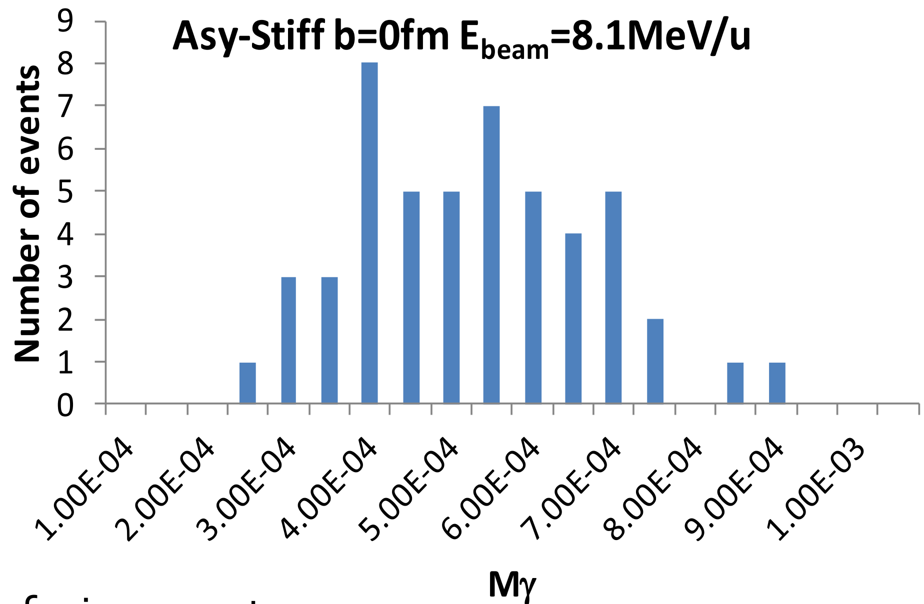
A BNV calculation analyze one event .
One event mimics one fusion reaction with:

- a fixed impact factor
- beam energy
- projectile and target

As each fusion can be different from the others, it is necessary to **quantify the fluctuations** which are intrinsic in the model. Namely, it is important to check on an event by event basis how the DD γ-rays yield change for fixed parameters.

A BNV calculation produce for one event:

- the dipole moment evolution with time
- the density evolution with time
- the conjugated of dipole moment evolution with time



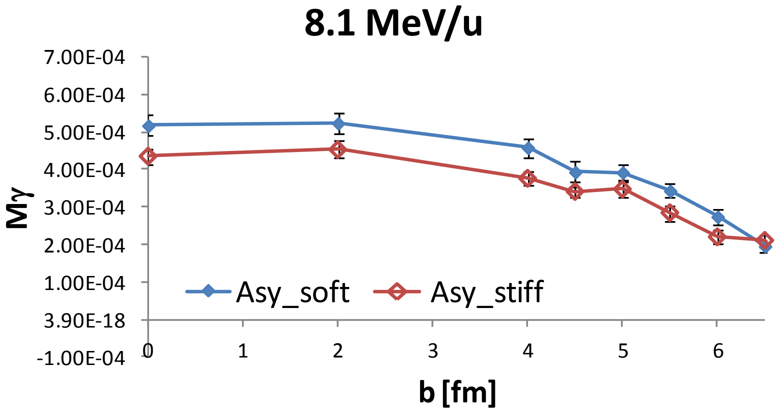
We produce 50 fusion events

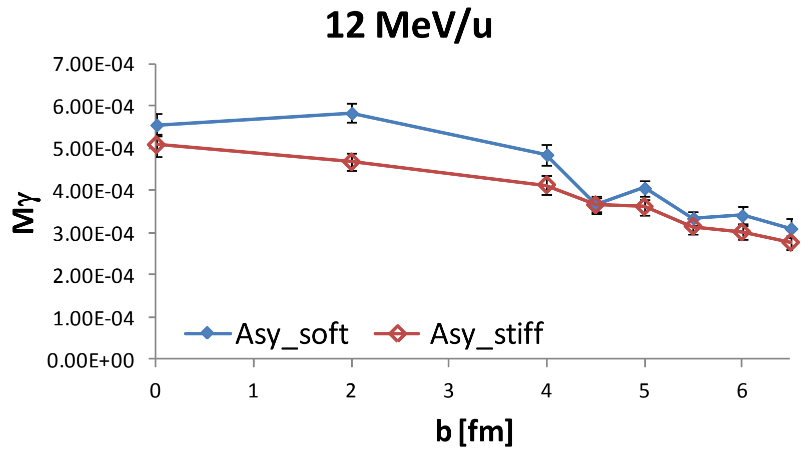
average yield - standard error is about 4%

Note that experimentally we have measured millions of fusion events

BNV: preliminary results $^{16}O + ^{116}Sn$

The BNV-DD γ multiplicity for different beam energy and impact factor

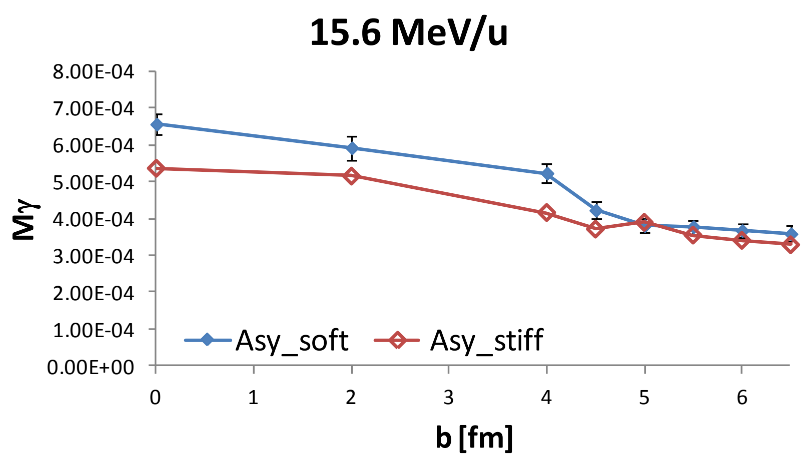




Fusion is expected for impact factor between 0-7 fm. Nuclei's center of mass distance at contact is 8.9fm

There is a clear dependence of γ multiplicity with the impact factor.

- Mγ decrease with impact factor (more significant at small value of E_{beam}).
- **The differences between Asy-Stiff and Asy-Soft are larger at small value of b**

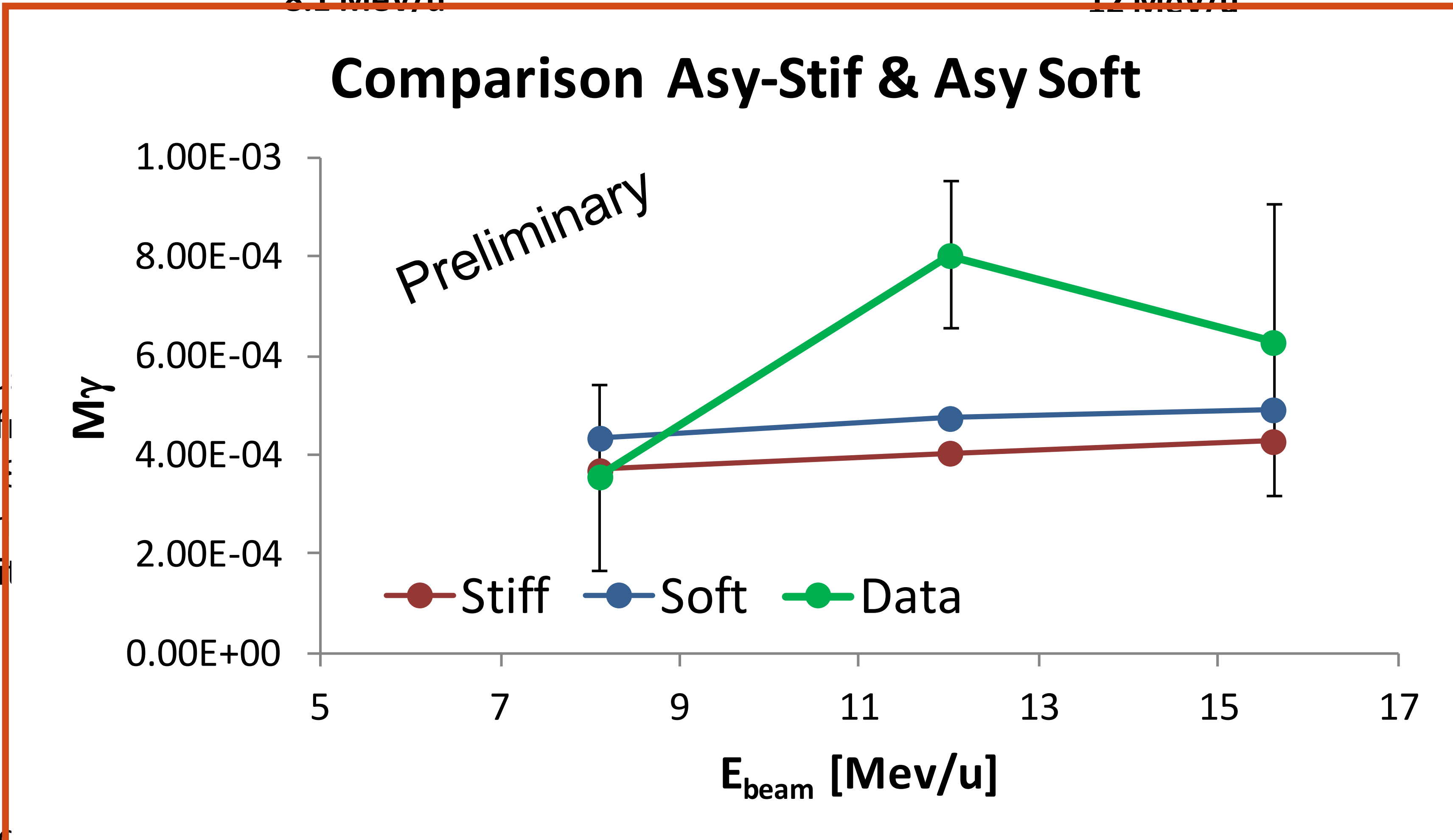


A correct weighted average of the calculations for different impact factor is critical as the fusion cross section is maximum at large impact factor (low DD γ-yield) and viceversa.

BNV: preliminary results $^{16}O + ^{116}Sn$

The BNV-DD γ multiplicity for different beam energy and impact factor

8.1 MeV/u 12 MeV/u



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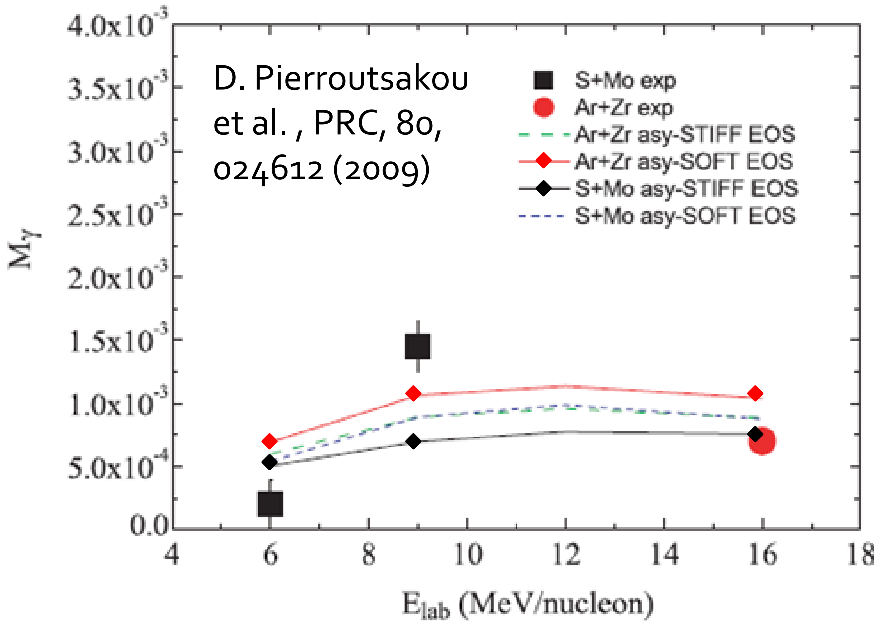
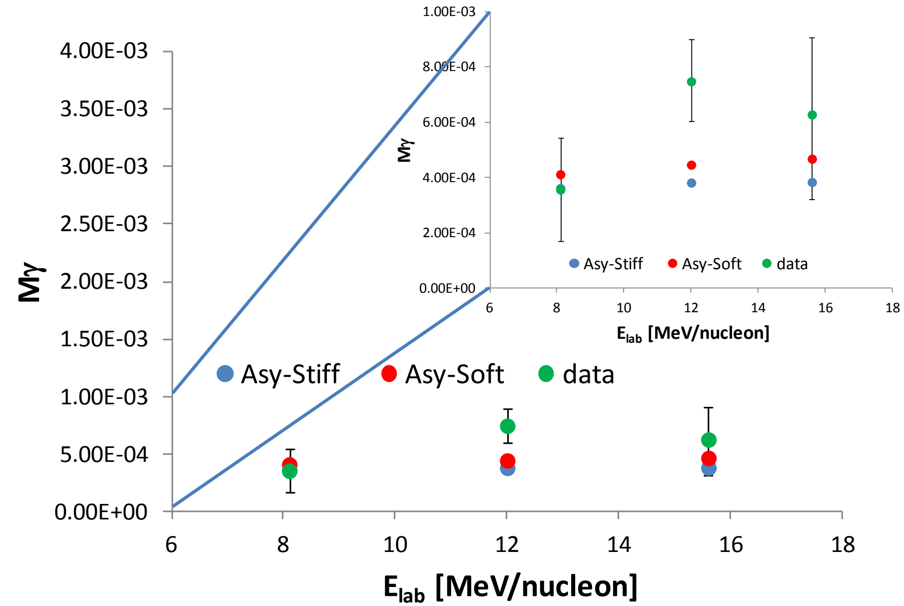
section is maximum at large impact factor (low DD γ-yield) and viceversa.

Comparison between Results and Theory





Results for two different entrance channels to obtain the same compound.
Absolute yield expected to be different because D(0)=20.6-18.2 fm (left) and D(0)=8.6 fm (right).
Pierroutsakou et al.: rise and fall behavior
Our data: rise and …
The comparison of data with theoretical predictions of this multiplicity shows that the rise and fall behavior isn't predicted from theory.

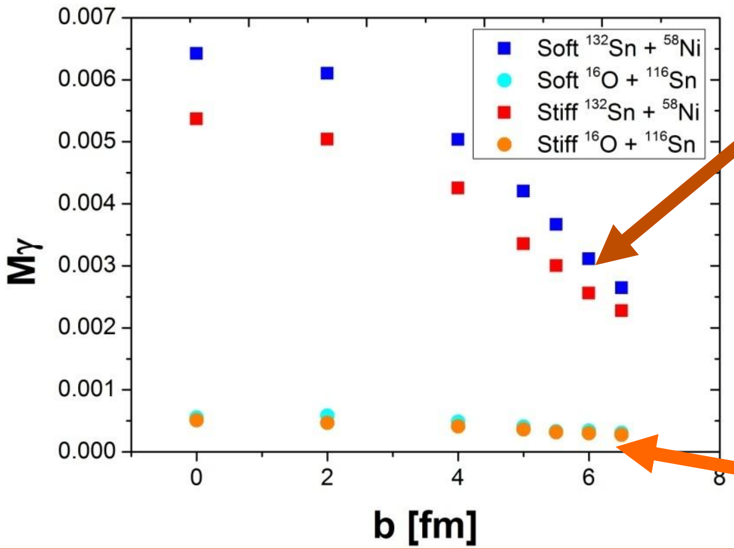
BNV reaction: $^{132}Sn+^{58}Ni$

Beam energy: 12MeV/u
The dipole moment :D(0) = 45.4 fm (in $^{16}O + ^{116}Sn$ D(0) = 8.6 fm)

The Mγ for $^{132}Sn+^{58}Ni$ is **one order of magnitude larger** than the Mγ for $^{16}O + ^{116}Sn$.
Also in this case there is a clear dependence of γ multiplicity with the impact factor.

- Mγ decreases with impact factor
- The differences between Asy-Stiff and Asy-Soft are **larger at small value of b**

Comparison between the DD γ yield from **BNV** between: $^{132}Sn + ^{58}Ni$ and $^{16}O + ^{116}Sn$



Exotic Beam

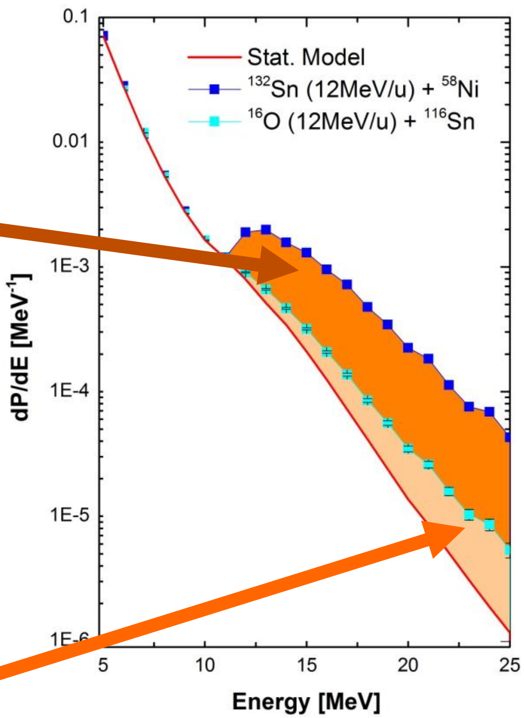
$^{132}Sn + ^{58}Ni$:

Theory – Prevision

Alternative case:
$^{68}Ni + ^{58}Ni$
D(0) = 21.2 fm

Now $^{16}O + ^{116}Sn$:

Theory – exp. Data



Conclusions

- We have measured the **DD γ-ray yield** ($^{16}O+^{116}Sn$)
  - There is a 46% increase going from 8 MeV/u to 12 MeV/u
  - The yield moves from $8.04\ 10^{-4} \pm 1.51\ 10^{-4}$ for 12 MeV/u to $6.28\ 10^{-4} \pm 3.07\ 10^{-4}$ for 15 MeV/u

- We have measured the **angular distribution**
  - We have observed a quenching of 0.36 relative to a perfect dipole

- Theoretical calculation from **BNV-model**.
  - The rise trend is not followed (same problem present in D. Pierroutsakou et al. , PRC, 80, 024612 (2009) and in A. Corsi et al, PLB,679, (2009), 197)
- Sensitivity to EOS at small b using stable beams
  - Some sensitivity to EOS ($^{16}O+^{116}Sn$)
- Large DD signal and large EOS sensitivity using exotic beams
  - Yield 10 times larger ($^{132}Sn+^{58}Ni$)
  - Eos sensitivity in the yield ($^{132}Sn+^{58}Ni$)

Garfield Hector Collaboration

A.Giaz[1], A.Corsi[1], F.Camera[1], S.Barlini[6], V.L.Kravchuk[3], R.Alba[8], P.Bednarczyk[4], A.Bracco[1], G.Baiocco[5], L.Bardelli[6], G.Benzoni[2], M.Bini[6], N.Blasi[2], S. Brambilla[2], M.Bruno[5], S.Carboni[6],G.Casini[6] , M.Ciemala[4], M.Cinausero[3], M.Chiari[6], M.Colonna[9], F.C.L. Crespi[1], M.D'Agostino[5], M.Degerlier[3], M.Di Toro[9], F.Gramegna[3], M.Kmiecik[4], S.Leoni[1], C.Maiolino[8], A.Maj[4], T.Marchi[3], K.Mazurek[4], W. Meczynski[4], B.Million[2], D.Montanari[1], L.Morelli[5], A.Nannini[6], R.Nicolini[1], G.Pasquali[6], S.Piantelli[6], A.Ordine[7], G.Poggi[6], V.Rizzi[3], C.Rizzo[9] , D.Santonocito[8], V.Vandone[1], G.Vannini[5], O.Wieland[2]

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Thank you for the attention