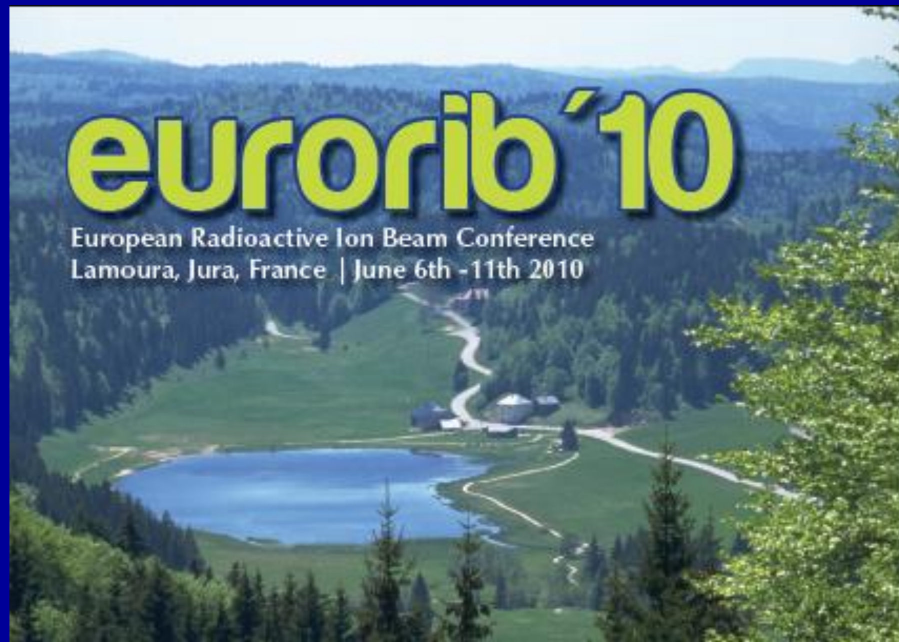

Dynamical dipole mode in fusion heavy-ion reactions

ROSETTA SILVESTRI

University & INFN Naples

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Dynamical Dipole in dissipative heavy-ion reactions

- The physical problem

- Experiments and

  → new results for $^{40,48}Ca + ^{152,144}Sm$ systems

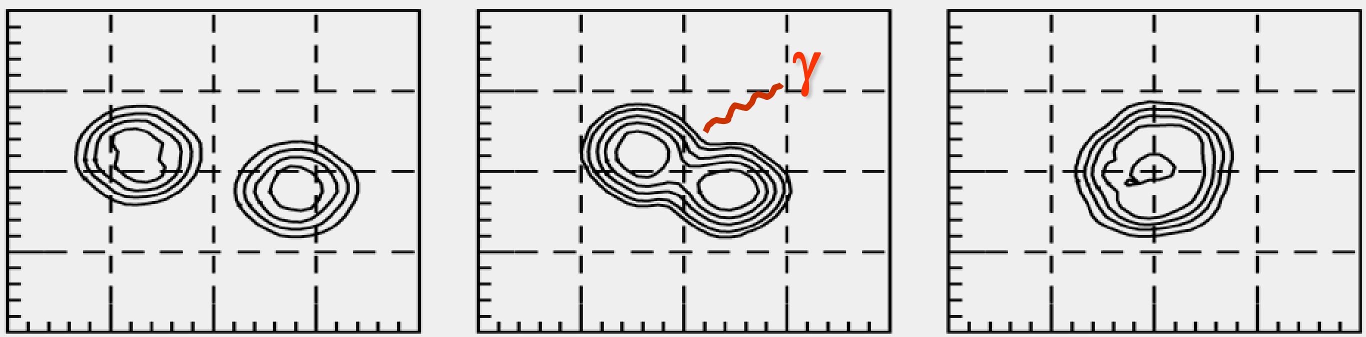
- Open problems and perspectives with stable and exotic beams

Dynamical Dipole: the physical problem

Dynamical Dipole: a collective dipole oscillation along the symmetry axis of the dinuclear system in charge asymmetric heavy-ion reactions

Prompt dipole γ-ray emission

- $E_{dd} < E_{GDR,stat}$
- Anisotropy



$$D_0 = \frac{Z_1 Z_2}{A}\left(\frac{N_1}{Z_1} - \frac{N_2}{Z_2}\right)(R_1 + R_2)$$

Initial Dipole Moment

D(t) : prompt dipole radiation

CN: stat. GDR

The intensity of the prompt γ radiation depends on the:

Initial dipole moment

Reaction dynamics (centrality, mass asymmetry, E_{lab})

Symmetry term of the EoS below saturation that is acting as a restoring force

The DD is a new cooling mechanism in fusion reactions that could facilitate the formation of the superheavy elements

Model independent observation

Experimental method:

Comparison of the energy spectra and the angular distributions of the γ-rays emitted in two reactions with **different charge asymmetry** that populate the **same** CN with **identical** excitation energy and **identical** spin distribution

Evidence of the dynamical dipole mode:

1) Extra yield γ (prompt dipole radiation) in the GDR energy region for the charge asymmetric system.

2) An anisotropic angular distribution of the γ-ray excess.

Dynamical Dipole: incident energy dependence

Compound Nucleus → ^{132}Ce $\Delta D(t=0) = 16.5$ fm

$E_{lab} \sim 6$ MeV/nucleon	$E_{lab} \sim 9$ MeV/nucleon	$E_{lab} \sim 16$ MeV/nucleon
$E^* = 117$ MeV, $L_{fus} \sim 83\hbar$	$E^* = 174$ MeV, $L_{fus} \sim 83\hbar$	$E^* = 284$ MeV, $L_{fus} \sim 83\hbar$
$^{32}S + ^{100}Mo$ D(t = 0) = 18.2 fm	$^{32}S + ^{100}Mo$ D(t = 0) = 18.2 fm	$^{36}Ar + ^{96}Zr$ D(t = 0) = 20.6 fm
$^{36}S + ^{96}Mo$ D(t = 0) = 1.7 fm	$^{36}S + ^{96}Mo$ D(t = 0) = 1.7 fm	$^{40}Ar + ^{92}Zr$ D(t = 0) = 4.0 fm
(LNL, SERPE)	(LNL, SERPE)	(LNS, MEDEA)

Experimental technique

→ γ-ray and charged particles in coincidence with evaporation residues

→ evaporation residues in singles (γ-ray & particle multiplicity)

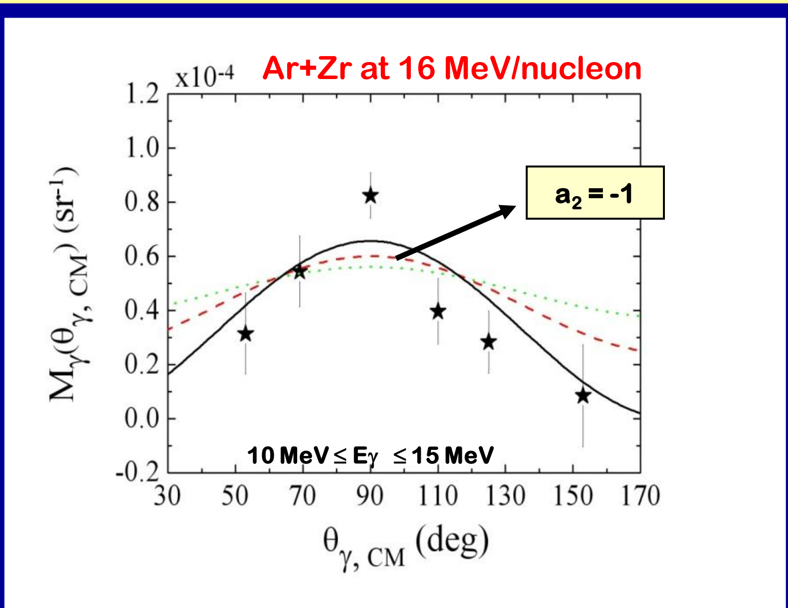
First systematic study of the dynamical dipole in fusion reactions

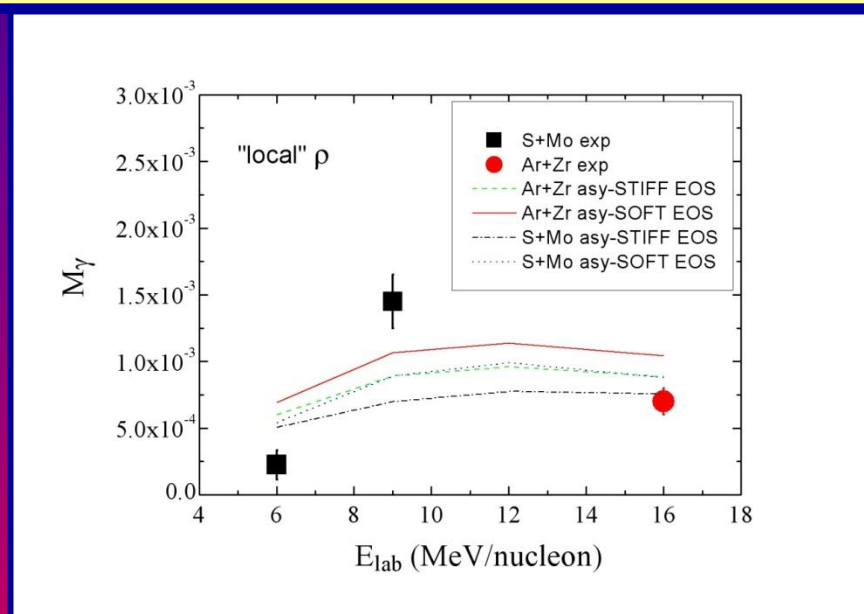
- Saturated CN spin: identical spin distribution
- Experimental evaluation of the effective E^* and A of the CN
- Absence of normalization factors in the γ-ray and particle spectra
- γ-ray angular distributions

Dynamical Dipole: ^{132}Ce

Observation of an extra γ yield at

$E_{dd} < E_{GDR}$ = 14 MeV → large deformation of the emitting source





Large anisotropy of the γ-rays excess around 90° with respect to the beam direction compatible with a dipole oscillation along the beam axis
→ prompt dipole radiation is confined during the first moments of the di-nuclear system formation

The DD yield shows a pronounced maximum at E_{lab} ~ 9 MeV/nucleon while the BNV calculations display a smoother behaviour with E_{lab}.

D. Pierroutsakou *et al.*, EPJA 17 (2003) 71 ,PRC 71 (2005) 054605

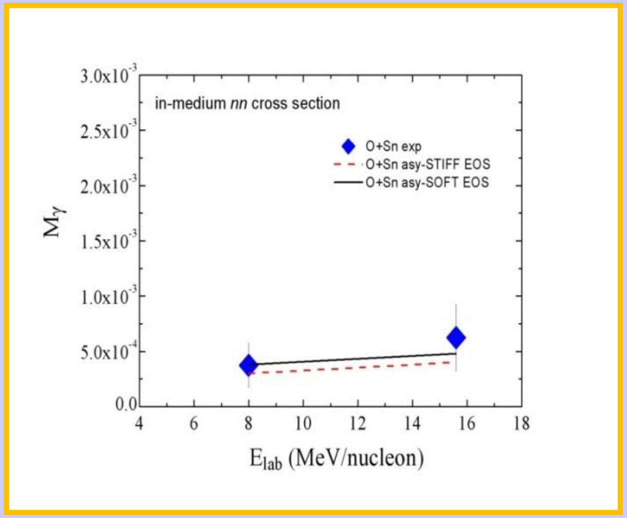
B. Martin *et al.*, PLB 664 (2008) 47

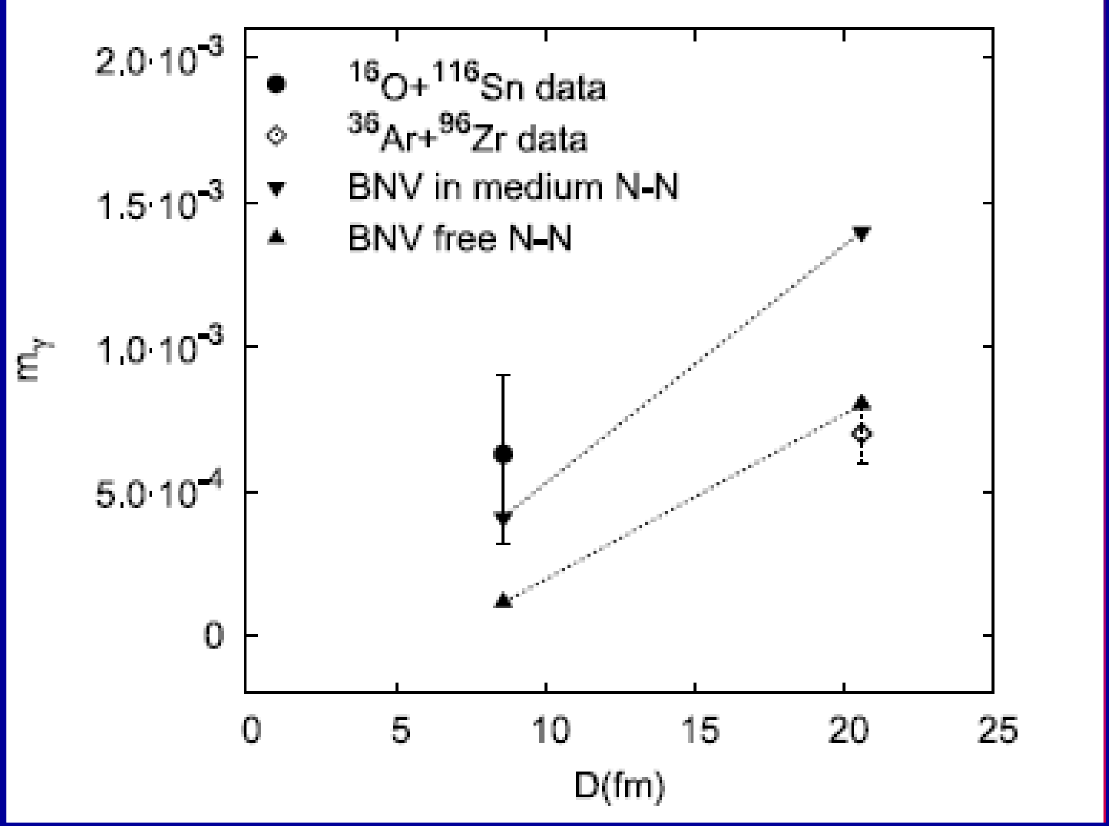
CN ^{132}Ce: ^{16}O+^{116}Sn *vs.* ^{36}Ar+^{96}Zr at 16 MeV/nucleon

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

CN ^{132}Ce

^{16}O+^{116}Sn (D(t)= 8.6 fm)
at 8 and 16 MeV/nucleon
E_{dd}= E_{GDR} = 14 MeV





Rather flat dependence of the dipole yield on the initial dipole moment

→ No possibility to reproduce the data simultaneously by using the same nn cross sections.

→ Further investigation is needed to shed light on the interplay between the different parameters that influence the DD features.

Dynamical Dipole: cooling in fusion reactions

As a fast cooling mechanism of the composite system the prompt dipole radiation could be used to favour the superheavy element formation through hot fusion reactions

Cold fusion reactions → larger CN survival probability

Hot fusion reactions → larger CN formation probability

Interesting: to investigate the existence of the dynamical dipole mode in heavier composite systems

Dynamical Dipole mode in heavier systems: ^{192}Pb

The dynamical dipole mode existence was investigated in both fusion-evaporation and fission events at 10 and 11 MeV/nucleon by using a target-projectile combination with a much higher charge asymmetry difference than previously.

$^{40}Ca + ^{152}Sm$	$^{48}Ca + ^{144}Sm$
E_{lab} = 440 MeV	E_{lab} = 485 MeV
D(t=0) = 30.6 fm	D(t=0) = 5.3 fm
Δ= 0.22	Δ= 0.18

^{192}Pb E^*= 236 MeV

ΔD(t=0)=25.6 fm

L_{fus} =74$\hbar$

$L_{fus,evap}$=36$\hbar$

B_f(l=0) = 10.4 MeV

$\sigma_{fusion-fission}$ = 251 mb
$\sigma_{fusion-evap}$ = 77 mb

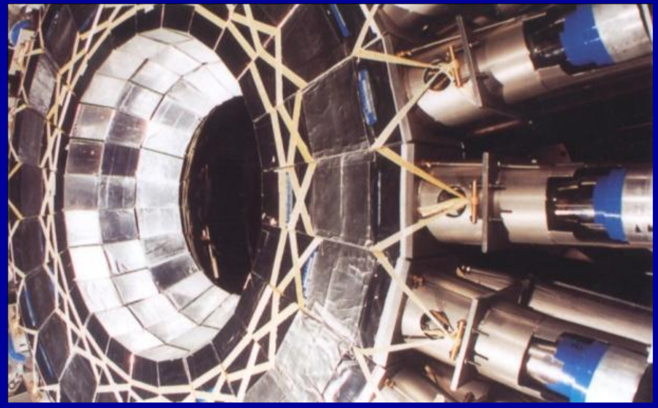
$\sigma_{fusion-fission}$ = 213 mb
$\sigma_{fusion-evap}$ = 64 mb

PACE 2 calculations

Experimental apparatus

γ-ray detectors,
particles with Z=1,2 (E, ToF)

MEDEA (LNS) : 180 BaF_2 (48 at θ =90°),
d=22 cm ($\Delta\Omega$ = 3.37π sr)



Evaporation residue detectors

4 position sensitive PPACs (from SERPE apparatus) symmetrically around the beam → θ=7° ± 3.75° at d=70 cm from the target ($\Delta\Omega_{total}$= 0.089 sr)

Fission fragment detectors

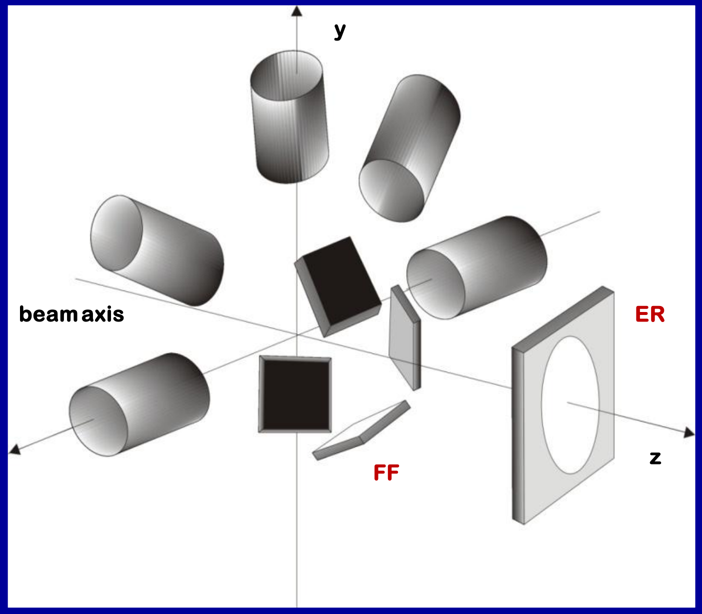
4 position sensitive PPACs (from SERPE apparatus) symmetrically around the beam

θ= 53° ± 11° ($\Delta\phi$ =22°)

at d=16 cm from the target ($\Delta\Omega_{PPAC}$= 0.16 sr)

They define a plane perpendicular
and a plane collinear to the 90° BaF_2 detectors

→ γ-ray-fragment angular correlations
at θ =0° and 90° with respect to the spin axis



Observables

Evaporation events

Detection of evaporation residues in singles and in coincidence with γ-rays and charged particles

- γ-ray (particles) multiplicity spectra
- γ-ray (particles) angular distribution with respect to the beam axis

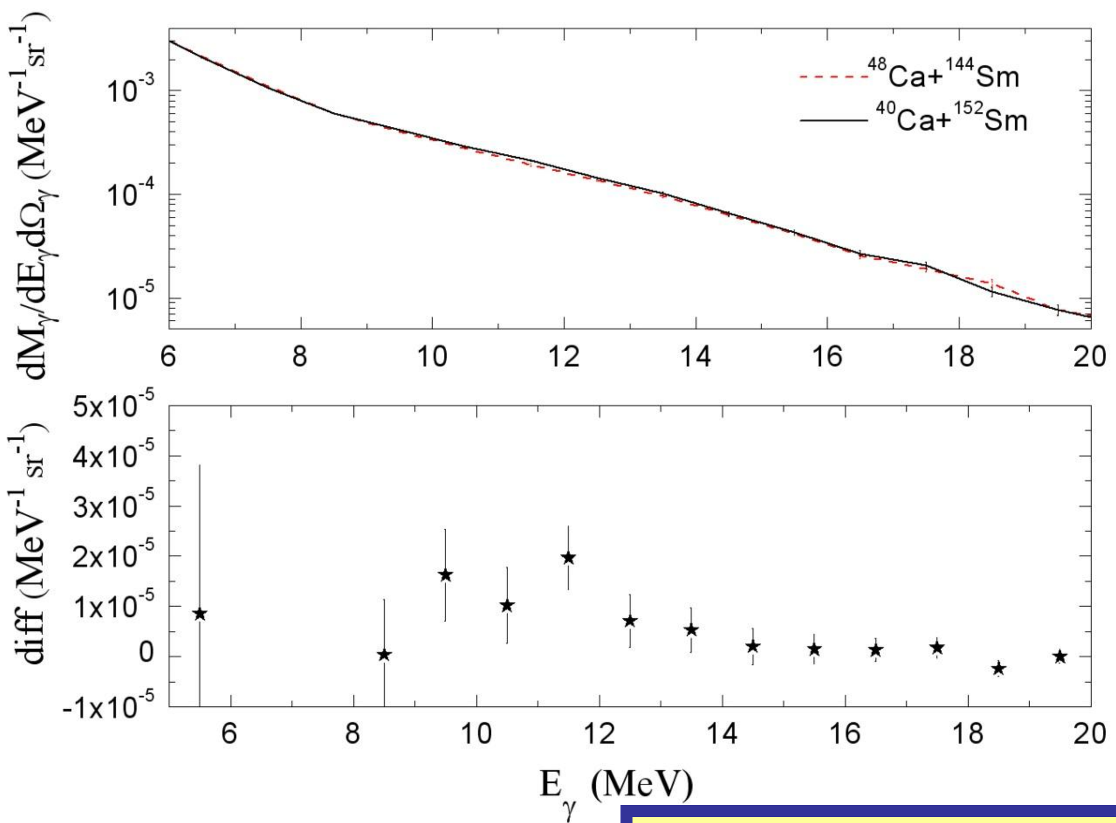
Fission events

Detection of the two fission fragments in singles and in coincidence with γ-rays and charged particles

- γ-ray (particles) multiplicity spectra
- γ-ray-fragment angular correlation with respect to the spin axis
- fragment mass and TKE distribution

$^{40,48}Ca + ^{152,144}Sm$: Fusion-evaporation γ-ray spectra at $\theta_\gamma = 90^\circ$ & $\theta_\gamma = 112^\circ$

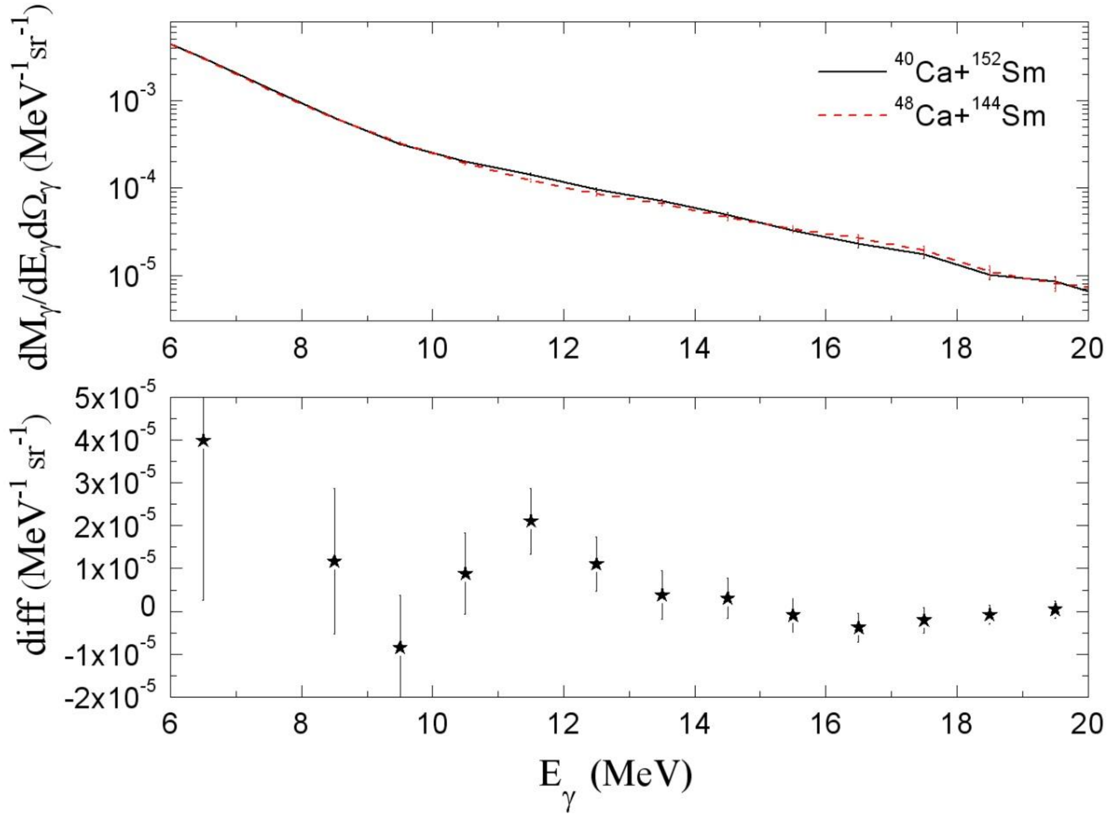
$M_\gamma(\theta_\gamma)$ =(8 ± 2) 10^{-5} γ/ sr (efficiency taken into account)



PRELIMINARY RESULTS
with a part of the collected statistics
by using BaF_2 situated at θ=83˚, 97˚, 112˚

$^{40,48}Ca+^{152,144}Sm$: Fission γ-ray spectra at $\theta_\gamma=90^\circ$ & $\theta_\gamma=112^\circ$

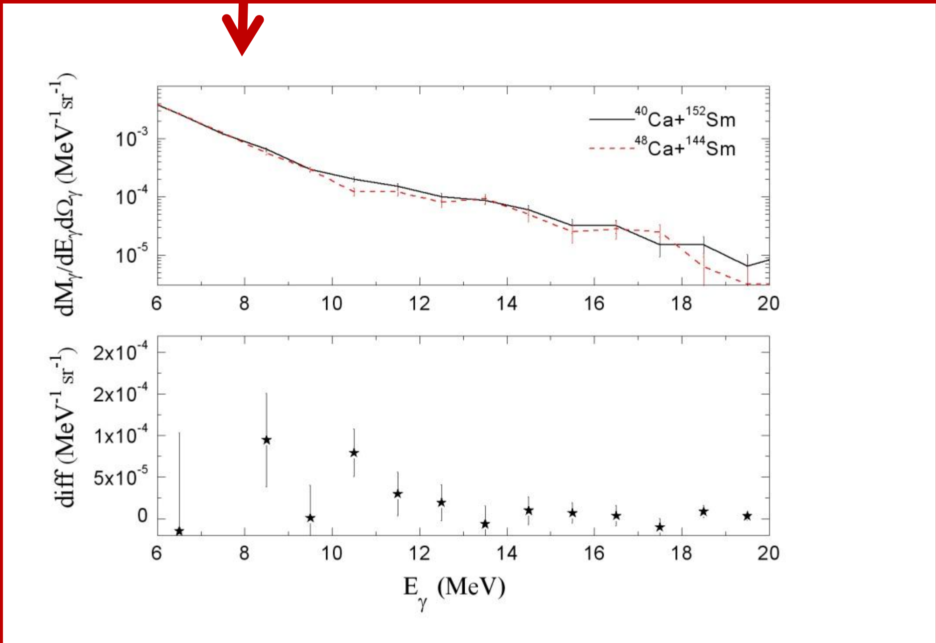
$M_\gamma(\theta_\gamma)$ =(6 ± 3) 10^{-5} γ/ sr (efficiency taken into account)

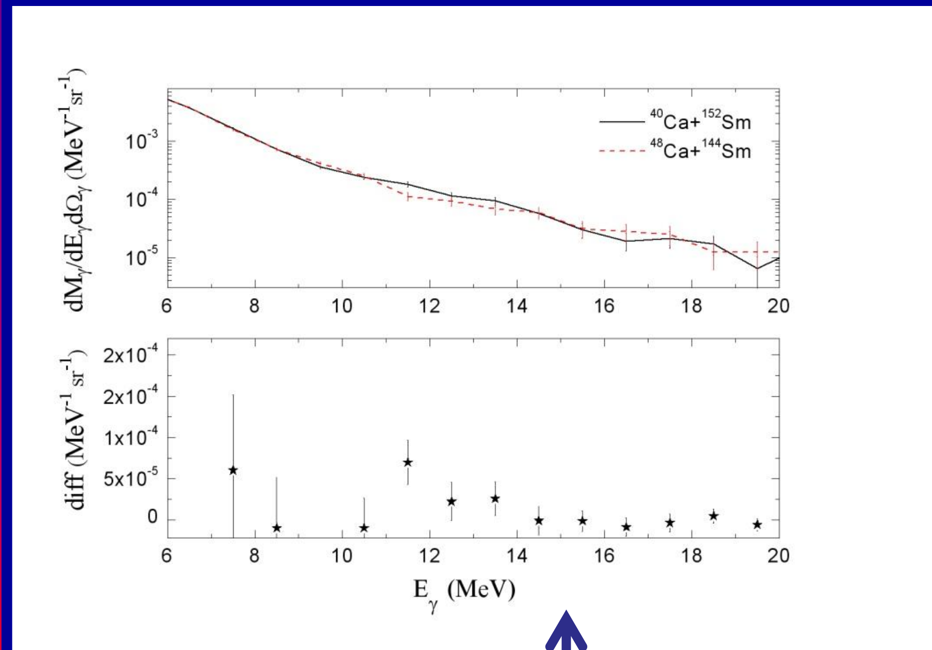


$^{40,48}Ca+^{152,144}Sm$:

Fission γ-ray spectra at $\theta_\gamma=0^\circ$ and $\theta_\gamma=90^\circ$

At θ=0° with respect to the spin direction the dipole yield should be maximum: $M_\gamma(\theta=0^\circ)=(3.1 \pm 0.9)\ 10^{-4}\ \gamma/sr$



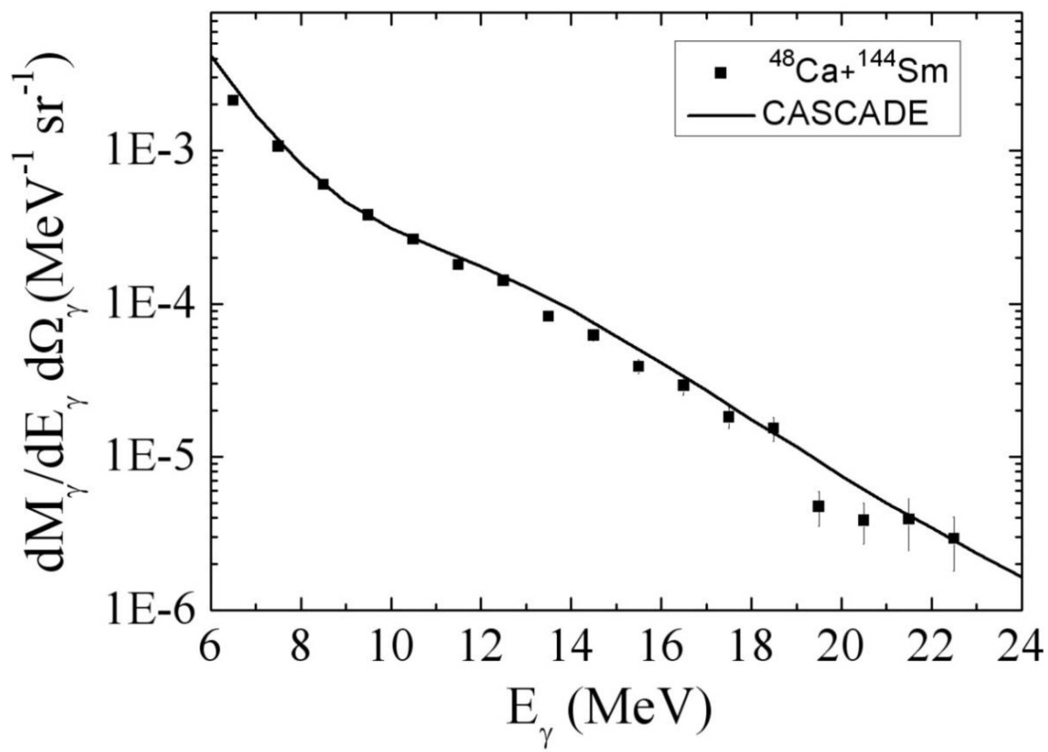


At θ=90° with respect to the spin direction the dipole yield should be minimum: no dipole within error bars (more statistics is needed)

Fusion-evaporation γ-ray spectra at $\theta_\gamma=90^\circ$ & $\theta_\gamma=112^\circ$

CN: ^{192}Pb, E*= 236 MeV, a=A/10 MeV^{-1}

E_{GDR}=13.6 MeV, Γ_{GDR}= 12 MeV, F_{GDR}= 1 TRKSR



Summary of the $^{40,48}Ca+^{152,144}Sm$ reactions

Preliminary results show that :

1. The DD mode survives also in heavier composite systems being centered at an energy E_{dd}~10 MeV lower than that of the statistical GDR, in agreement with expectations

2. At the same angles,
   the DD yield of the Ca+Sm reaction pair at 11 MeV/nucleon
   $M_\gamma(\theta_\gamma) = (8 \pm 2)\ 10^{-5}\ \gamma/\mathrm{sr}$
   is comparable with that of the Ar+Zr at 16 MeV/nucleon
   $M_\gamma(\theta_\gamma) = (8 \pm 1)\ 10^{-5}\ \gamma/\mathrm{sr}$
   even if it corresponds to a larger initial dipole moment:

the role of the mass should be important

Dynamical Dipole mode and RIBs

1) Systematic study of the DD by using different projectile-target combinations to form the same CN at E_{lab} between 5 and 15 MeV/nucleon.

2) Maximization of the phenomenon.

Proj.	Target	Beam	CN	D(t=0) fm	Δ(t=0)
^{112}Cd	^{80}Se	Stable	^{192}Pb	1.8	0.06
^{48}Ca	^{144}Sm	Stable	^{192}Pb	5.3	0.18
^{86}Kr	^{106}Pd	RIB	^{192}Pb	8.0	0.03
^{44}Ar	^{148}Gd	RIB	^{192}Pb	8.4	0.20
^{110}Cd	^{82}Se	Stable	^{192}Pb	11.2	0.05
^{88}Kr	^{104}Pd	RIB	^{192}Pb	17.4	0.03
^{38}Ar	^{154}Gd	RIB	^{192}Pb	18.5	0.23
^{37}Ar	^{155}Gd	RIB	^{192}Pb	23.0	0.23
^{94}Sr	^{98}Rb	RIB	^{192}Pb	23.6	0.01
^{36}Ar	^{156}Gd	RIB	^{192}Pb	27.4	0.24
^{90}Kr	^{102}Pd	RIB	^{192}Pb	26.8	0.02
^{40}Ca	^{152}Sm	Stable	^{192}Pb	30.6	0.22
^{96}Sr	^{96}Rb	RIB	^{192}Pb	33.0	0.00
^{34}Ar	^{158}Gd	RIB	^{192}Pb	36.1	0.25

Asysoft EoS with respect to Asystiff EoS

E_{sym} larger at $\rho < \rho_0$
Larger isovector restoring force

Larger centroid
Larger width
Larger yield (→ larger oscillation amplitude)

The differences in the DD parameters can be observed experimentally for the "exotic" system ^{132}Sn + ^{58}Ni at E_{lab} = 10 MeV/nucleon

R. Silvestri

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

Summary

CONCLUSIONS

- First systematic study of the DD features as a function of the beam energy in the S+Mo and Ar+Zr systems leading to the ^{132}Ce CN.
- Investigation for the first time of the DD in both fusion-evaporation and fission events in the Ca+Sm reactions at 11 MeV/nucleon leading to a ^{192}Pb CN.

OPEN PROBLEMS & PERSPECTIVES

- ✓ Better understanding of the interplay of the different parameters influencing the dynamical dipole features.
- ✓ Continuation of the study of the DD in heavy systems related with the formation of superheavy elements.
- ✓ Information on the density dependence of the nuclear matter EoS at $\rho<\rho_0$ by taking advantage of the use of radioactive beams.

EXPERIMENTS

A. Boiano, G. Inglima, M. La Commara, B. Martin, C. Parascandolo, D. Pierroutsakou, M. Romoli, M. Sandoli, R. Silvestri

Universita' di Napoli "Federico II"- Dipartimento di Scienze Fisiche & INFN, Sezione di Napoli, Napoli, Italy

M. Mazzocco, C. Signorini

Universita' di Padova - Dipartimento di Fisica & INFN, Sezione di Padova, Padova, Italy

A. Guglielmetti, C. Mazzocchi

Universita' di Milano - Dipartimento di Fisica & INFN, Sezione di Milano, Milano, Italy

F. Farinon

GSI, Darmstadt , Germany

R. Alba, C. Agodi, R. Coniglione, E. De Filippo, A. Del Zoppo, C. Maiolino, D. Santonocito

Universita' di Catania - Dipartimento di Fisica e Astronomia & INFN, Laboratori Nazionali del Sud and INFN, Sezione di Catania, Catania, Italy

U. Emanuele, A. Trifirò, M. Trimarchi

Universita' di Messina - Dipartimento di Fisica & INFN, Gruppo Collegato di Messina, Messina, Italy

THEORY

V. Baran*, M. Colonna, M. Di Toro, C. Rizzo

Universita' di Catania - Dipartimento di Fisica e Astronomia & INFN, Laboratori Nazionali del Sud and INFN, Sezione di Catania, Catania, Italy

** NIPNE-HH and Bucharest University, Bucharest, Romania*