Study of the Dynamical Dipole Resonance with stable and radioactive beams

D. Pierroutsakou
INFN-Naples, Italy

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Outline

- The physical problem
- Brief overview: experiments and theory
- DD in $^{40,48}Ca+^{152,144}Sm$ -> ^{192}Pb: new results
- Perspectives with the SPES RIBs

Nuclear collective modes: a well organized behavior of a complex system

Giant Dipole Resonance (GDR) → out of phase collective oscillation of protons and neutrons of the nucleus: emission of dipole γ-rays

Dynamical Dipole (DD) → excitation of a **pre-equilibrium GDR** in charge-asymmetric heavy-ion collisions: emission of **prompt** dipole γ–rays

DD: why to study

1) insight on the reaction dynamics: charge equilibration

2) informations on the density dependence of the nuclear matter EOS at $\rho < \rho_0$ (neutron stars, supernovae explosion, halo nuclei …): a way to probe the isovector part of the in-medium effective interaction at low densities

3) new cooling mechanism in fusion reactions

DD: theory and experiment

Several theoretical models were used to describe the DD γ emission such as: Time dependent Hartree-Fock, Boltzmann-Nordheim-Vlasov, Constrained Molecular Dynamics, Isospin-dependent Quantum Molecular Dynamics

C. Simenel et al., PRL86 (2001) 2971, A. S. Umar and V. E.Oberacker, Phys. Rev.C76 (2007) 014614, P. Chomaz, M. Di Toro, and A. Smerzi, Nucl. Phys. A563(1993) 509, V. Baran et al., Nucl. Phys. A600, 111 (1996) 111, M. Papa et al., Phys. Rev. C 68 (2003) 034606; 72, (2005) 064608, . Baran, D. Brink, M. Colonna and M. Di Toro, PRL87 (2001) 182501, L. Wu et al PRC 81 (2010) 047602] , Ma et al Phys. Rev. C 87 (2013) 014621

Experimentaly the DD radiation was probed in peripheral and fusion-evaporation heavy-ion reactions

L. Campajola et al., Zeit. für Phys. 352 (1995) 421, Flibotte et al., Phys. Rev. Lett. 77 (1996) 1448, M. Sandoli, Z. Phys. A357 (1997) 67 and EPJA6 (1999) 275, , M.Papa et al., PRC 68 (2003) 034606 and PRC 72 (2005) 064608, D. Pierroutsakou et al., EPJA16 (2003) 423, F. Amorini et al., PRC 69 (2004) 014608

DD data in fusion-evaporation reactions

A study of the DD excitation function in the range (6 – 16) MeV/nucleon was performed and first angular distribution data were given (**SERPE @ LNL and MEDEA @ LNS**) in the reaction pairs leading to the **^{132}Ce nucleus** :

^{36,40}Ar+^{96,92}Zr D(t=0)= (20.6-4)fm

^{32,36}S+^{100,96}Mo D(t=0)= (18.2-1.7)fm

D. Pierroutsakou et al., EPJA 17 (2003) 71, PRC 71 (2005) 054605, PRC 80 (2009) 024612, B. Martin et al., PLB 664 (2008) 47

Data on the same compound nucleus in a similar E_{lab} range were obtained by the Milan group and NUCLEX collaboration (**HECTOR + GARFIELD @ LNL**) by using a different reaction and a different technique (*see talk S. Barlini*):

^{18}O+^{116}Sn D(t=0) = 8.6 fm

A. Corsi et al PLB 679 (2009) 197, A. Giaz et al., (INPC 2013)

Evidence of DD radiation has been shown also at higher E_{lab}=25 MeV/nucleon (**TRASMA @ LNS**) in the reaction pair:

^{40}Ca+^{48}Ca,^{46}Ti (D(t)=(15.4-3-9) fm

F. Amorini et al., PRC 69 (2004) 014608

DD: where we are

Few data exist providing the **absolute value** of the DD multiplicity and its **angular distribution** to be compared with calculations.

Calculations are not able to reproduce simultaneously the experimental findings, while the comparison of the experimental data sets with each other show that different aspects on the DD excitation should be still clarified

The above elements call for further experimental investigation to disentagle the influence of the different reaction parameters on the DD features and to constraint the theoretical models

DD in heavier nuclei

^{192}Pb

PhD C. Parascandolo

DD: cooling in fusion reactions

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

Cold fusion reactions → larger CN survival probability

Hot fusion reactions → larger CN formation probability

V. Baran *et al.,* PRL 87(2001) 182501
C. Simenel *et al.,* PRC 76(2007) 024609

Does the DD yield decrease with increasing the mass of the reaction partners as TDHF calculations predict???

C. Simenel *et al.,* PRL 86(2001) 2971

➡ Investigate the existence and the features of the DD in heavier composite systems

DD in fusion reactions: 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) for the charge asymmetric system at $E_{DD}<E_{GDR}$

2)anisotropic γ-ray excess angular distribution

Dynamical Dipole in ^{192}Pb at E_{lab} ~ 11 MeV/nucleon

simultaneous investigation in fusion-evaporation and fission events simultaneously for the first time

$^{40}Ca + ^{152}Sm$	$^{48}Ca + ^{144}Sm$
E_{lab} = 440 MeV	E_{lab} = 485 MeV
$D(t=0) = 30.6\ fm$	$D(t=0) = 5\ fm$
$\Delta = 0.22$	$\Delta = 0.18$

^{192}Pb E*=220 MeV

$L_{fus} = 74\hbar$

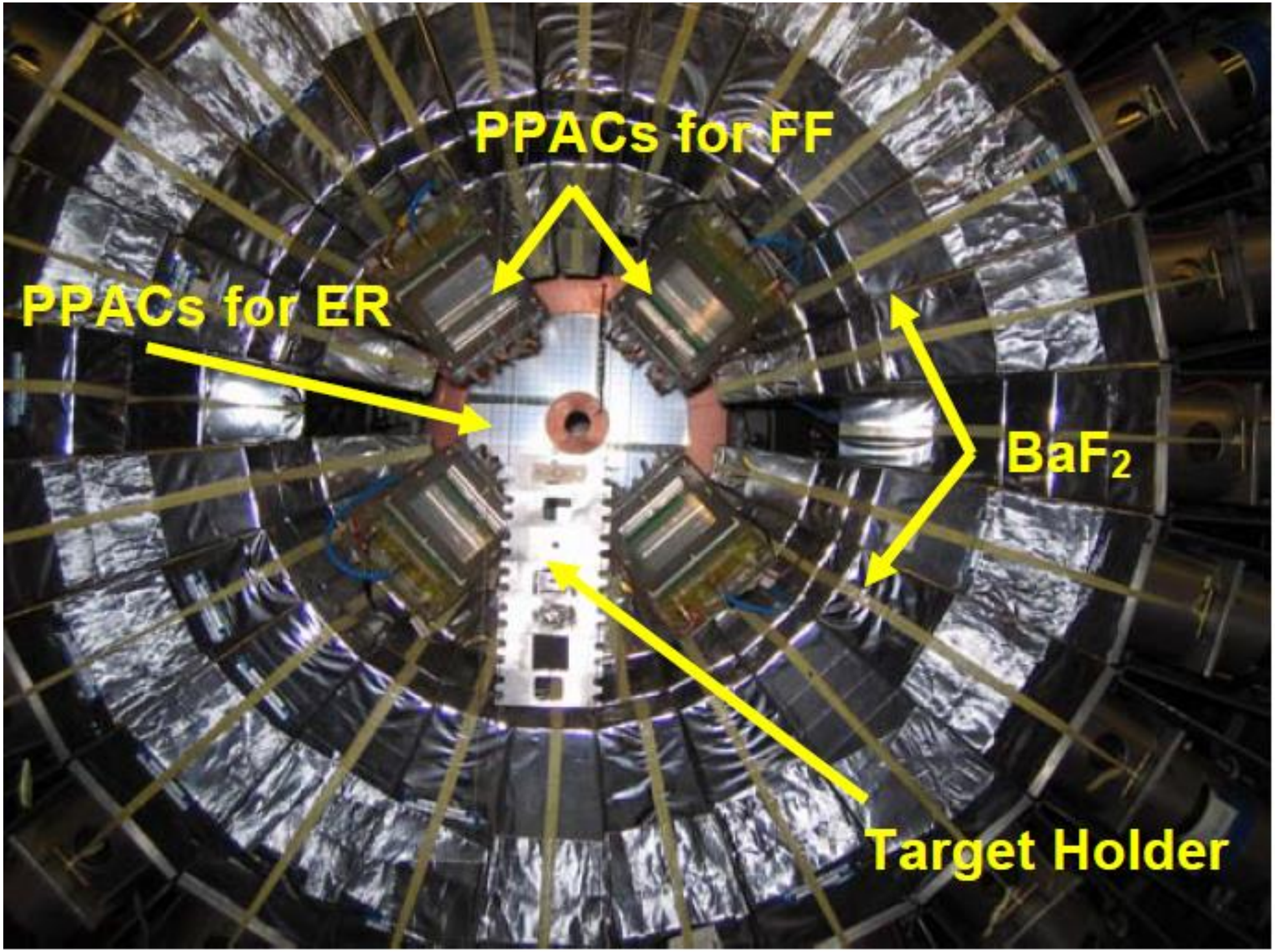
$L_{fus,evap} = 36\hbar$

$B_f(l=0) = 10.4\ MeV$

Detection of evaporation residues and fission fragments in singles and in coincidence with γ-rays (charged particles)

No normalization factors in γ–ray and particle spectra
CN saturated spin: identical spin distribution
Identical E* determined from the light particle energy spectra at different angles

Experimental set up: MEDEA + PPACs



Experimental set up

γ-ray and charged particle detectors

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

Evaporation residue detectors

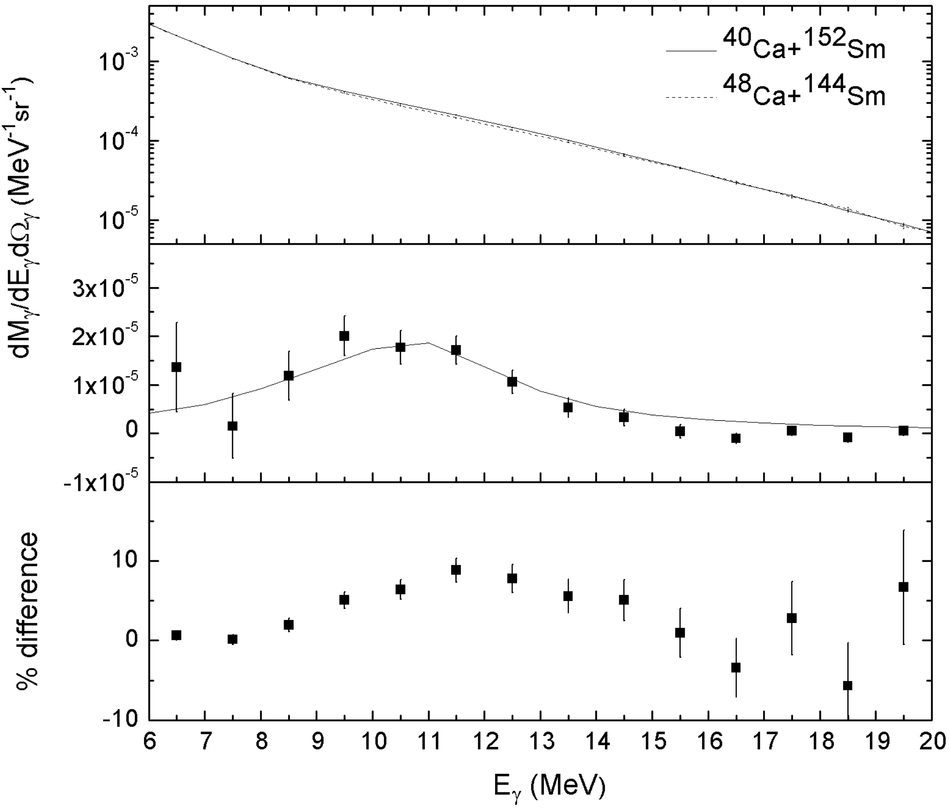
4 position sensitive PPAC's symmetrically around the beam
θ=7° ± 3.75° at d=70 cm from the target ($\Delta\Omega_{\tau otal}$= 0.089 sr)

Fission fragment detectors

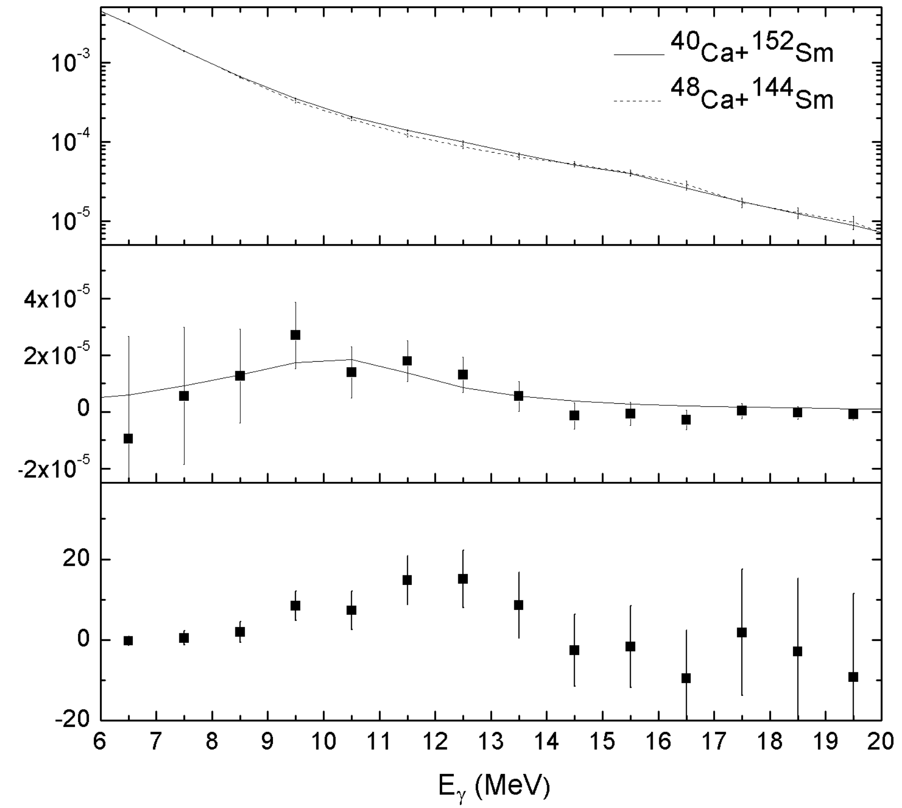
4 position sensitive PPAC's symmetrically around the beam at θ = 52.5° ± 11° ($\Delta\phi$=22°) at d=16 cm from the target ($\Delta\Omega_{PPAC}$= 0.16 sr)

γ ray excess

Evaporation



Fission



A γ ray excess was observed in the charge asymmetric system independently of the exit channel: pre-equilibrium emission

The DD survives in heavy composite system

E_{DD} = 11 MeV, Γ_{DD}=3.5 MeV

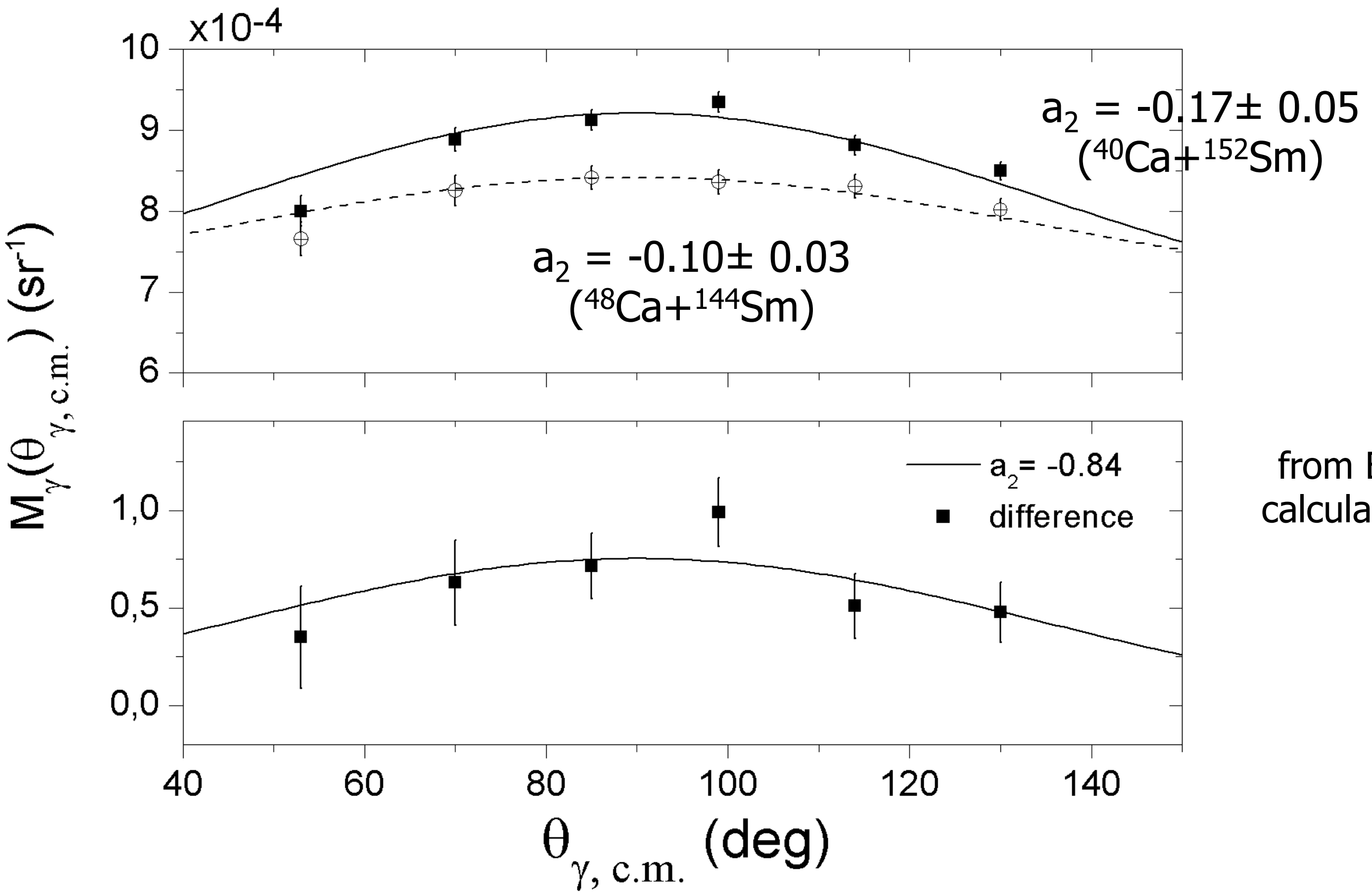
$dM_\gamma/d\Omega_\gamma$= (1.0±0.3) 10^{-4} γ/sr (8-16 MeV)

E_{DD} < E_{GDR} = 13.5 MeV *emission before shape equilibration*

DD γ-ray angular distribution in evaporation events

$$M(\vartheta_\gamma) = M_0[1 + Q_2 a_2 P_2(\cos\vartheta_\gamma)]$$

Very asymmetric energy integrated (10-14 MeV) angular distribution of the DD γ-rays with respect to the beam direction: pre-equilibrium emission



from BNV calculations

DD: Theory

BNV transport model: the reaction dynamics is described in a microscopic approach based on semiclassical transport equations where mean field and two body collisions are treated in a self-consistent way

↓

EoS dependent on ρ + nuclear medium reduced n-n cross sections

↓

Evolution of the dipole moment D(t)=(NZ/A) * X(t)

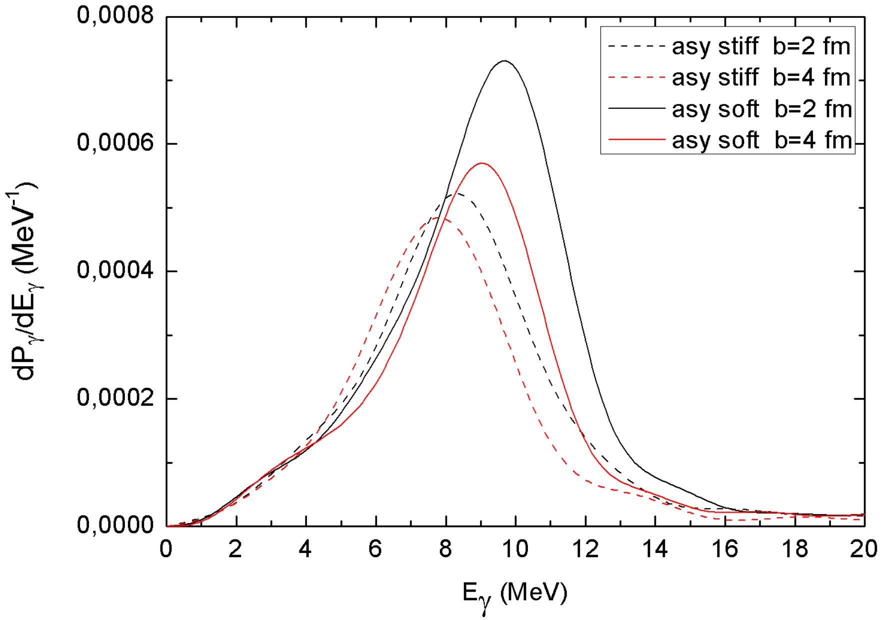
↓

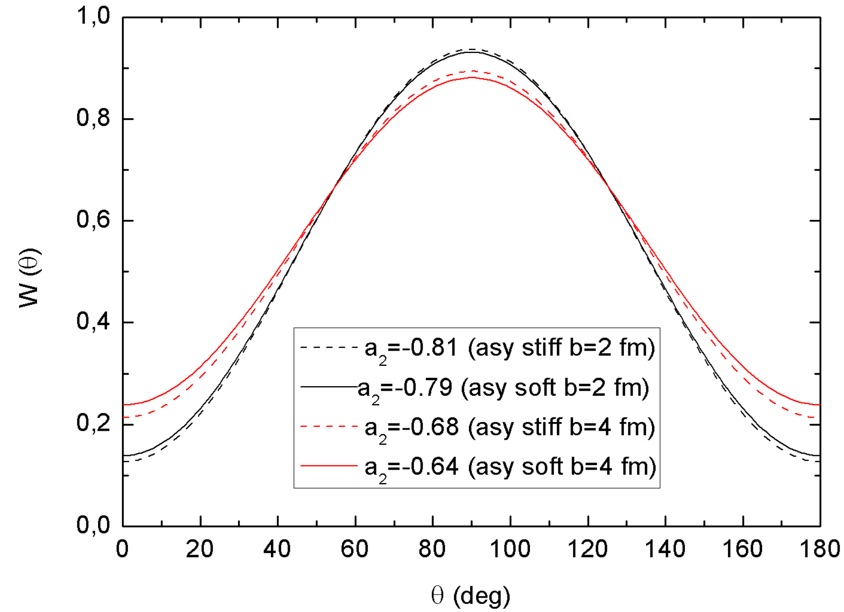
Dynamical Dipole γ-ray emission obtained from the **Bremsstrahlung formula**:

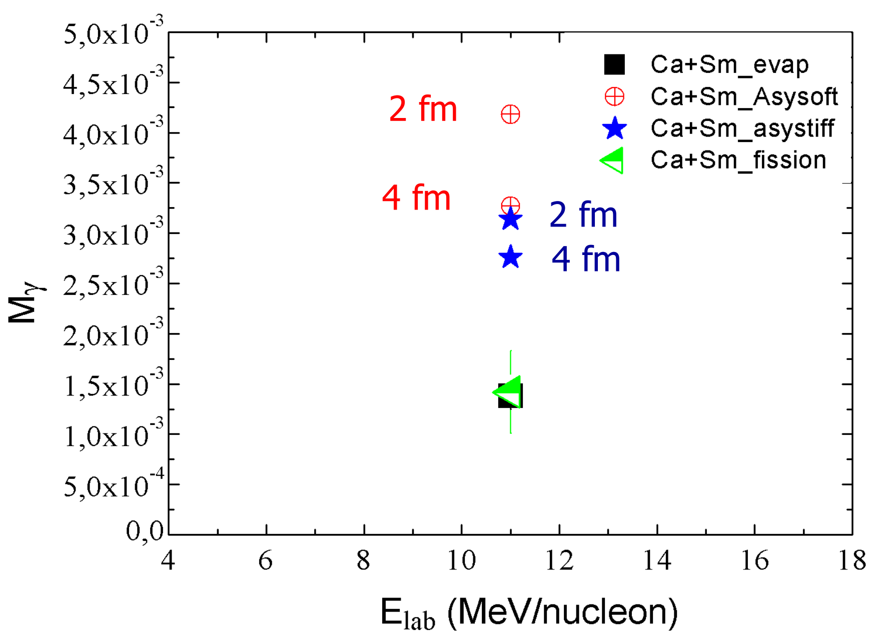
$$\frac{dP}{dE_\gamma} = \frac{2e^2}{3\pi\hbar c^3 E_\gamma}\left(\frac{NZ}{A}\right)^2 \left|X''(\omega)\right|^2$$

V. Baran, D.M. Brink, M. Colonna and M. Di Toro, PRL 87 (2001) 182501

BNV calculations for $^{40}Ca+^{152}Sm$ at E_{lab}=11A MeV







Integration over impact parameter for central collisions:

1) E_{GDR}-E_{DD}=2.5 MeV, Γ_{DD}=4 MeV, angular distribution in agreement with the data

2) DD strength largely overpredicts the data for both Asysoft and Asystiff choices: mass effect? Target defomation?

→ further investigation is needed

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

- The DD survives in heavy composite systems;
- $E_{DD} < E_{GDR} \rightarrow$ pre-equilibrium emission;
- Large anisotropy of DD γ-ray angular distribution -> pre-equilibrium emission;
- The DD γ yield was observed in both evaporation and fission events -> pre-equilibrium emission;
- BNV transport calculations predict centroid, width and angular distributions of the DD in agreement with the data but they overpredict the yield: other parameters should be taken into account

Perspectives with stable and radioactive beams

Systematic study of the DD with charge asymmetry, incident energy, mass asymmetry and mass by using stable and radioactive beams produced by SPES. Radioactive beams maximize the initial dipole moment between interacting ions. Moreover, the combination of stable and radioactive beams allow to have a large variety of target-projectile combinations.

Perspectives with stable and radioactive beams

Projectile	Target	Beam type	CN	D(t=0) fm	Δ (t=0)
^{112}Cd	^{80}Se		^{192}Pb	1.8	0.06
^{48}Ca	^{144}Sm		^{192}Pb	5.3	0.18
^{86}Kr	^{106}Pd		^{192}Pb	8.0	0.03
^{110}Cd	^{82}Se		^{192}Pb	11.2	0.05
^{88}Kr	^{104}Pd	RIB	^{192}Pb	17.4	0.03
^{93}Sr	^{99}Ru	RIB	^{192}Pb	19.0	0.01
^{94}Sr	^{98}Ru	RIB	^{192}Pb	23.6	0.01
^{32}S	^{160}Dy		^{192}Pb	24.1	0.26
^{90}Kr	^{102}Pd	RIB	^{192}Pb	26.8	0.02
^{40}Ca	^{152}Sm		^{192}Pb	30.6	0.22
^{96}Sr	^{96}Ru	RIB	^{192}Pb	33.0	0.00
^{134}Te	^{58}Ni	RIB	^{192}Hg	41.3	0.14

Symmetry Energy dependence on ρ at $\rho<\rho_0$ by studying the DD in ^{132,124}Sn+ ^{58}Ni at E_{lab}= 10A MeV

Asysoft EOS with respect to Asystiff EOS

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

DD parameters: Asysoft with respect to Asystiff EOS
Larger centroid, larger width, larger yield, different angular distribution for high impact parameters
The differences in the DD parameters can be observed experimentally
for the more "exotic" system **^{132}Sn+^{58}Ni (D= 45 fm)**
DD yield larger by 30% with the Asysoft EoS choice

V. *Baran, M. Di Toro, M. Colonna et al., PRC79(2009) 021603*

Reactions to study with the SPES RIBs:

^{190}Pt CN: **^{132}Sn**+^{58}Ni (I)= *3.11*10^{7} pps* (D=45 fm) and ^{48}Ca+^{142}Ce (D=3.13 fm)

^{190}Hg CN: **^{132}Te**+^{58}Ni (I)= *8.4*10^{8} pps* (D=38.5 fm) and ^{48}Ca+^{142}Nd (D=2.2 fm)

^{192}Hg CN: **^{135}I**+^{58}Ni (I)= *3.5*10^{9} pps* (D=39.5 fm) and ^{48}Ca+^{144}Ce (D=0 fm)

^{192}Hg CN: **^{134}Te**+^{58}Ni (I)= *2.3*10^{8} pps* (D=41.3 fm) and ^{48}Ca+^{144}Nd (D=0 fm)

We are interested in Te**, **Kr**, **Sr**, **Sn** and **Cs RIBs

Need of a high purity pulsed RIB with a time resolution of 1 ns

I=5*10^{8} pps necessary to obtain the DD energy- and angle-integrated yield with a relative error of about 10% with a solid angle coverage of 4.3 sr (34% of 4π) in a 10-days run.

A larger intensity by one order of magnitude needed for decreasing the error down to 3% to allow more accurate comparisons with theoretical predictions and to study the DD angular distribution with enough statistics.

Requests for an experimental set up to use with RIBs

γ-ray detection :

Energy resolution~ 7% at 1 MeV

High efficiency for high energy (25-30 MeV) γ rays

Time resolution ~ 1 ns

Neutron rejection from the γ spectra with TOF and pulse shape analysis

Granularity for spin selection

Detection of evaporation residues, fission fragments, complex fragments

In case of incident energy larger 8 MeV/nucleon, particle pre-equilibrium emission sets in : **detection of light charged particles and neutrons**

SERPE apparatus

γ-rays

6 clusters of 7 BaF_2 (hexagones of TAPS standard type d_{inner}= 5.9 cm, L= 25 cm= 12 X_o, X_o = radiation length,) all faces optically polished

at 28 cm from the target in and out of plane

$\varepsilon_\gamma \sim 5.10^{-3}$ for E_γ = 15 MeV, $\Delta\Omega_{cluster}$ = 0.27 sr

$\Delta\Omega_{tot}$ = 1.62 sr

reaction products

4 position sensitive PPACs at θ= 7°, d=70 cm, $\Delta\Omega$=0.089 sr for evaporation residues

4 position sensitive PPACs at θ = 50°, d=15 cm, $\Delta\Omega$=0.16 sr (for fission fragments)

12 three-stage telescopes (IC+ Silicon Strip detectors +CsI (Tl) crystals) for peripheral reaction fragments

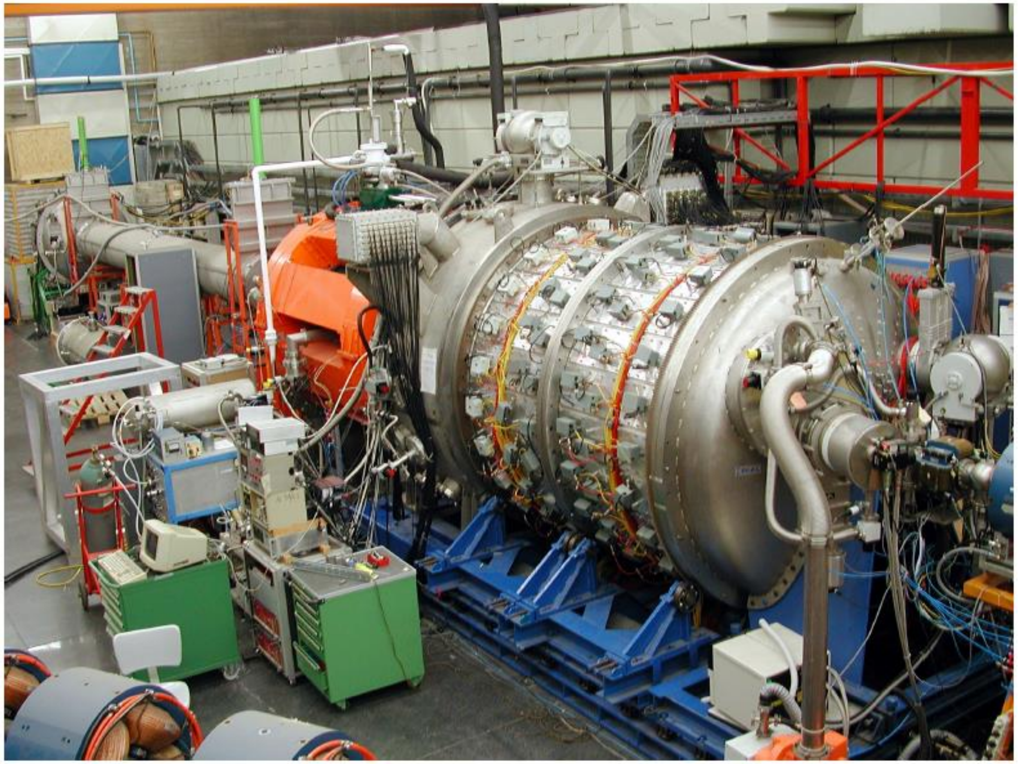
TRASMA apparatus at LNS

9 clusters of 7 BaF_2 : 3 clusters identical to those of the SERPE apparatus

$\Delta\Omega_{cluster} = 0.27$ sr

SERPE+TRASMA $\Delta\Omega_{tot} = 4.05$ sr (32% of 4π, 19% with identical BaF_2)

MEDEA apparatus at LNS



180 BaF_2
d=22 cm ($\Delta\Omega = 3.37\pi$ sr)

Detection of γ-rays and light charged partcles

TOF and pulse shape discrimination: neutron rejection

Other existing or under construction apparatuses

Different existing or under construction arrays of second generation scintillators (better energy resolution, good time resolution, efficiency if in large volume) can be employed

for the detection γ rays

HECTOR+LaBr3:Ce *(talk of F. Camera)*

Composite array **PARIS** *(talk of A. Maj)*

.....

NEDA *(talk J. Nyberg)* , **CLYC** *(talk of F. Camera)* for detection of neutrons

GARFIELD, FAZIA *(talk S. Barlini, G. Casini),* **FARCOS** *(talk Pagano),*

… for the detection of charged particles

LOI for SPES

Study of the Dynamical Dipole Resonance mode with the SPES radioactive beams

D. Pierroutsakou[1], C. Parascandolo[1], R. Alba[2], V. Baran[3], M. Colonna[2], A. Del Zoppo[2], A. Guglielmetti[4], T. Glodariu[3], M. La Commara[5], G. La Rana[5], C. Maiolino[2], M. Mazzocco[6], A. Pakou[7], C. Rizzo[2], D. Santonocito[2], C. Signorini[6], O. Sgouros[7], F. Soramel[6], V. Soukeras[7], S. Stiliaris[8], E. Strano[6], L. Stroe[3], D. Torresi[6], E. Vardaci[5]

[1] *INFN - Sezione di Napoli, via Cinthia, I-80126, Napoli, Italy*
[2] *INFN, Laboratori Nazionali del Sud, via Santa Sofia, I-95123 Catania, Italy*
[3] *NIPNE-HH, 077125 Magurele, Romania*
[4] *Università degli Studi di Milano, Milano, Italy and INFN- Sezione di Milano, via Celoria 16, I-20133 Milano, Italy*
[5] *Dipartimento di Scienze Fisiche, Università di Napoli, via Cinthia, I-80126, Napoli, Italy*
[6] *Dipartimento di Fisica and INFN - Sezione di Padova, via Marzolo 8, I-35131, Padova, Italy*
[7] *Department of Physics and HINP, The University of Ioannina, 45110 Ioannina, Greece*
[8] *Department of Physics, National and Kapodistrian,University of Athens and the Institute of Accelerating Systems & Applications, (IASA), 15771 Athens, Greece*