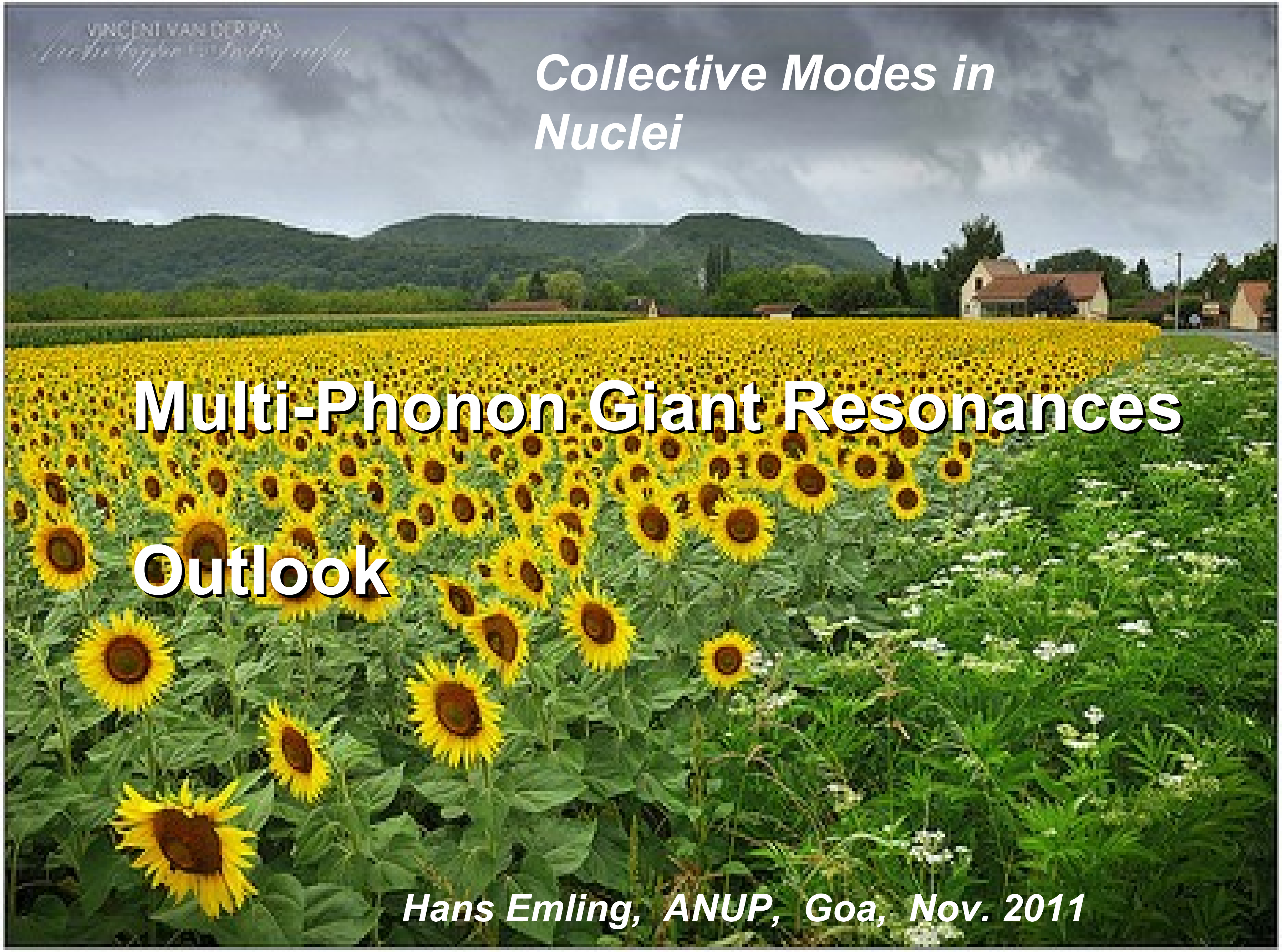


Collective Modes in Nuclei

Multi-Phonon Giant Resonances

Outlook

Hans Emling, ANUP, Goa, Nov. 2011

Multi-phonon giant resonances

Observation of multi-phonon states
=
direct proof of vibrational character

$$E_n = n \cdot \hbar\omega$$

- Existence
- Harmonicity of nuclear response
- Damping/Coupling of multi-phonon states
- 'Applications' (RHIC, LHC, RIB production)
- ....

Quantized Harmonic Oszillator

P_n ~ Poisson distributed

(Bose statistics)

$E_n = n\ E_1$

$\Gamma_n = n\ \Gamma_1$

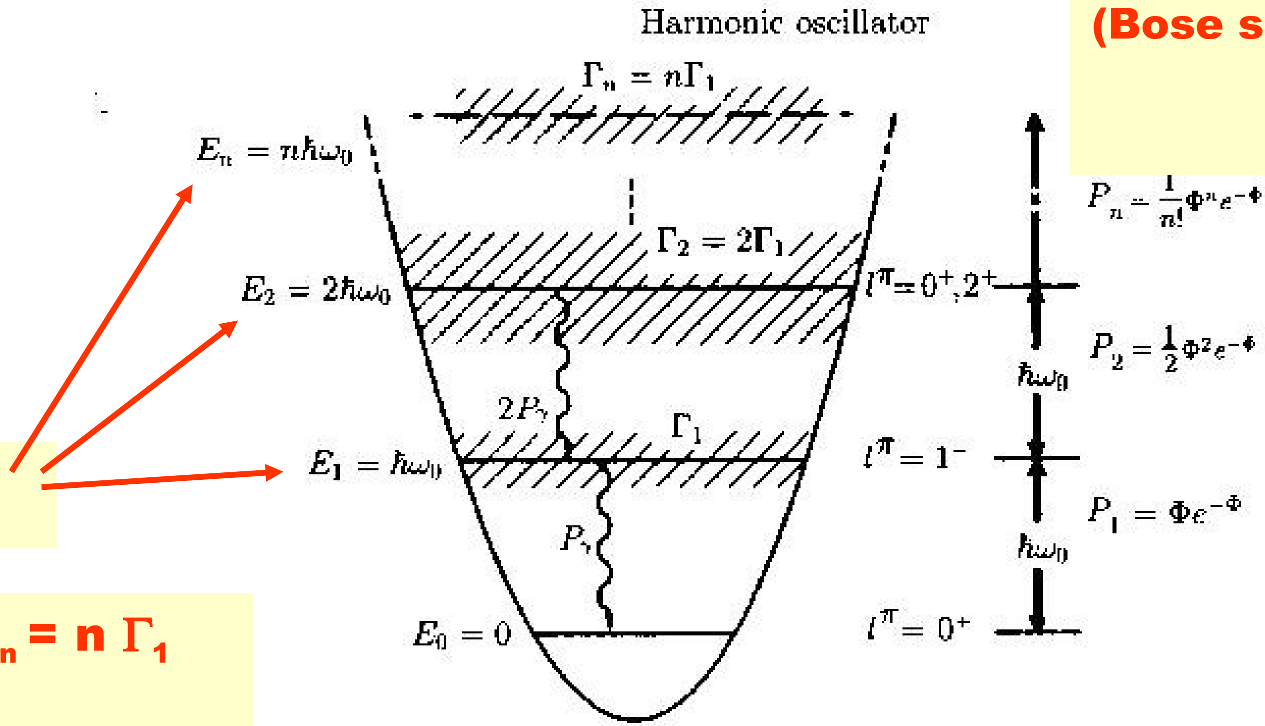


FIG. 9.2. Multiphonon states of a one-dimensional linear harmonic vibrator of $J^\pi = 1^-$ phonons (IVGDR). After (EML94).

Two-phonon giant resonances were observed in:

- Double-charge exchange reactions: **DIAS , DGDR ($\Delta T_z = \pm 2$)** [Los Alamos]

S. Mordechai, H. Fortune, J. O'Donell, G.Lui, M. Burlein, A. Waosmaa, S. Greene, C. Morris, N. Auerbach, S. Yoo, and C. Moore, Phys. Rev. C41, 202 (1990).

- Inelastic heavy-ion scattering : isoscalar **DGQR** [Orsay]

P. Chomaz and N. Frascaria, Phys. Rep. 252, 275 (1995)

- Relativistic Coulomb breakup: isovector **DGDR ($\Delta T_z = 0$)** [GSI]

T. Aumann, P. F. Bortignon, and H. Emling, Ann. Rev. Nucl. Part. Sci. 48, 351 (1998).

[early review articles]

Double charge-exchange reaction ($^{+}\pi$, $^{-}\pi$)

Features of ($^{+}\pi$, $^{-}\pi$) reaction:

$\mathbf{\Delta S = 0}$ in forward scattering (pion is spinless)
$\mathbf{\Delta T = 2 \; ; \; \Delta T_z = -2}$; $T = T_z$ favored

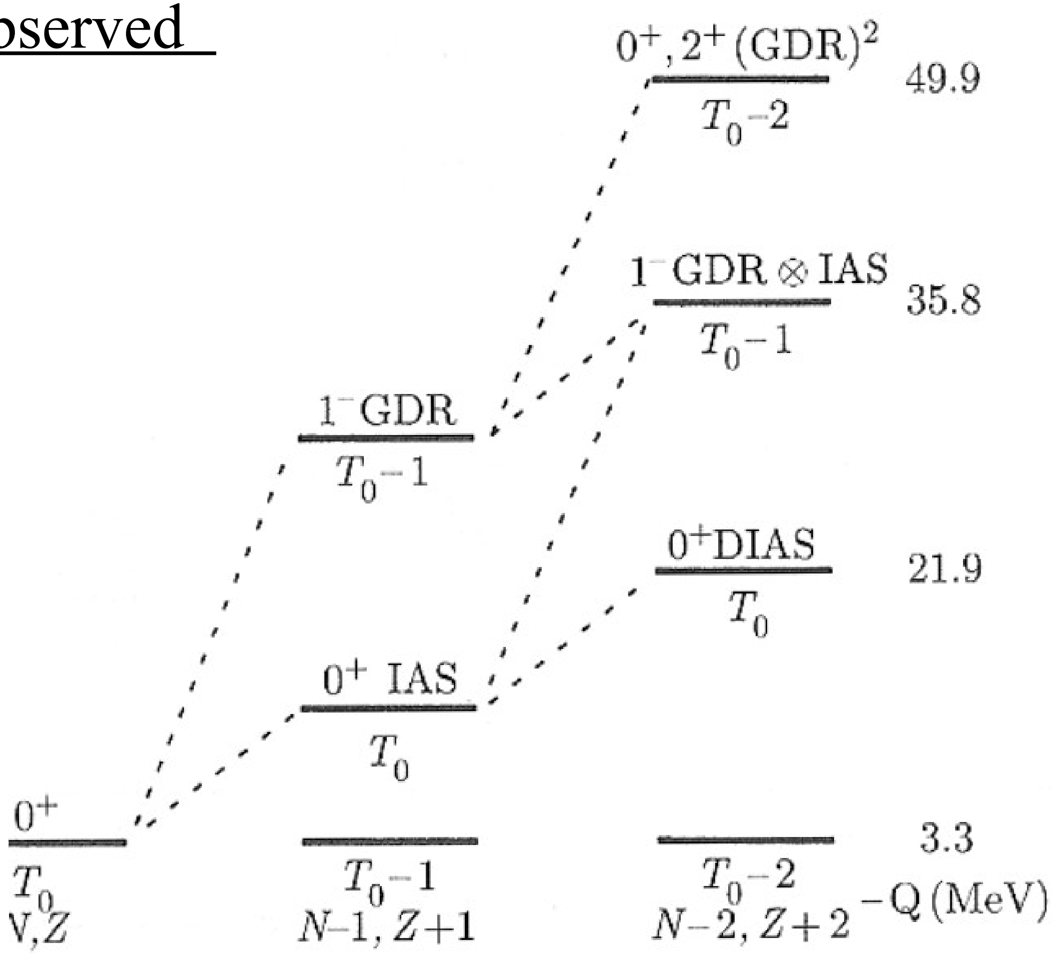
IAS and GDR strongly populated in pion reactions
(pion strongly absorbed at nucl. surface
\+ surface-peaked IAS,GDR transition density)

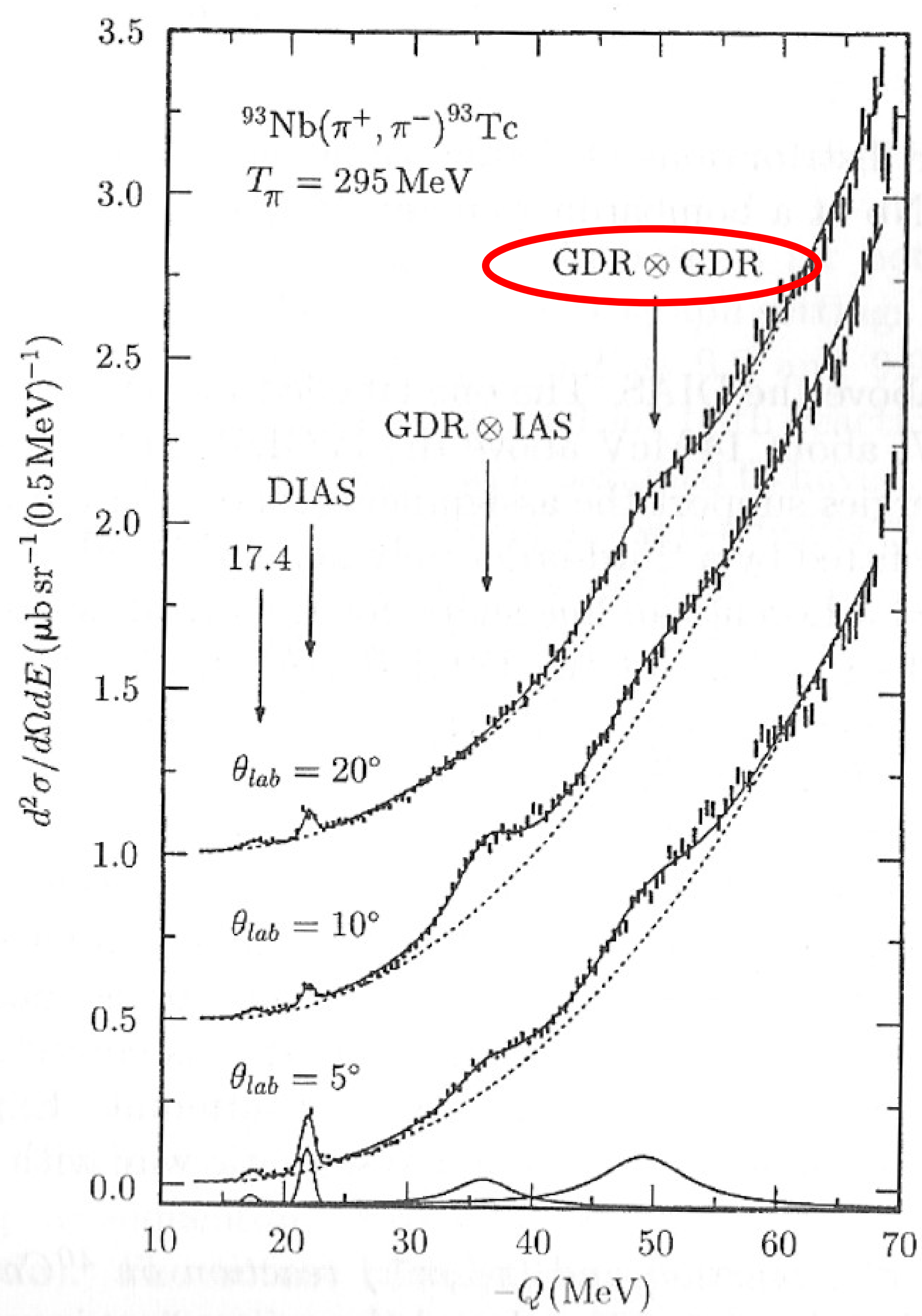
Experiments performed at LAMPF / Los Alamos,
pion energies 200 – 300 MeV + EPICS spectrometer

Double charge-exchange reactions

($^{+}\pi$, $^{-}\pi$)

Double IAS (DIAS) , double GDR (DGDR), and GDR ☺ IAS observed





LAMF data
[MOR96]

Double charge-exchange reactions
$(^{+}\pi , ^{-}\pi)$

short SUMMARY:

DGDR systematically observed in A = 12 … A=197 nuclei

excitation energy and width within expectation for
a sequential excitation

angular distributions show $\Delta L = 2$ pattern

But: cross sections difficult to analyze
$\Delta L = 0$ component seemingly missing

Double isoscalar GQR

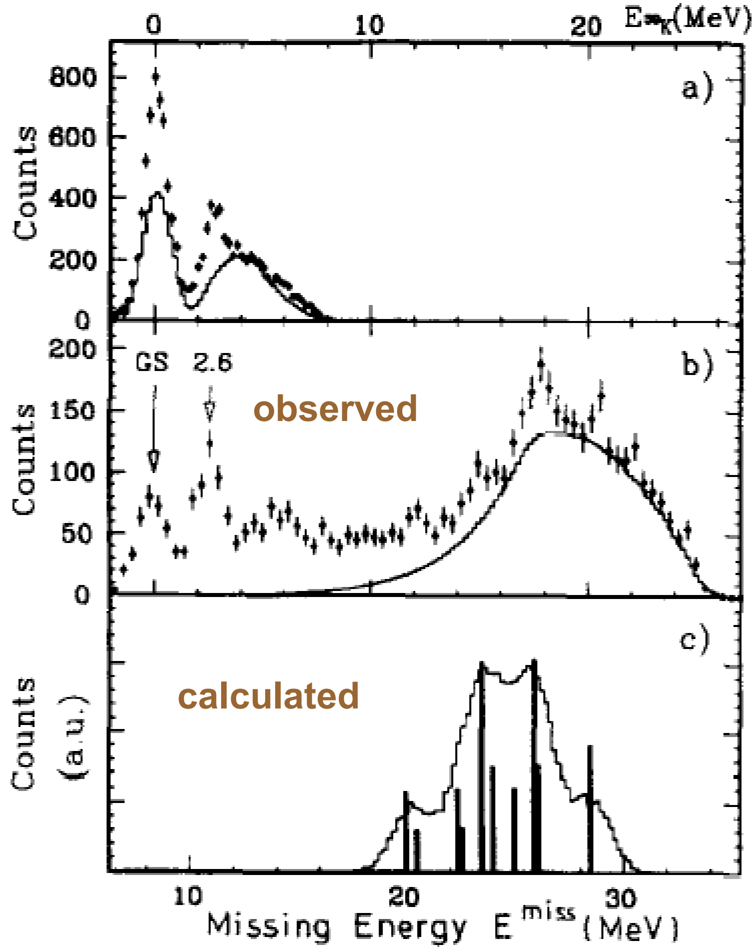
Evidence for

two-phonon giant quadrupole resonance

from <u>direct-proton decay</u>

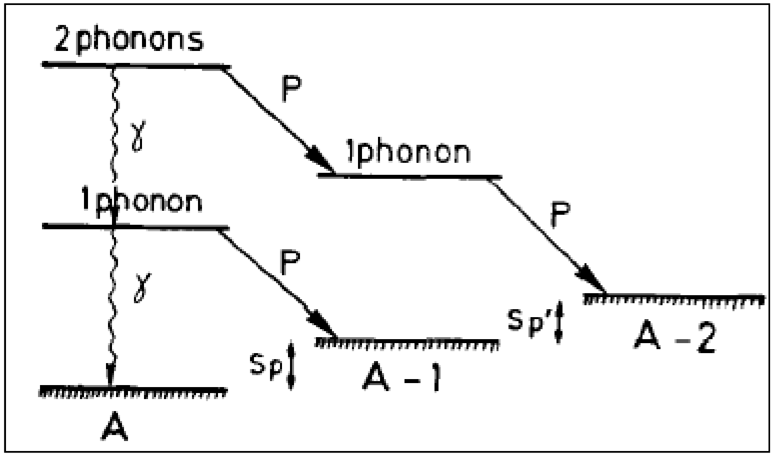
(missing mass spectra, ^{40}Ca + ^{40}Ca)

J.A.Scarpaci et al., Phys.Rev.Lett., 1994



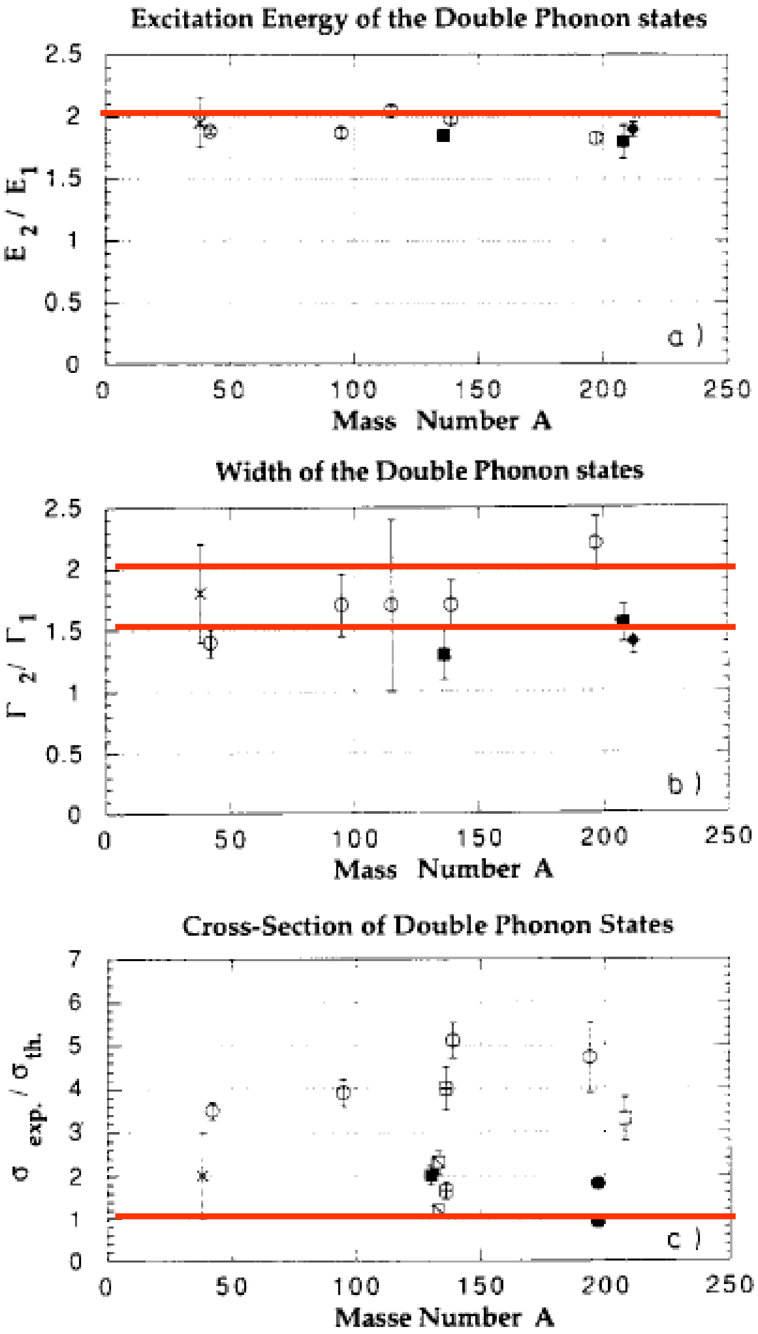
observed

calculated



SUMMARY

P. Chomaz and N. Frascaria, Phys. Rep. 252, 275 (1995)



Double-Phonon Giant Dipole Resonance (DGDR)

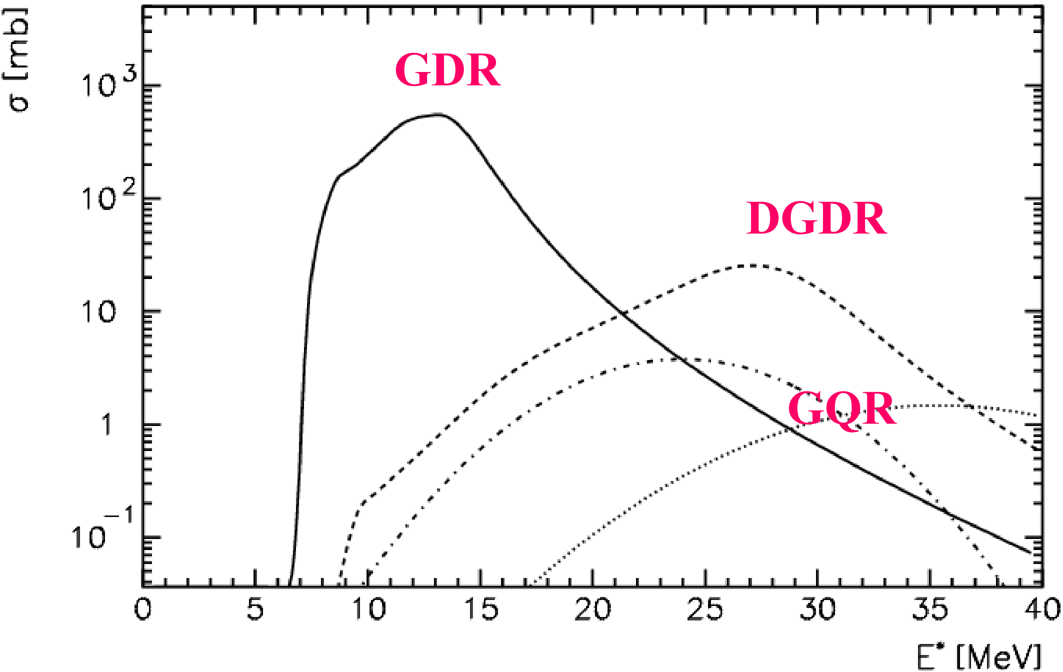
Relativistic heavy-ion collisions

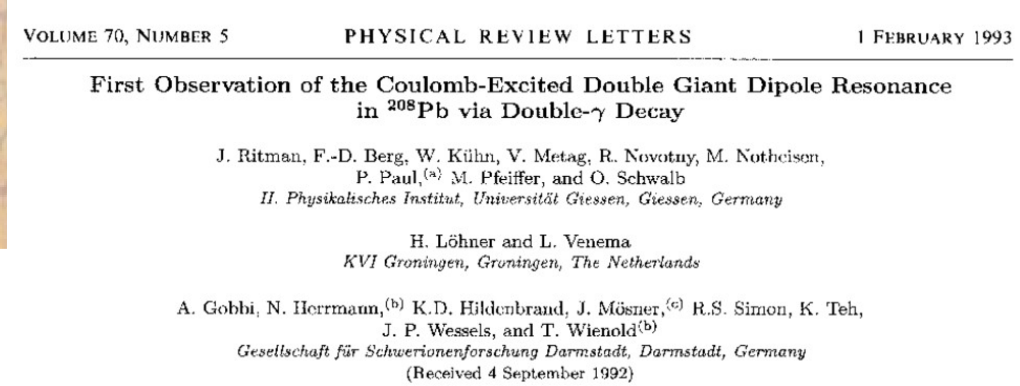
LARGE cross sections :

~ barns for GDR

~ 100 mb for DGDR

see lecture T. Aumann for details





VOLUME 70, NUMBER 5 PHYSICAL REVIEW LETTERS 1 FEBRUARY 1993

First Observation of the Coulomb-Excited Double Giant Dipole Resonance in ^{208}Pb via Double-γ Decay

J. Ritman, F.-D. Berg, W. Kühn, V. Metag, R. Novotny, M. Notheisen,
P. Paul,(a) M. Pfeiffer, and O. Schwalb
II. Physikalisches Institut, Universität Giessen, Giessen, Germany

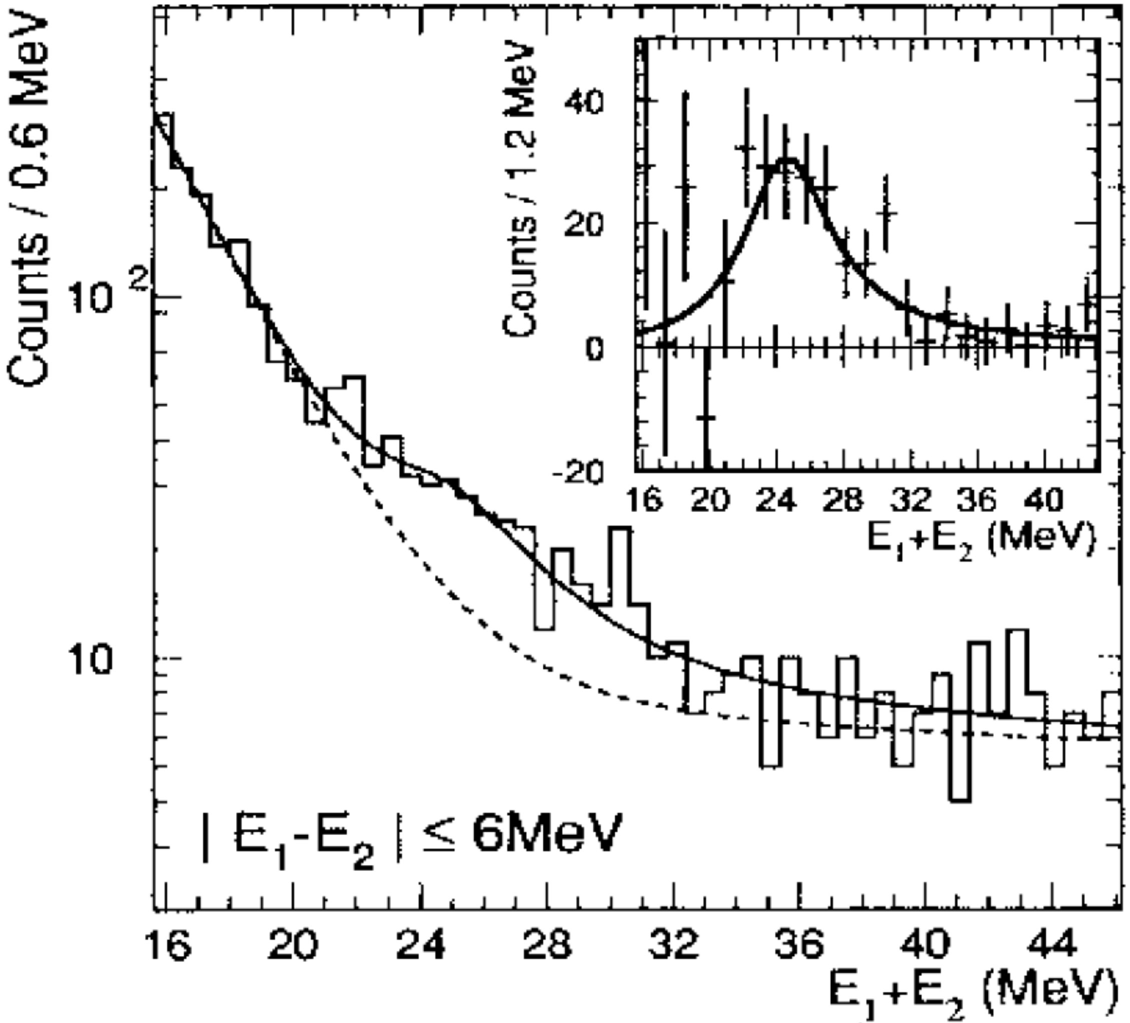
H. Löhner and L. Venema
KVI Groningen, Groningen, The Netherlands

A. Gobbi, N. Herrmann,(b) K.D. Hildenbrand, J. Mösner,(c) R.S. Simon, K. Teh,
J. P. Wessels, and T. Wienold(b)
Gesellschaft für Schwerionenforschung Darmstadt, Darmstadt, Germany

(Received 4 September 1992)

Double-photon decay:

10^{-4} branch



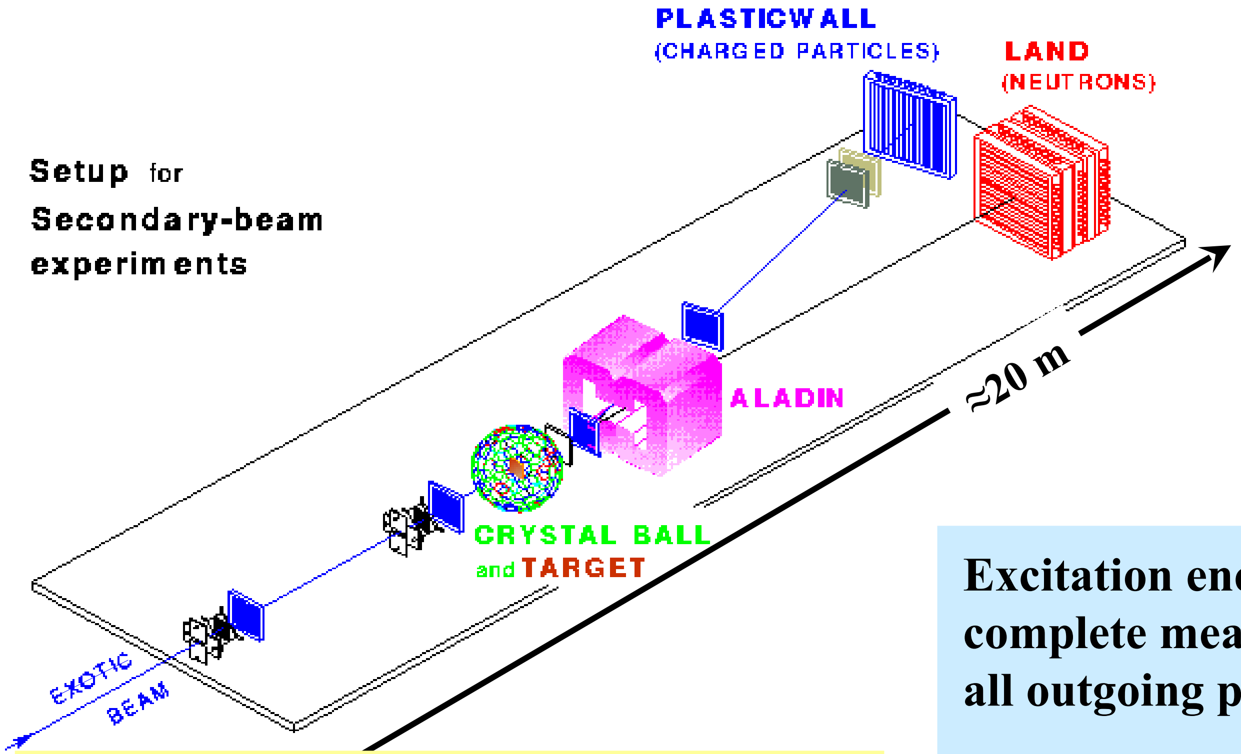
DGDR and TGDR – summary of results LAND collaboration

K. Boretzky et al., Phys.Rev.C 68, 024317 (2003)

S. Ilievski et al. , Phys. Rev. Lett. (2004)

LAND experimental setup&method

The invariant mass measurement



The experiment

- e.g., ^{208}Pb ~ 500 MeV/A
-
- select projectile breakup
- (neutron emission)
- background measured with empty target
- nuclear contribution measured with C target

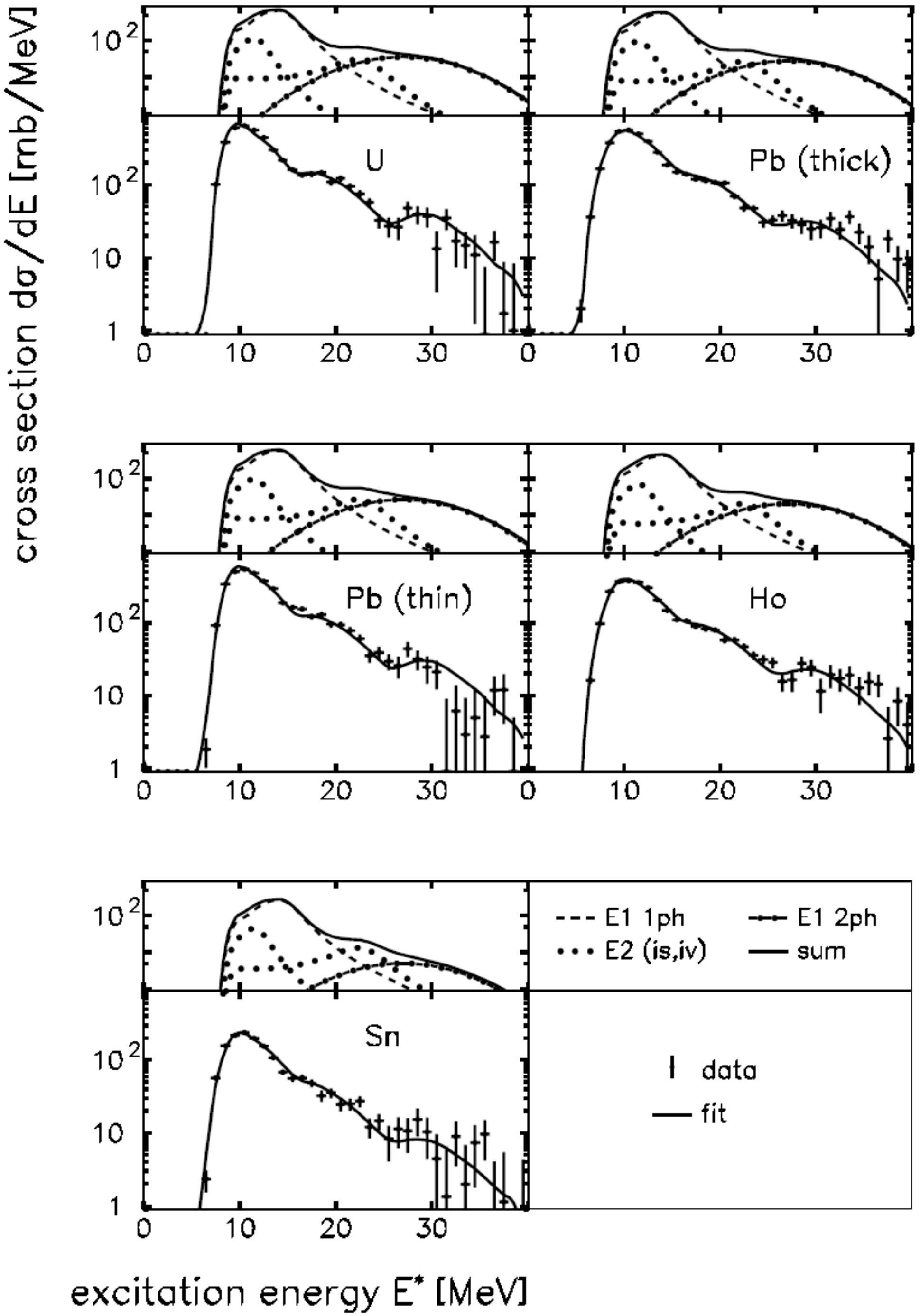
Excitation energy – from kinematically complete measurement of momenta of all outgoing particles:

$$\left(m_{proj}+E^{*}\right)^{2}=\left(\sum_{j} P_{j}\right)^{2}$$

notice:

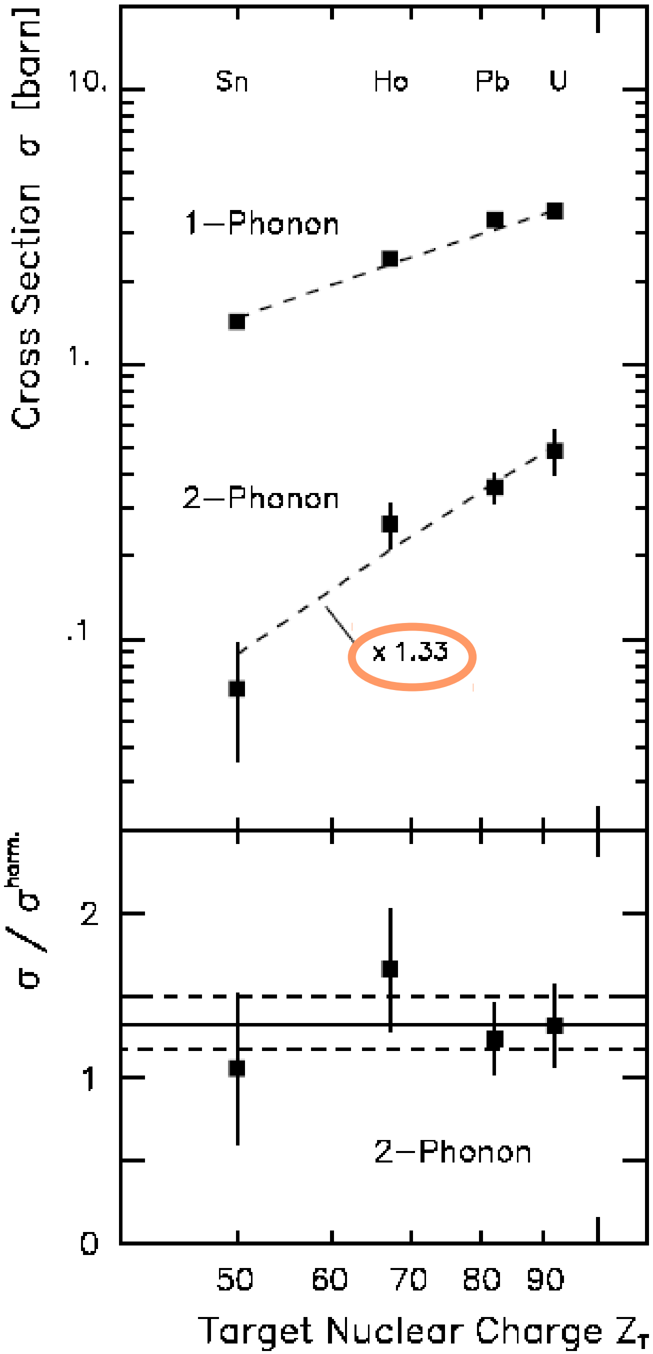
total kinetic energy ~ 100 GeV
measured exc. energy ~ 10 MeV
achieved resolution ~ 1 MeV

^{208}Pb



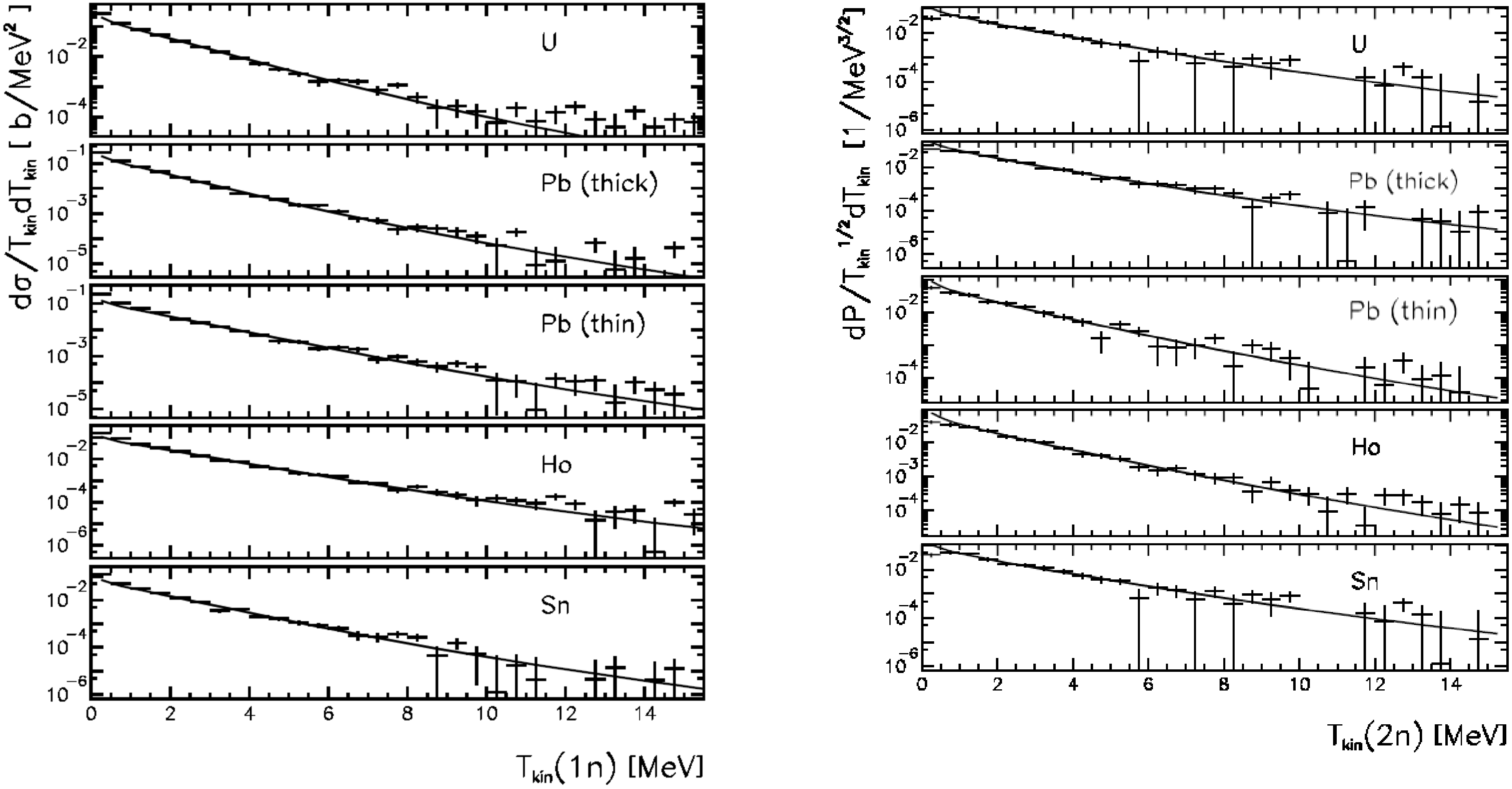
please notice
perfect fit of
one-phonon part

K. Boretzky et al., Phys.Rev.C 68, 024317 (2003)


Cross Section σ [barn]
10.
1.
.1
Sn
Ho
Pb
U
1–Phonon
2–Phonon
x 1.33
σ / σ^harm.
2
1
0
2–Phonon
50
60
70
80
90
Target Nuclear Charge Z_T

1.33

quick look into the decay of DGDR



Neutron decay spectra in ^{208}Pb

→ Maxwell distribution (here, linearized)

Harmonic response ?

Deviations from harmonic response:

- Splitting of $I^\pi = 0^+$ and $I^\pi = 2^+$ states
- Shifts in centroid energy

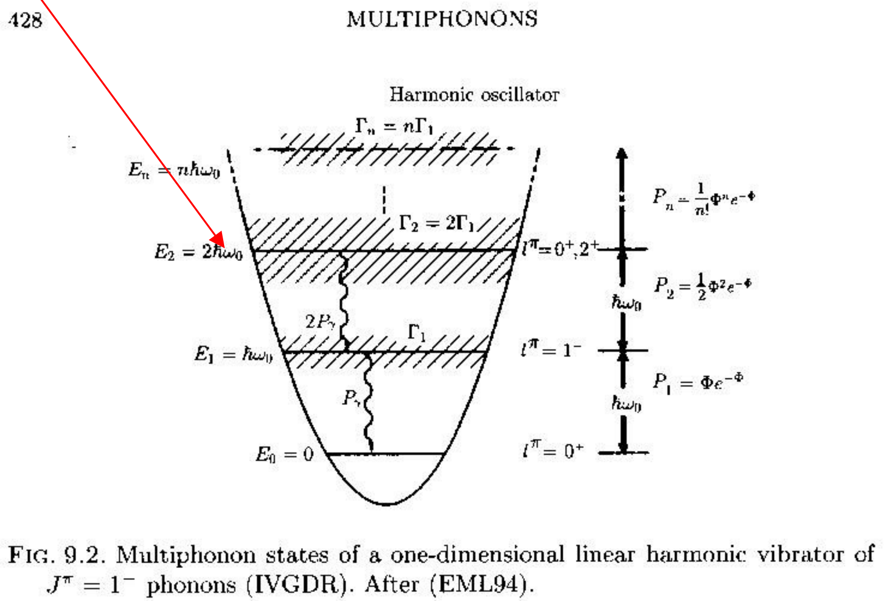
Experimental resolution

and

physical resolution

(= spreading width)

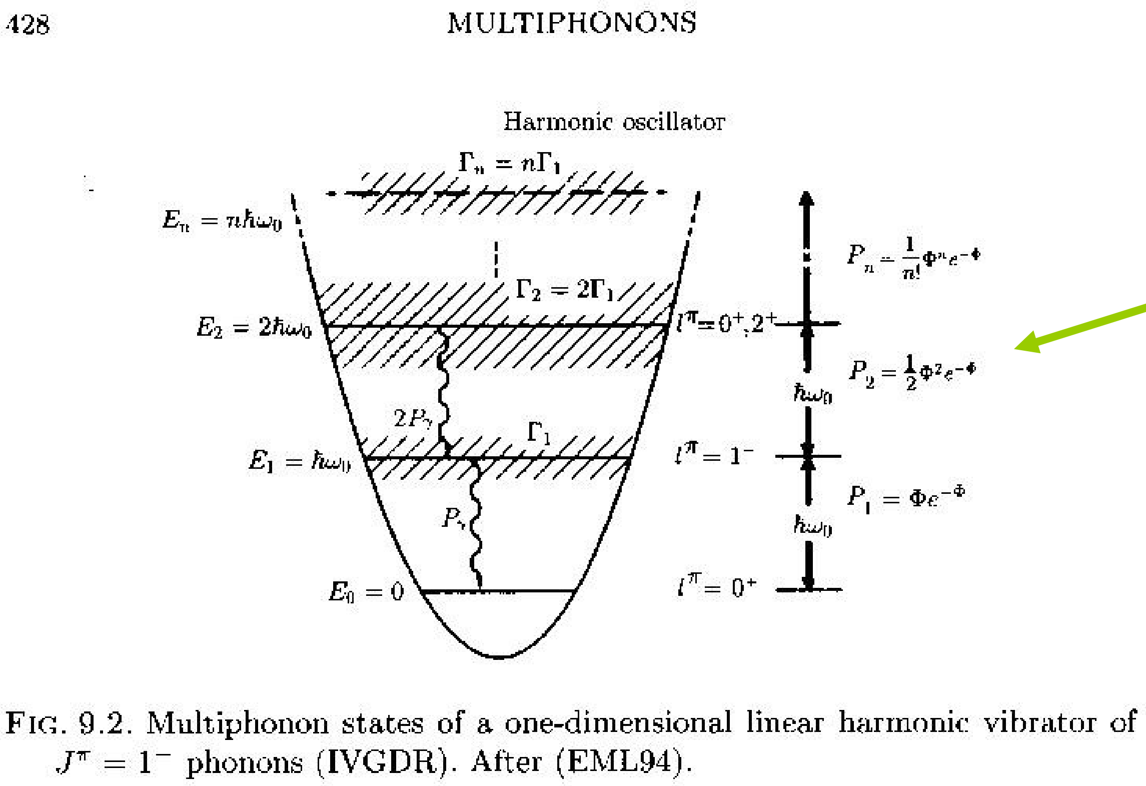
much too poor



428 MULTIPHONONS

FIG. 9.2. Multiphonon states of a one-dimensional linear harmonic vibrator of $J^\pi = 1^-$ phonons (IVGDR). After (EML94).

Harmonic response ?



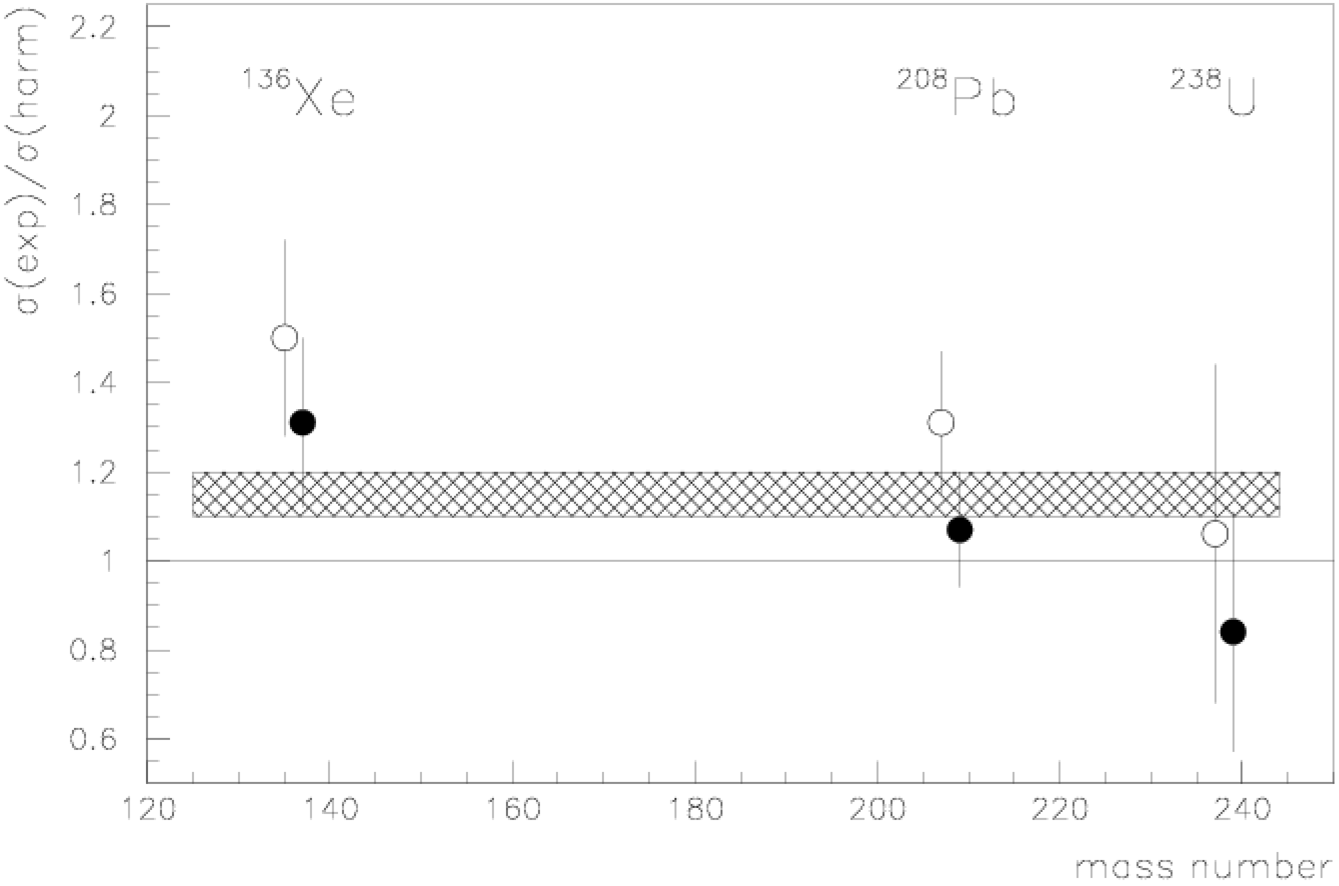
428 MULTIPHONONS

FIG. 9.2. Multiphonon states of a one-dimensional linear harmonic vibrator of $J^\pi = 1^-$ phonons (IVGDR). After (EML94).

Excitation probabilities ?

The Double-Phonon Giant Dipole Resonance in ^{136}Xe, ^{208}Pb, and ^{238}U

K. Boretzky et al.



' Cross section enhancement '
evoked many discussions

Anharmonicities ?

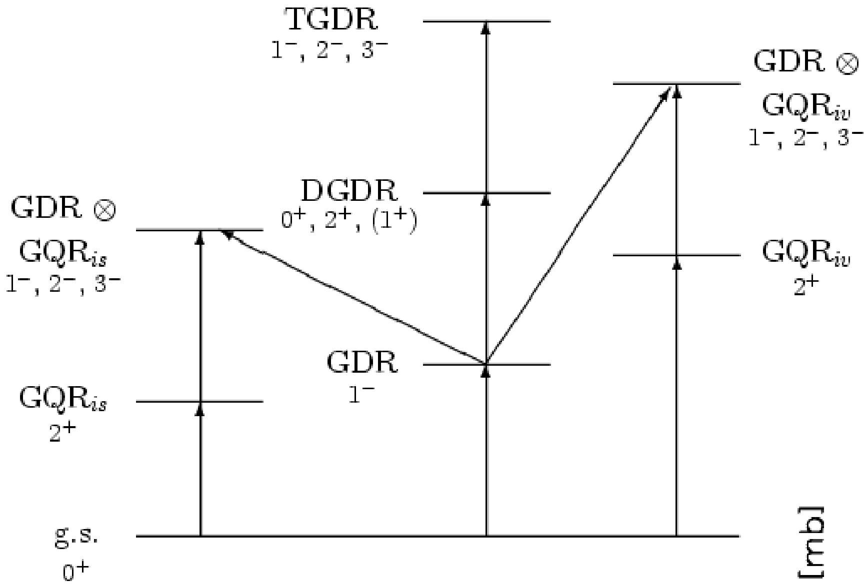
but also many attempts

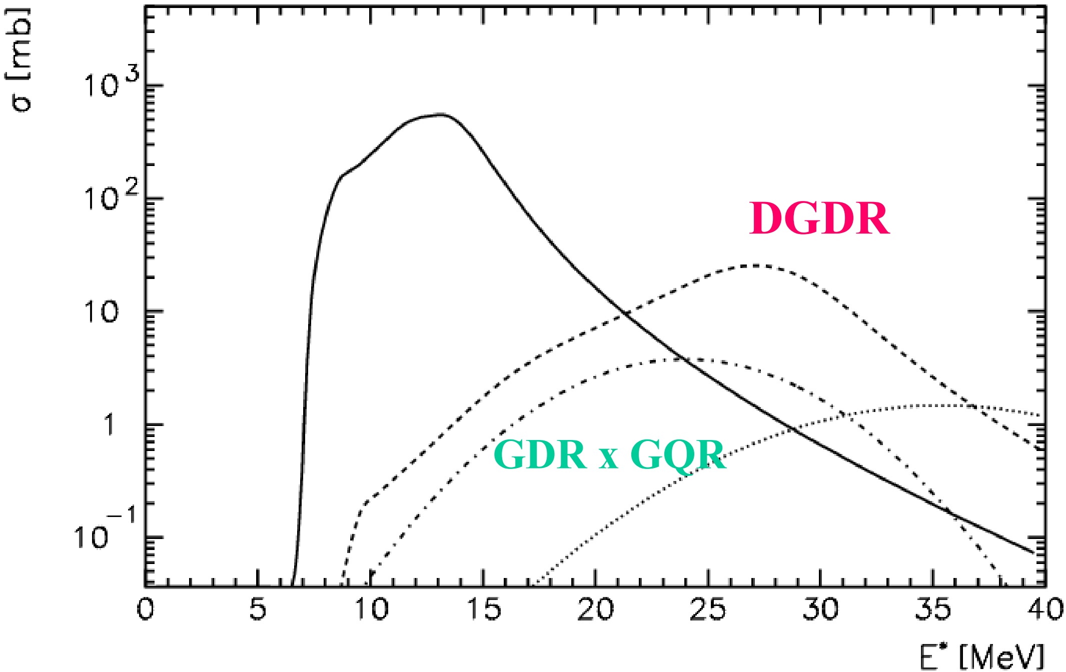
to find explanation

by means of other effects

‘Mixed’ – Phonon Contributions

Lanza, Volpe, Chomaz et al.



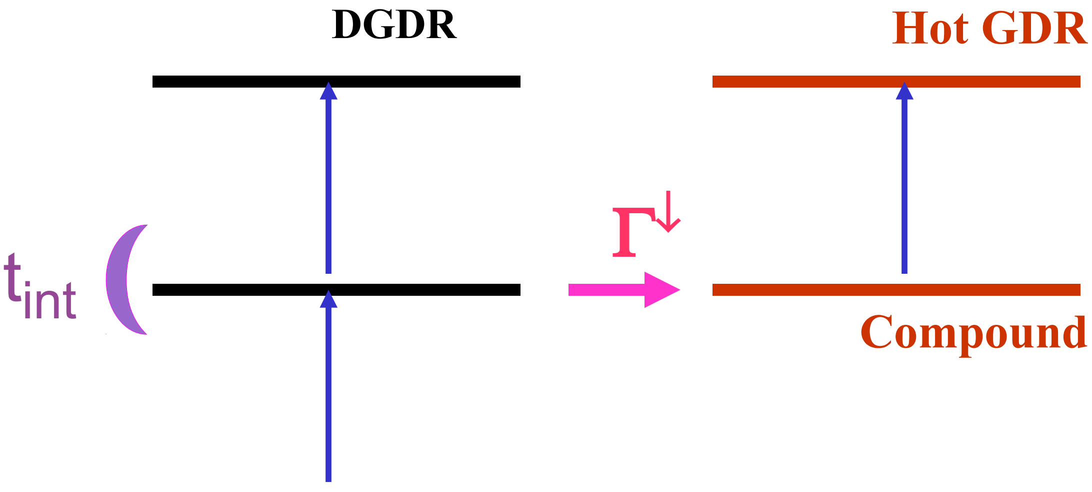


contributions from mixed-phonon states typically on a 10% level

in the following, tentatively subtracted

II. Dynamical Effects

See papers:
B. Carlsson et al.,
Gu and Weidenmueller

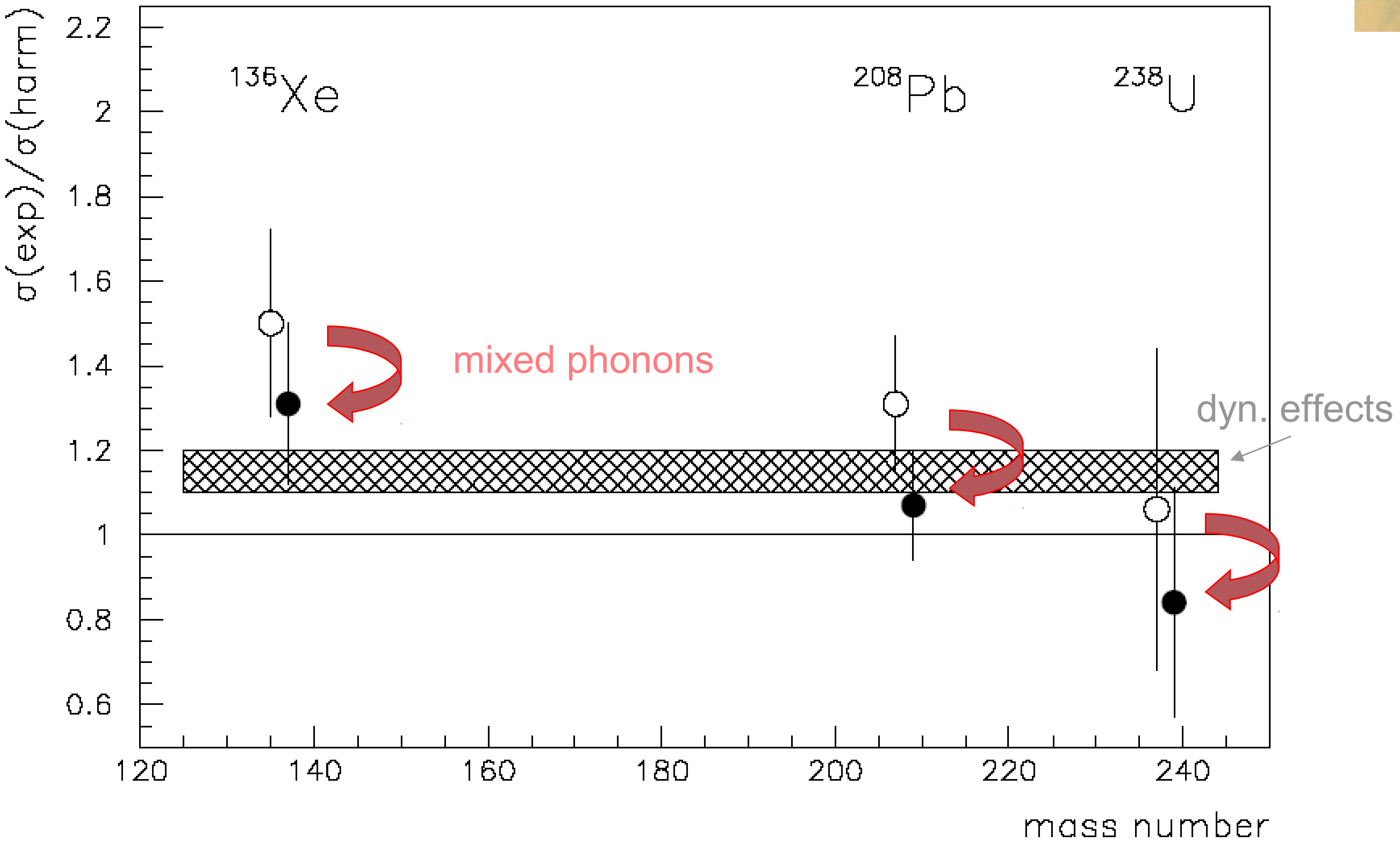


$\hbar / \Gamma^{\downarrow} \sim 10^{-21}$ s

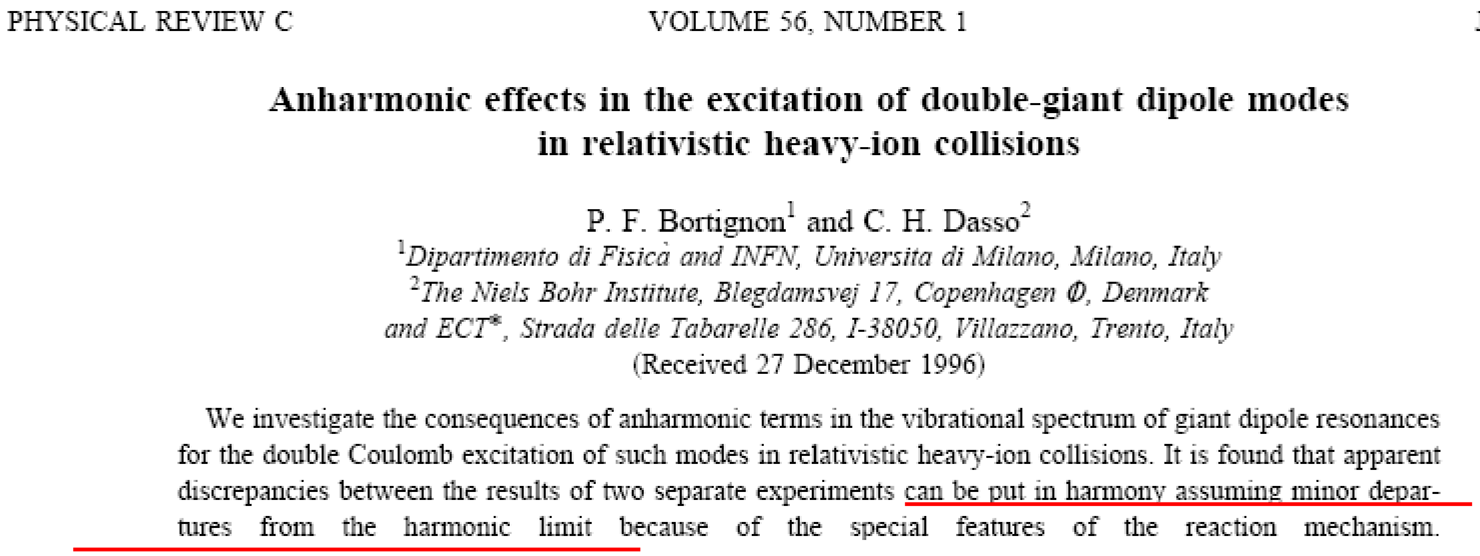
$t_{int} \sim 10^{-22}$ s

~ 10 %

should have a much more significant effect at lower beam velocities

σ(exp)/σ(harm)
2.2
2
1.8
1.6
1.4
1.2
1
0.8
0.6
120
140
160
180
200
220
240
mass number
^{136}Xe
^{208}Pb
^{238}U
mixed phonons
dyn. effects

P.F. Bortignon and C.H. Dasso, Phys. Rev. C **56**, 574 (1997).



PHYSICAL REVIEW C VOLUME 56, NUMBER 1 JULY 1997

Anharmonic effects in the excitation of double-giant dipole modes in relativistic heavy-ion collisions

P. F. Bortignon[1] and C. H. Dasso[2]
[1]*Dipartimento di Fisicà and INFN, Universita di Milano, Milano, Italy*
[2]*The Niels Bohr Institute, Blegdamsvej 17, Copenhagen Ø, Denmark*
*and ECT**, *Strada delle Tabarelle 286, I-38050, Villazzano, Trento, Italy*

(Received 27 December 1996)

We investigate the consequences of anharmonic terms in the vibrational spectrum of giant dipole resonances for the double Coulomb excitation of such modes in relativistic heavy-ion collisions. It is found that apparent discrepancies between the results of two separate experiments can be put in harmony assuming minor departures from the harmonic limit because of the special features of the reaction mechanism.

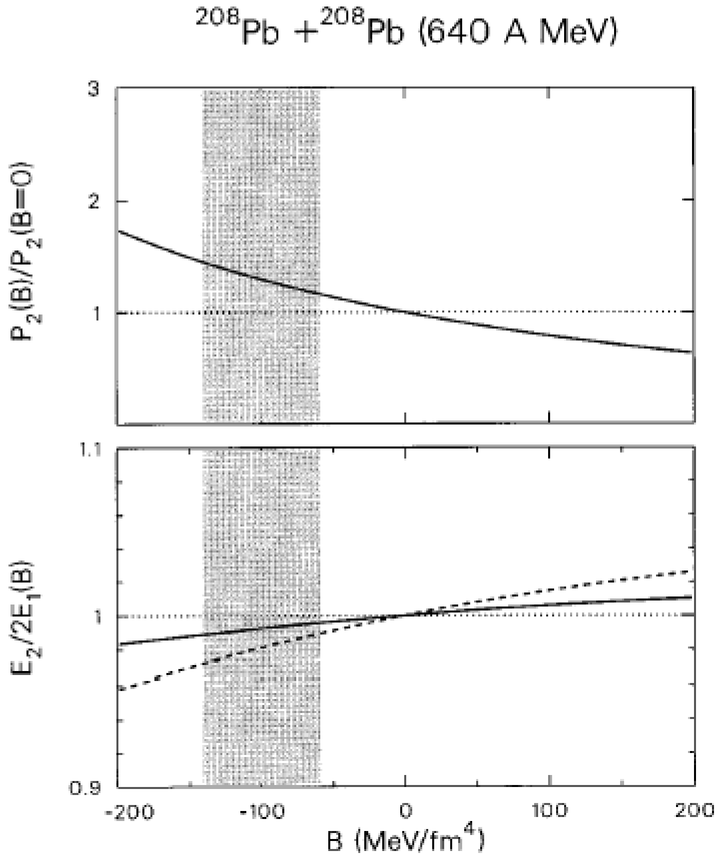


FIG. 1. Calculations for the reaction ^{208}Pb+^{208}Pb at a bombarding energy of 640A MeV. Top: Probability for the excitation of the second $\lambda=1$ state in lead as a function of the anharmonicity parameter B. The values are normalized to the harmonic case ($B=0$). Bottom: Ratio between the energy of the ''two-phonon'' state and twice the energy of the ''one-phonon'' state in lead as a function of the anharmonicity parameter B. The full-drawn and dashed curves correspond, respectively, to the components with angular momentum $L=2$ and 0. Unperturbed values for the mode are $\hbar\omega_0=13.4$ MeV and mass parameter $d=1.2$ MeV$\hbar^2$. The calculations are for an impact parameter $b=30$ fm. The shaded area indicates the range of values of B that leads to enhancements of about 30%.

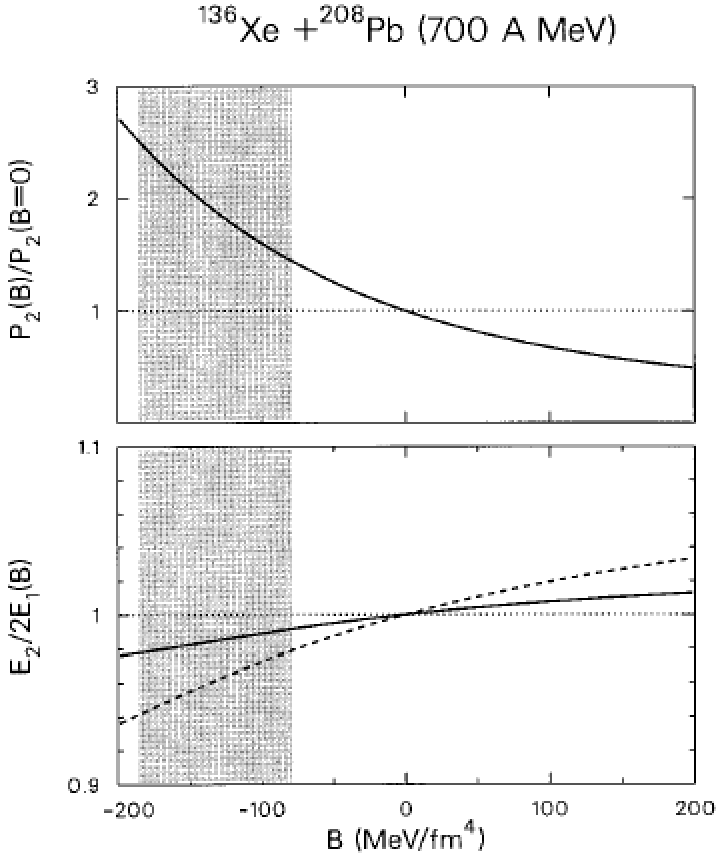


FIG. 2. Analogous to Fig. 1 but for the reaction ^{136}Xe+^{208}Pb at a bombarding energy of 700A MeV. Unperturbed values for the mode in xenon are $\hbar\omega_0=15.2$ MeV and mass parameter $d=0.8$ MeV $\hbar^2$. The shaded area in this case has been obtained from that in Fig. 1 exploiting the mass-scaling law discussed in the text.

PHYSICAL REVIEW C, VOLUME 64, 064605

Anharmonicities of giant dipole excitations

D. T. de Paula,[1] T. Aumann,[2] L. F. Canto,[1] B. V. Carlson,[3] H. Emling,[2] and M. S. Hussein[4]
[1]*Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postal 68528, 21945-970 Rio de Janeiro, Brazil*
[2]*Gesellschaft für Schwerionenforschung (GSI), Planckstrasse 1, D-64291 Darmstadt, Germany*
[3]*Departmento de Física, Instituto Tecnológico de Aeronáutica CTA, 12228-900 São José dos Campos, São Paulo, Brazil*
[4]*Instituto de Física, Universidade de São Paulo, Caixa Postal 66318, 05389-970 São Paulo, Brazil*

(Received 26 July 2001; published 16 November 2001)

$$H=H_0+F(x,y,z;t), \tag{1}$$

where H_0 is the anharmonic oscillator describing the intrinsic motion of the projectile,

$$H_0=\frac{1}{2D}(p_x^2+p_y^2+p_z^2)+\frac{C}{2}(x^2+y^2+z^2)$$
$$+\frac{B}{4}(x^2+y^2+z^2)^2, \tag{2}$$

$$H_0=\hbar\omega\left[\frac{1}{2}(\pi^2+\rho^2)+\beta\rho^4\right]. \tag{4}$$

In the above, the commonly used variable transformations

$$\rho_i=\sqrt{\frac{D\omega}{\hbar}}r_i; \quad \pi_i=\frac{p_i}{\sqrt{D\hbar\omega}}, \tag{5}$$

have been made, where r_i and p_i stand for the components of the position and momentum operators, respectively. The oscillator frequency is given by

$$\hbar\omega=\hbar\sqrt{\frac{C}{D}}, \tag{6}$$

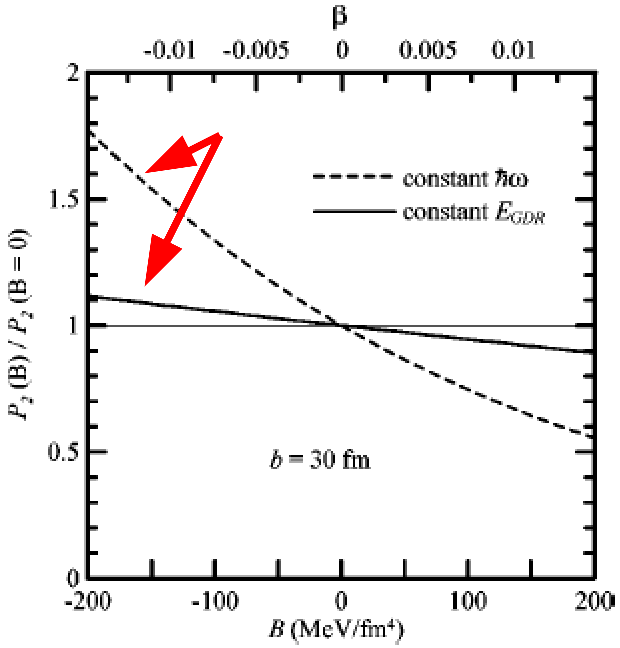


FIG. 2. The enhancement in the excitation of the DGDR in the collision of ^{208}Pb+^{208}Pb at 640*A* MeV for the impact parameter *b* = 30 fm. The solid line represents the results of the present calculation while the dashed line corresponds to a constant oscillator frequency.

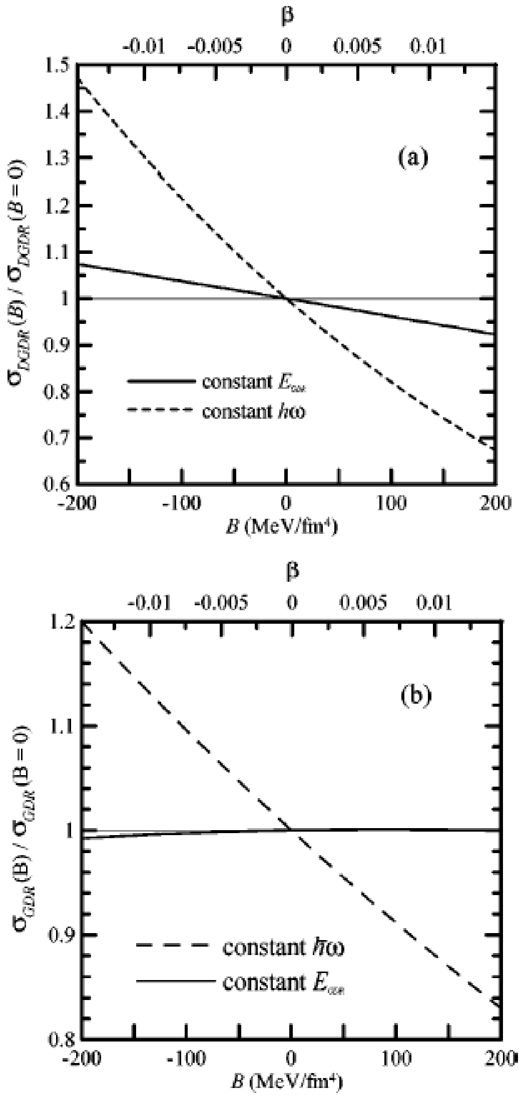


FIG. 3. Enhancement factor of the (a) DGDR and (b) GDR cross sections in the collision of ^{208}Pb+^{208}Pb at 640*A* MeV. The dashed lines correspond to the results obtained with fixed oscillator frequency, while the full lines correspond to a fixed E_{GDR}.

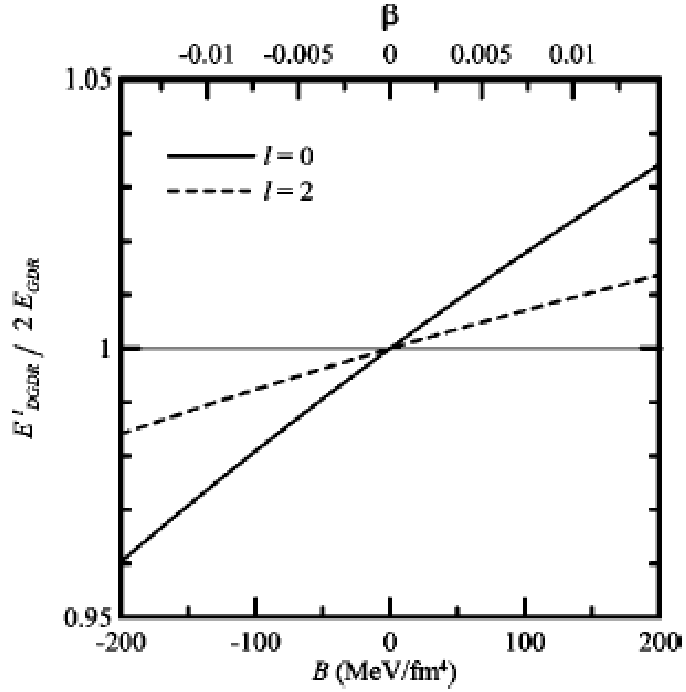


FIG. 1. The ratio $E^{l}_{DGDR}/(2\,E_{GDR})$ vs the anharmonicity para eter B, for ^{208}Pb. The solid line is for $l=2$ and the dashed line $l=0$. The reduced mass for the oscillation of protons against n trons is used for the mass parameter D.

and the dimensionless strength β is related to B as

$$B=\left[\frac{4(\hbar\omega)^3 D^2}{\hbar^4}\right]\beta.$$

$$E_{GDR}(\beta)=\hbar\omega(1+5\beta),$$

$$E^{l=0}_{DGDR}(\beta)=2\hbar\omega(1+7.5\beta),$$

$$E^{l=2}_{DGDR}(\beta)=2\hbar\omega(1+6\beta).$$

$$\langle GDR\|E1\|GS\rangle=e\left(\frac{S_1}{\hbar\omega}\right)^{1/2}(1-2.5\,\beta),$$

$$\langle DGDR,l=0\|E1\|GDR\rangle=e\left(\frac{S_1}{\hbar\omega}\right)^{1/2}\sqrt{\frac{2}{3}}(1-5\,\beta),$$

$$\langle DGDR,l=2\|E1\|GDR\rangle=e\left(\frac{S_1}{\hbar\omega}\right)^{1/2}\sqrt{\frac{10}{3}}(1-3.5\beta),$$

$$S_1=\frac{9}{4\pi}\frac{\hbar^2}{2m_0}\frac{NZ}{A}.$$

In order to maintain $E_{GDR}(\beta)$ at the experimental value, namely, $E_{GDR}(\beta)=E^{\exp}_{GDR}$ (13.4 MeV, in the present case), the oscillator frequency must be renormalized as β is changed. The resulting renormalized frequency, from Eq. (8), is

$$\hbar\omega(\beta)=\frac{E^{\exp}_{GDR}}{(1+5\,\beta)}. \qquad (11)$$

Triple – Phonon GDR ?

relativistic Coulomb-Fission of ^{238}U

simple-minded argument:

Multi-phonon states are located at increasing excitation energy

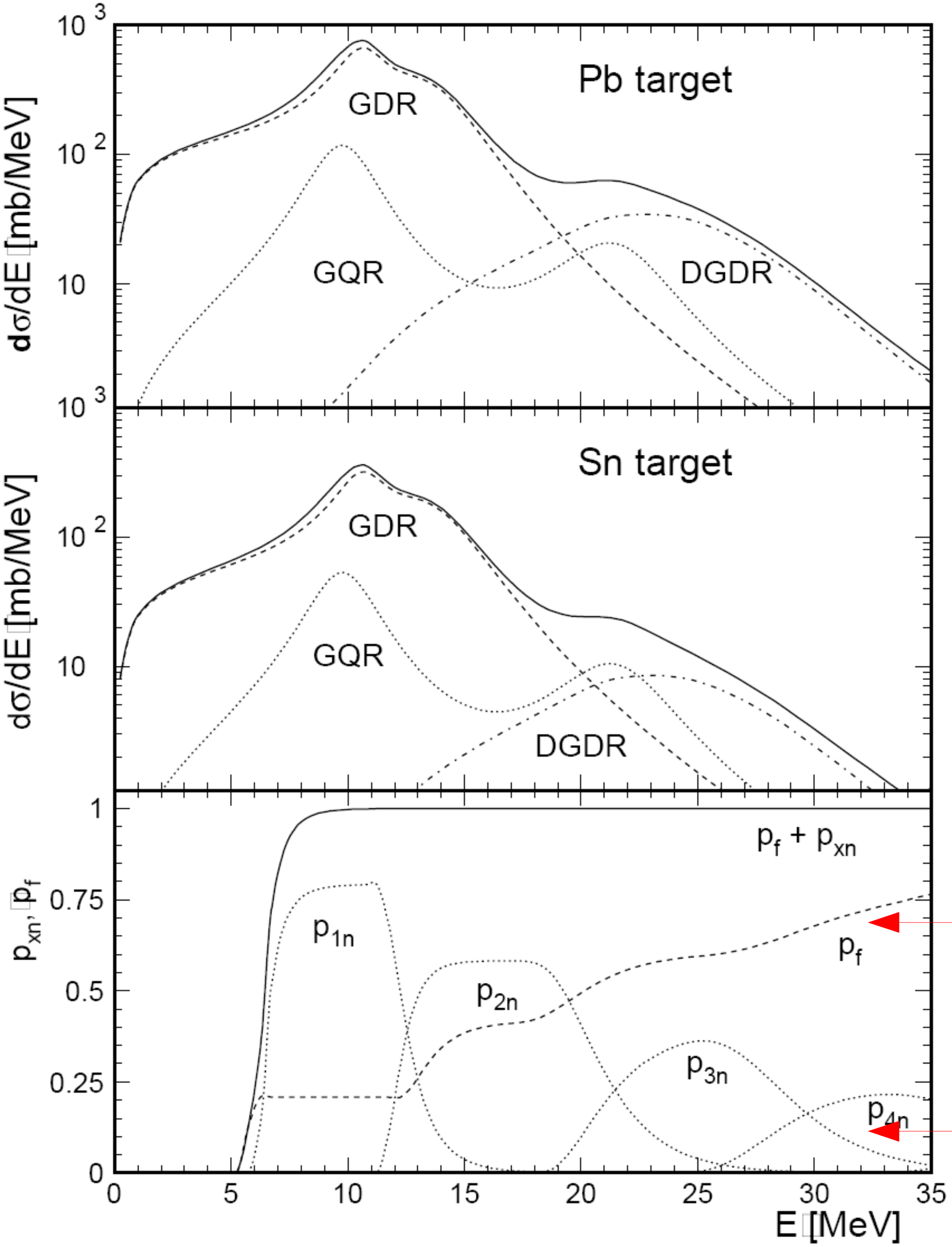
+

Fission probability increases steeply with excitation energy

↓

Higher-phonon states appear enriched in fission channel

(relative to neutron evaporation channel)



Coulomb
cross section

fission
probability p_f

neutron decay
p_{xn}

Evidence for multi-phonon giant resonances in electromagnetic fission of ^{238}U

S. Ilievski,[1,2] T. Aumann,[2] K. Boretzky,[1,3], Th.W. Elze,[1] H. Emling,[2] A. Grünschloß,[1] J. Holeczek,[4]
R. Holzmann,[2] C. Kozhuharov,[2] J.V. Kratz,[3] R. Kulessa,[4] A. Leistenschneider,[1] E. Lubkiewicz,[4]
T. Ohtsuki,[3,5] P. Reiter,[6] H. Simon,[7] K. Stelzer,[1] J. Stroth,[2] K. Sümmerer,[2] E. Wajda,[4] and W. Waluś[4]
(LAND Collaboration)

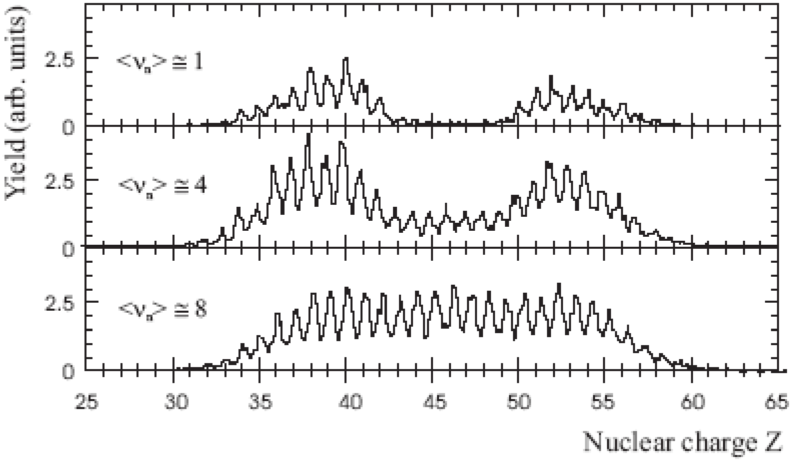
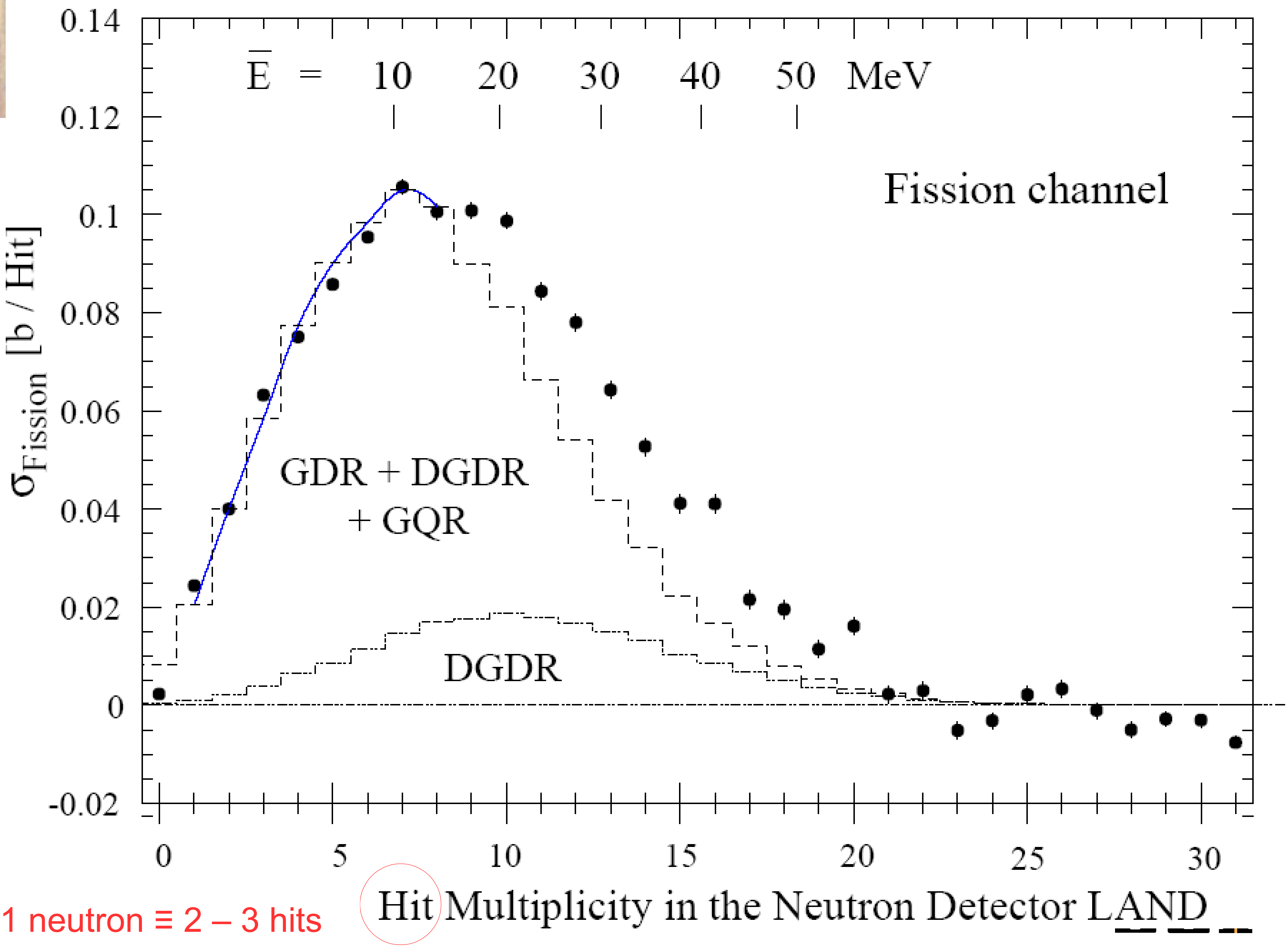


FIG. 1: Elemental distribution of fission fragments of ^{238}U projectiles (500 MeV/nucleon) in a lead target in coincidence with neutrons of a mean multiplicity • •$_n$ • as indicated. The sum of the nuclear charges of the two fission fragments is required to equal 92.

<u>Experiment:</u>
Land setup equipped with fission-fragment detectors

measure neutron multiplicity in coincidence to fission fragments

<u>use neutron multiplicity as a measure for excitation energy</u>
(from literature)



1 neutron ≡ 2 – 3 hits

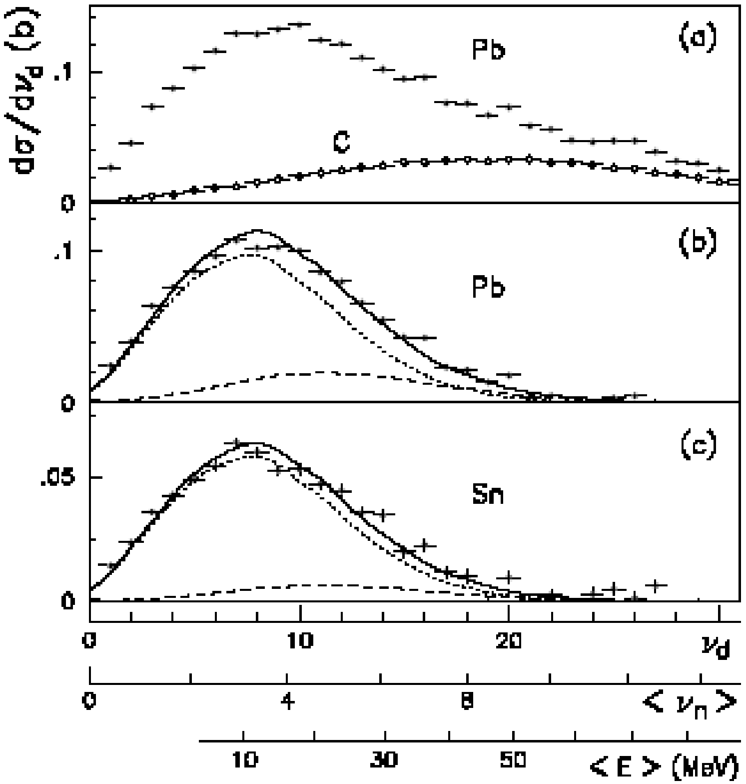


FIG. 2: Fission cross sections •••••$_d$ for ^{238}U (500 MeV/nucleon). The axis labels refer to detector multiplicity •$_d$, associated mean neutron multiplicity • •$_n$ • , and mean excitation energy • • • .
(a) Measured values for Pb and C targets.
(b) Measured electromagnetic fission cross sections for Pb target and calculated values (solid line). Calculated cross sections for the sum of single-phonon (multi-phonon) components is shown as dotted (dashed) curve.
(c) same as (b) but for the Sn target.

TABLE II: Calculated partial electromagnetic fission cross sections •••^{emf} and their peak energies •$_p$ for single and multi-phonon giant resonances in ^{238}U (500 MeV/nucleon) on Pb and Sn targets.

Resonance	•$_p$(MeV)	•••^{emf} (Pb)	•••^{emf} (Sn)
GDR	13.5	.66	.75
GQR$_{is}$	9.5	.07	.07
GQR$_{iv}$	21.	.06	.07
GDR⊗GDR	23.	.15	.09
GDR⊗GQR$_{is}$	21.	.02	.01
GDR⊗GQR$_{iv}$	32.	.013	.008
GDR⊗GDR⊗GDR	35.5	.023	.006

Summary

Two-phonon giant resonances were observed

- Double-charge exchange reactions: DIAS , DGDR ($\Delta T_z = \pm 2$) [Los Alamos]

- Inelastic heavy-ion scattering : isoscalar DGQR [Orsay, GANIL]

- Relativistic Coulomb breakup: DGDR ($\Delta T_z = 0$) [LAND, GSI]

T. Aumann, P. F. Bortignon, and H. Emling, Ann. Rev. Nucl. Part. Sci. 48, 351 (1998).

- Evidence for triple-phonon GDR

Harmonic Response (within ~ 10%)

Outlook

Physics
with
Rare-Isotope Beams

RIKEN, FRIB, SPIRALII, FAIR , EURISOL .....

Here: future FAIR facilities
emphasis on GR related topics

Preparing for FAIR (Startversion) ~2017/18

RIB -Intensity increase 3-4 orders of magnitude !

RIB at FAIR

External – Target Experiments (R^{3}B)

(T. Aumann)

Storage and Cooler Rings (EXL)

(P. Egelhof)

Electron – Ion collider (ELISe)

(H. Simon - coordinator)

Exotic nuclei and light-ion / electron scattering – shopping list

Experimental method	**Light-ion scattering** **Electron scattering**	relevant observables in Exotic nuclei
elastic scattering **(p,p)** **(e.e)**	nuclear matter distribution charge distribution	(neutron) Halo and Skin
inelastic scattering **(p,p'); $(^4He,^4He')$** **(e.e')**	surface collective states electric giant resonances	new collective modes
charge exchange **(p,n); $(d,^2He)$; $(^3He,t)$**	spin-isospin excitations;	(stellar) weak interaction rates;
transfer reaction **(p,d); $(d,^3He)$; (p,t)**	spectroscopic factors	single-particle structure
quasi-free scattering **(p,2p); (p,np); (p, p ^4He)** **(e,e'p)**	single-particle spectral function; cluster knockout	(inner-shell) single-particle structure nucleon-nucleon (cluster) correlations in-medium

EXL collaboration
see P. Egelhof

Light-Ion scattering in STORAGE RING:

Elastic (p,p) …
Inelastic (p,p'), (α,α') …
Charge exchange: (p,n), (^{3}He,t), (d,^{2}He) …
Quasifree (p,pn), (p,2p), (p, pα) …

- ❖ **Selective Spin-Isospin probes**
- ❖ **Form factor sensitive to transition multipolarity**

Reversed kinematics:

Excitation energy and Form factors from

low-energy/momentum recoils

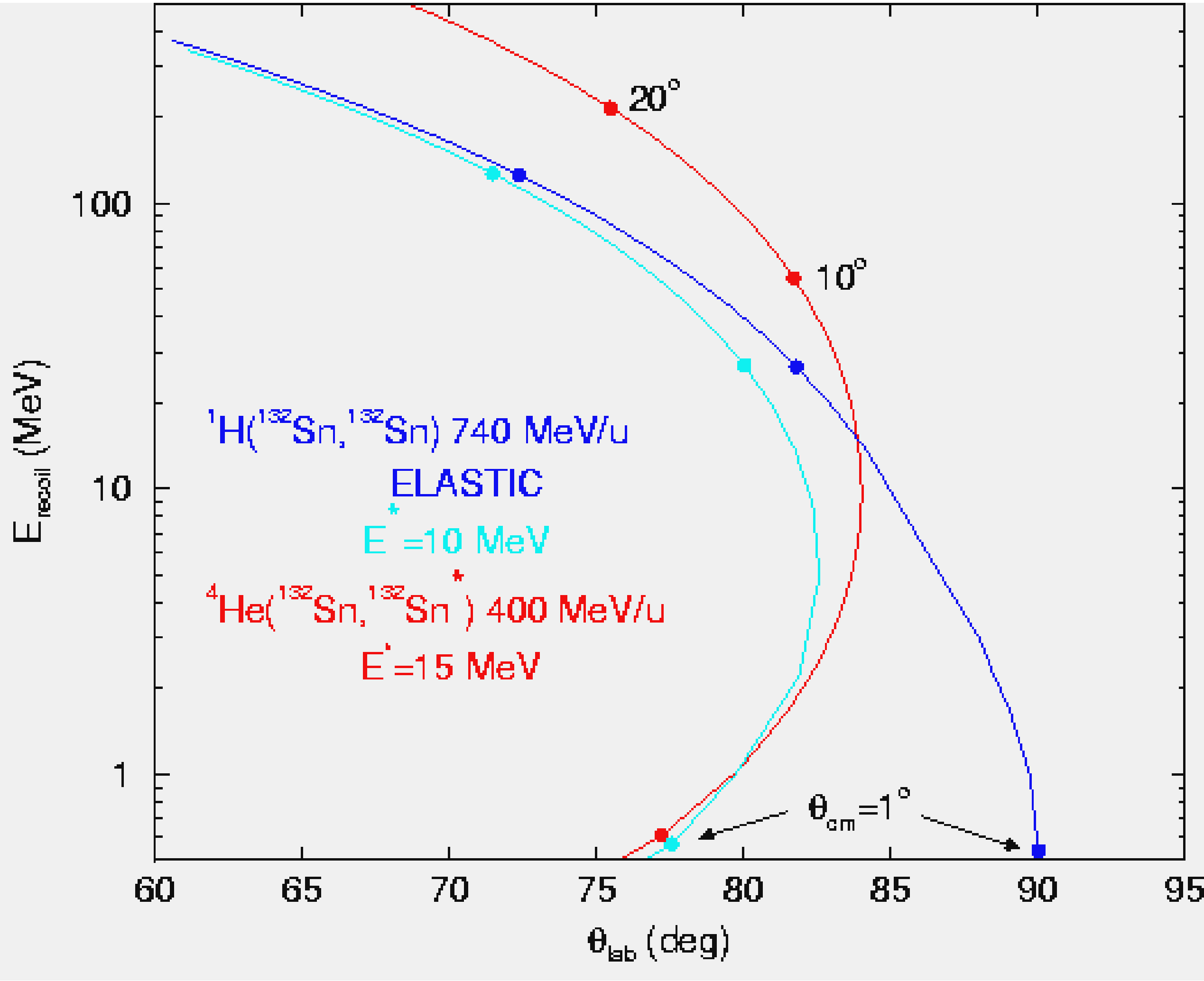
need THIN (gaseous) targets

→ STORAGE RING

regain luminosity by

- ➢ **accummulation/storage**
- ➢ **recirculation (10^6 s^{-1})**

regain resolution by cooling



Feasibility

Target: 10^{14} H atoms cm^{-2} ; beam loss included **740 AMeV** **100 AMeV**

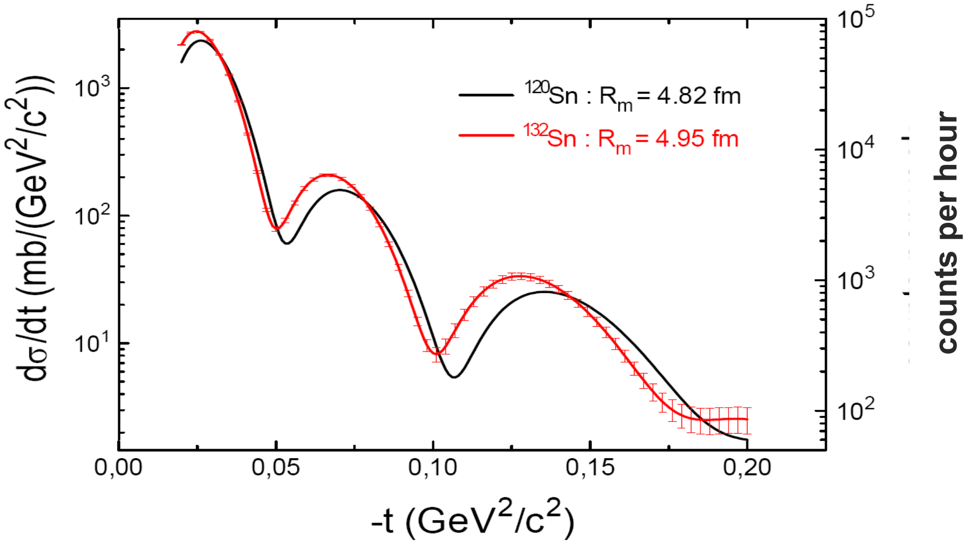
Nucleus	production rate [1/s]	Lifetime including losses in NESR [s]	Luminosity [cm^{-2} s^{-1}]	Luminosity [cm^{-2} s^{-1}]
^{11}Be	2 x 10^{9}	36	> 10^{28}	> 10^{28}
^{46}Ar	6 x 10^{8}	20	> 10^{28}	> 10^{28}
^{52}Ca	4 x 10^{5}	12	2 x 10^{26}	8 x 10^{25}
^{55}Ni	8 x 10^{7}	0.5	5 x 10^{26}	~ 10^{25}
^{56}Ni	1 x 10^{9}	3800	> 10^{28}	> 10^{28}
^{72}Ni	9 x 10^{6}	4.1	1 x 10^{27}	4 x 10^{26}
^{104}Sn	1 x 10^{6}	51	2 x 10^{27}	1 x 10^{27}
^{132}Sn	1 x 10^{8}	93	> 10^{28}	> 10^{28}
^{134} Sn	8 x 10^{5}	2.7	3 x 10^{25}	7 x 10^{24}
^{187}Pb	1 x 10^{7}	34	2 x 10^{28}	5 x 10^{27}

Typical cross sections : 0.1 – 100 mb/sr

Performance

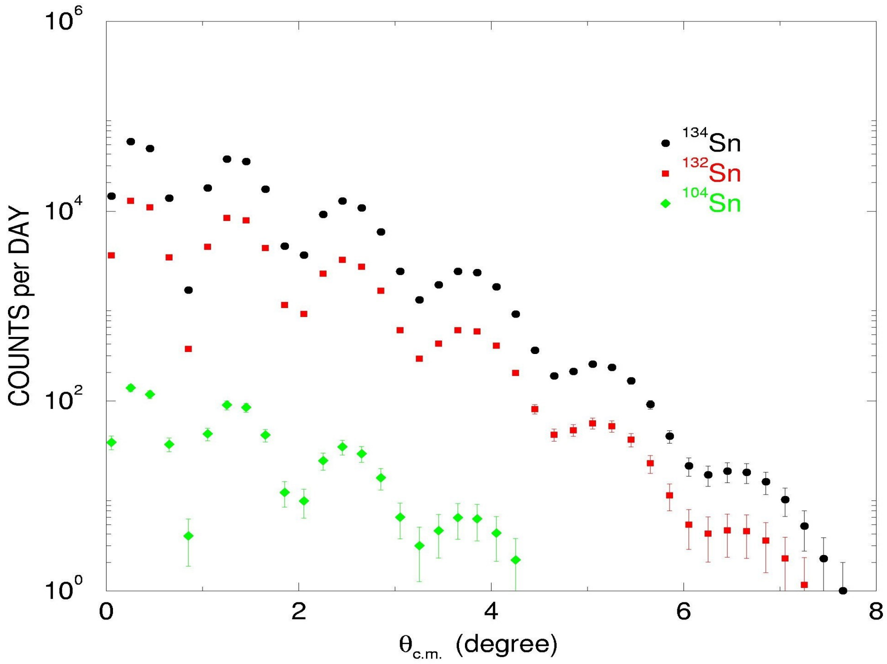
Elastic proton scattering ^{132}Sn

(Matter Distribution)

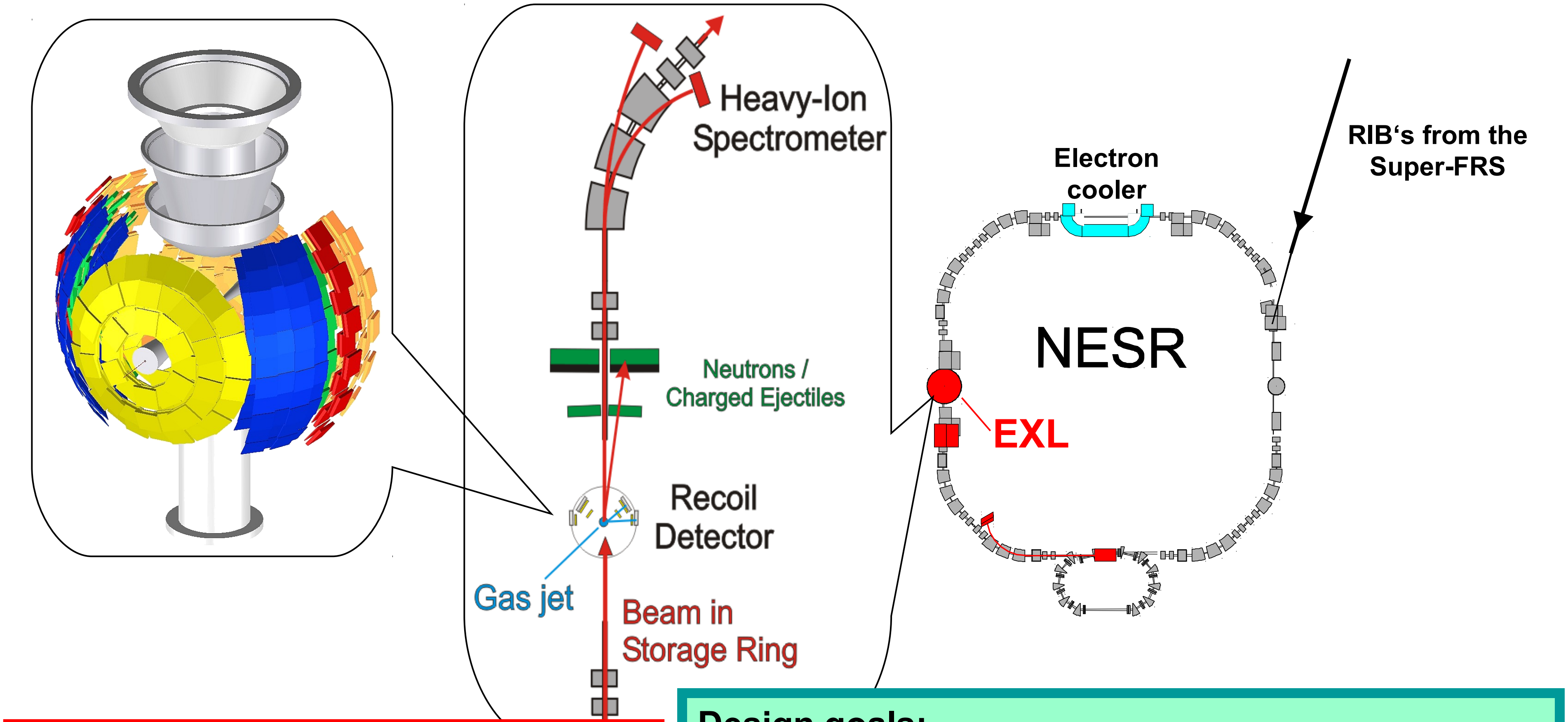


Inelastic alpha scattering on Sn isotopes

(Giant Monopole Resonance)



EXL: EXotic Nuclei Studied in Light-Ion Induced Reactions at the NESR Storage Ring



Detection systems for:

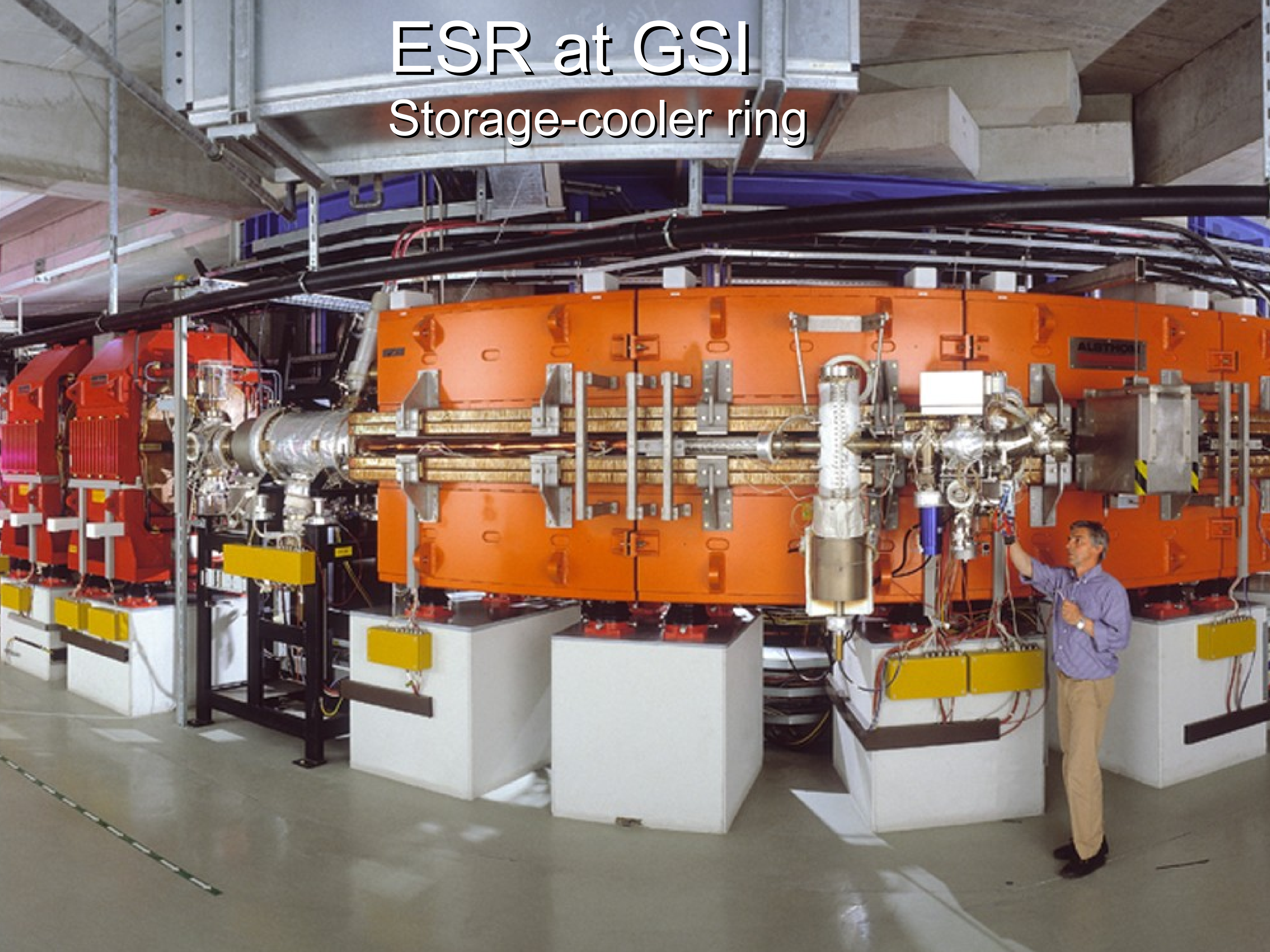
- Target recoils and gammas (p,α,n,γ)
- Forward ejectiles (p,n)
- Beam-like heavy ions

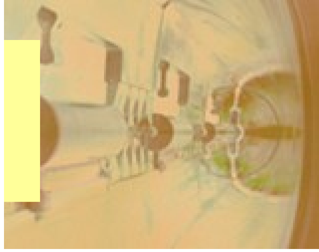
Design goals:

- Universality: applicable to a wide class of reactions
- High energy resolution and high angular resolution
- Large solid angle acceptance
- Specially dedicated for low q measurements with high luminosity ($> 10^{29}$ cm^{-2} s^{-1})

ESR at GSI

Storage-cooler ring





Start up of part of the EXL physics program with ^{56}Ni

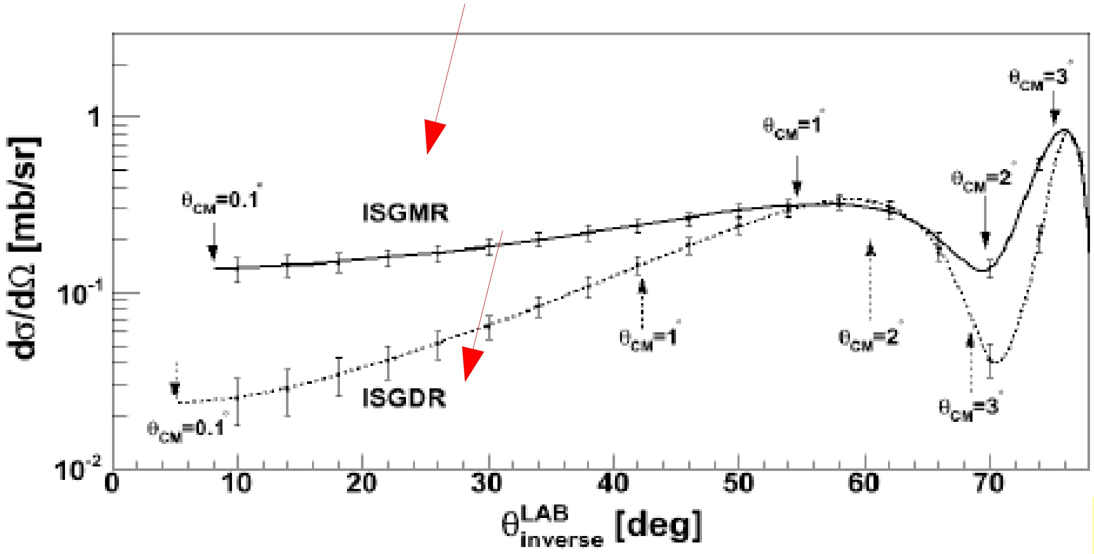
Spokesperson: Nasser Kalantar (KVI), Co-spokesperson: Peter Egelhof (GSI), GSI contact: H. Weick (GSI);

for the EXL collaboration

(p,p), (α,α'), (^{3}He,t) reactions

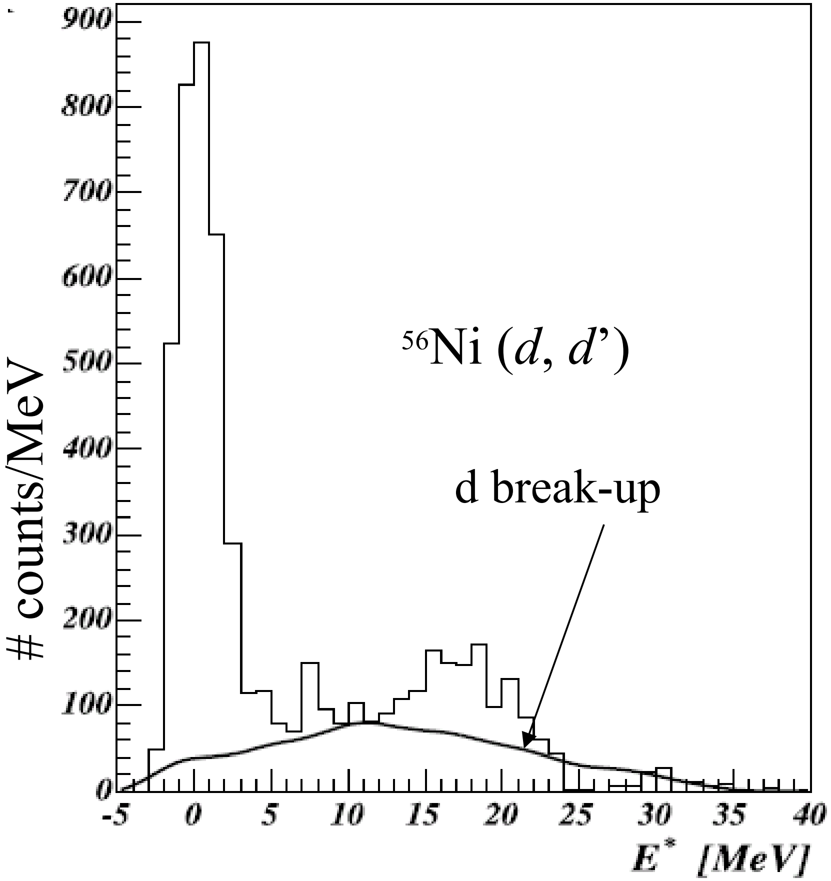
^{56}Ni: doubly magic

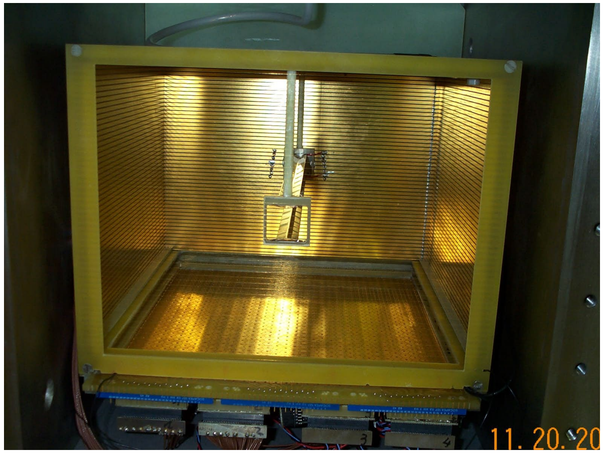
- (p,p) reactions: nuclear matter distr -**skin**
- (α,α`) reactions: giant resonances ISGMR, IVGDR, parameters of the EOS
- (^{3}He,t) reactions: Gamow-Teller matrix elements, important for astrophys.



EXL collaboration see P. Egelhof

Alternative – active target
MAYA @ GANIL





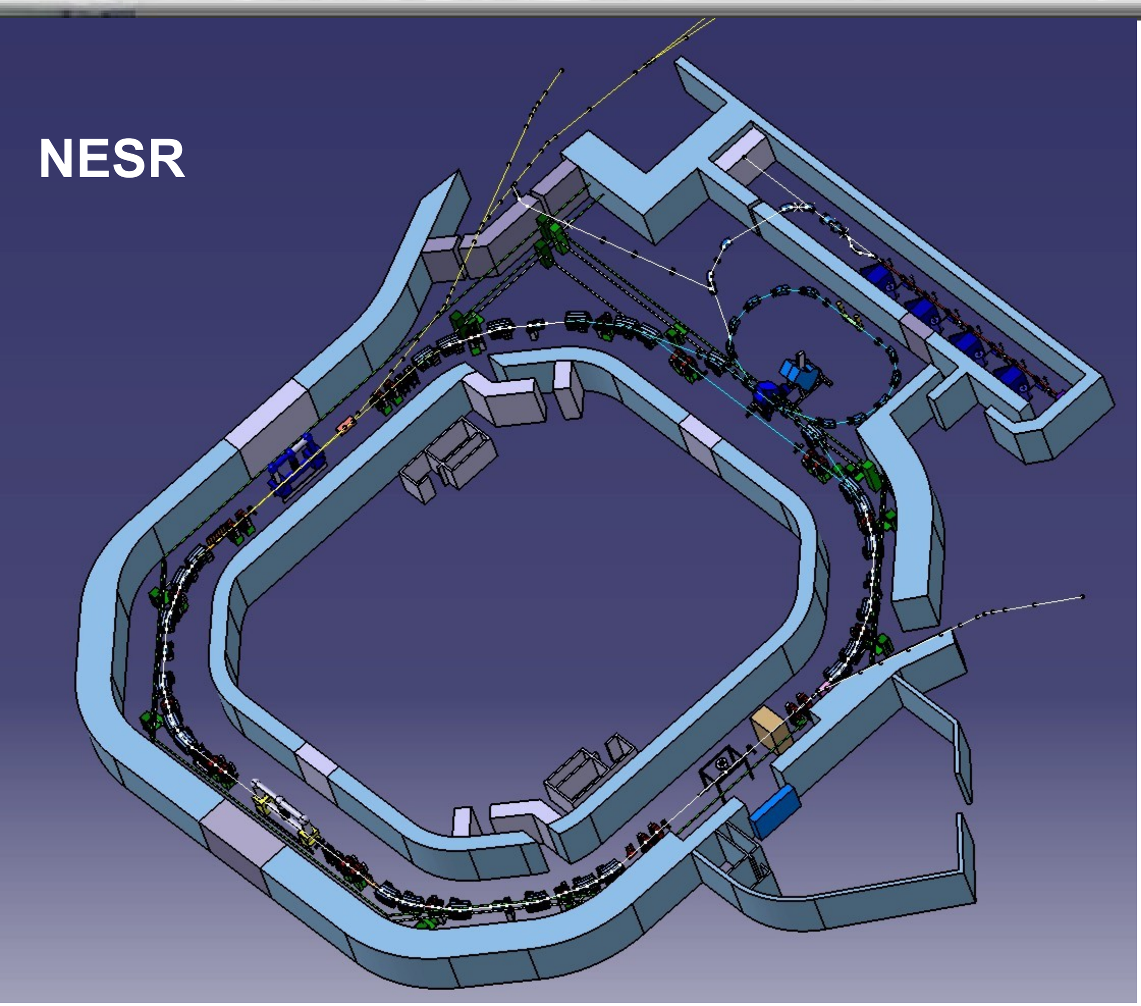
C. Monrozeau *et al*., Phys. Rev. Lett. **100**, 042501 (2008)

The ELISe electron rare isotope scattering experiment

Realization of an RIB electron collider setup

The **ELISe** experiment

Haik Simon • GSI / Darmstadt



- 125-500 MeV electrons
- 200-740 MeV/u RIBs

➔ up to 1.5 GeV CM energy

- spectrometer setup at the interaction zone & detector system in ring arcs

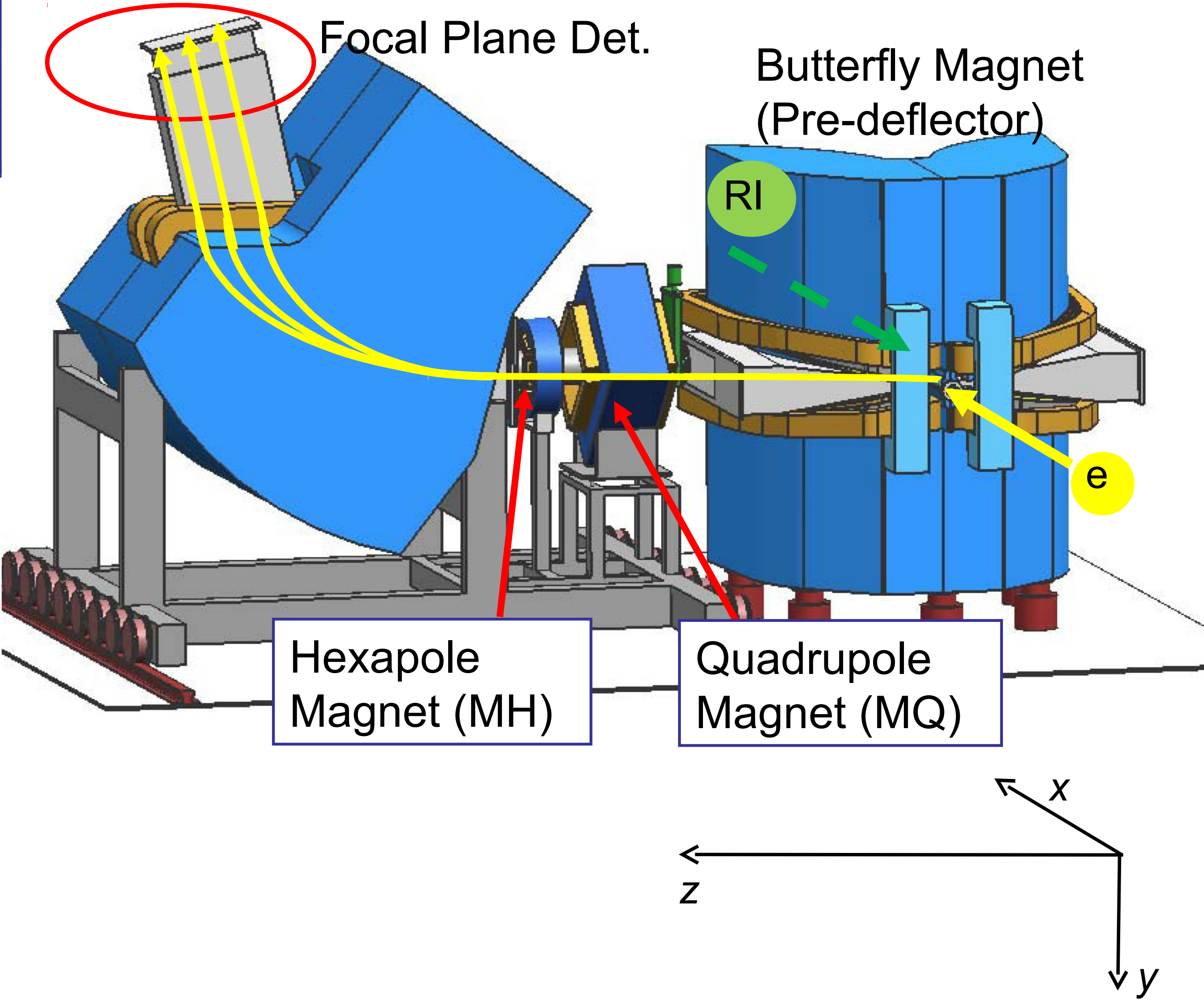
http://www.gsi.de/fair/reports/btr.html

AIC option:

- 30 MeV antiprotons

- detector system in ring arcs
- schottky probes

High Resolution Large Acceptance Spectrometer



Focal Plane Det.

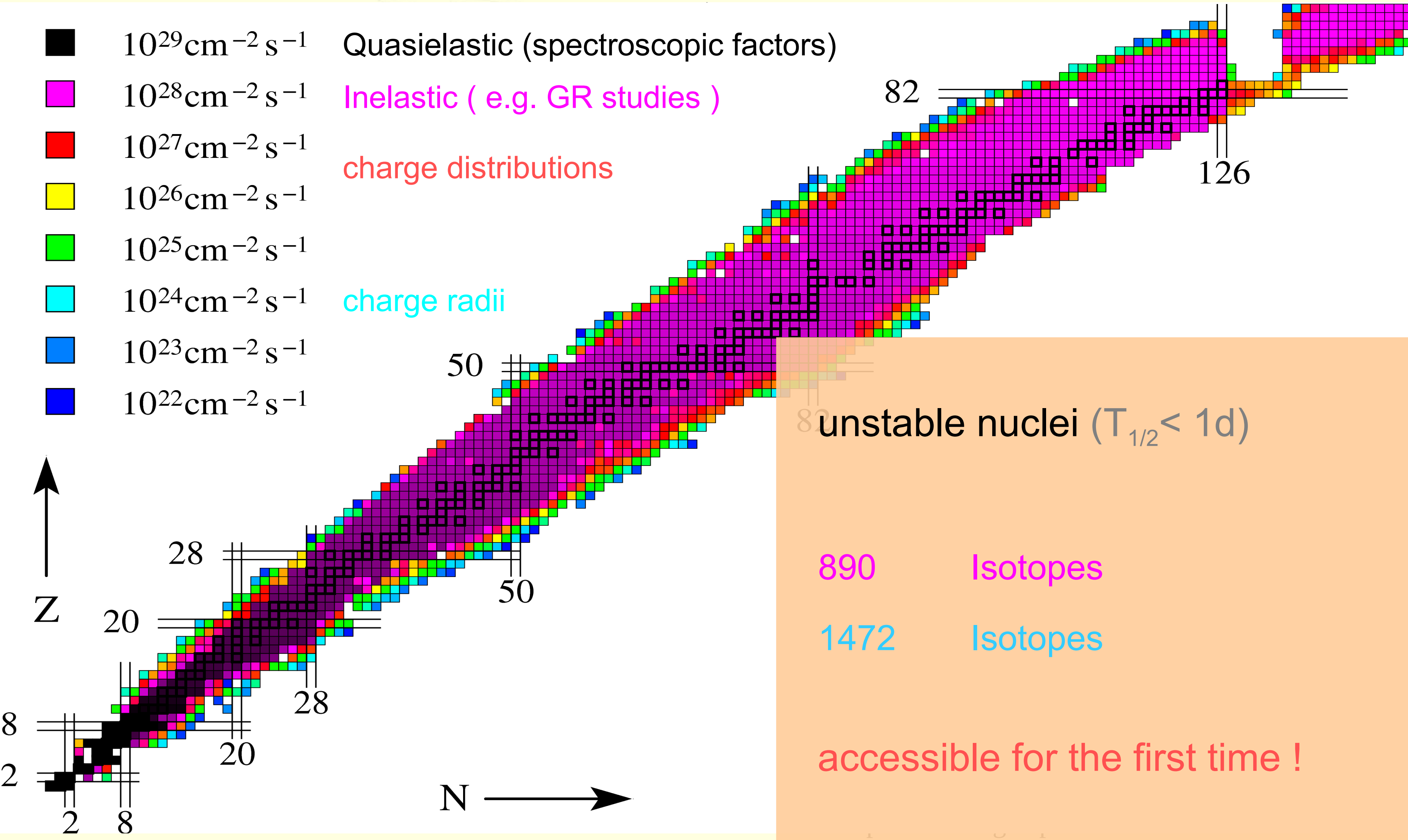
Butterfly Magnet (Pre-deflector)

Vertical Dipole Magnet (VM)

Hexapole Magnet (MH)

Quadrupole Magnet (MQ)

Expected Luminosities



■ $10^{29}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ Quasielastic (spectroscopic factors)
🟪 $10^{28}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ Inelastic (e.g. GR studies)
🟥 $10^{27}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ charge distributions
🟨 $10^{26}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
🟩 $10^{25}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
🟦 $10^{24}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ charge radii
🟦 $10^{23}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
🟦 $10^{22}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$

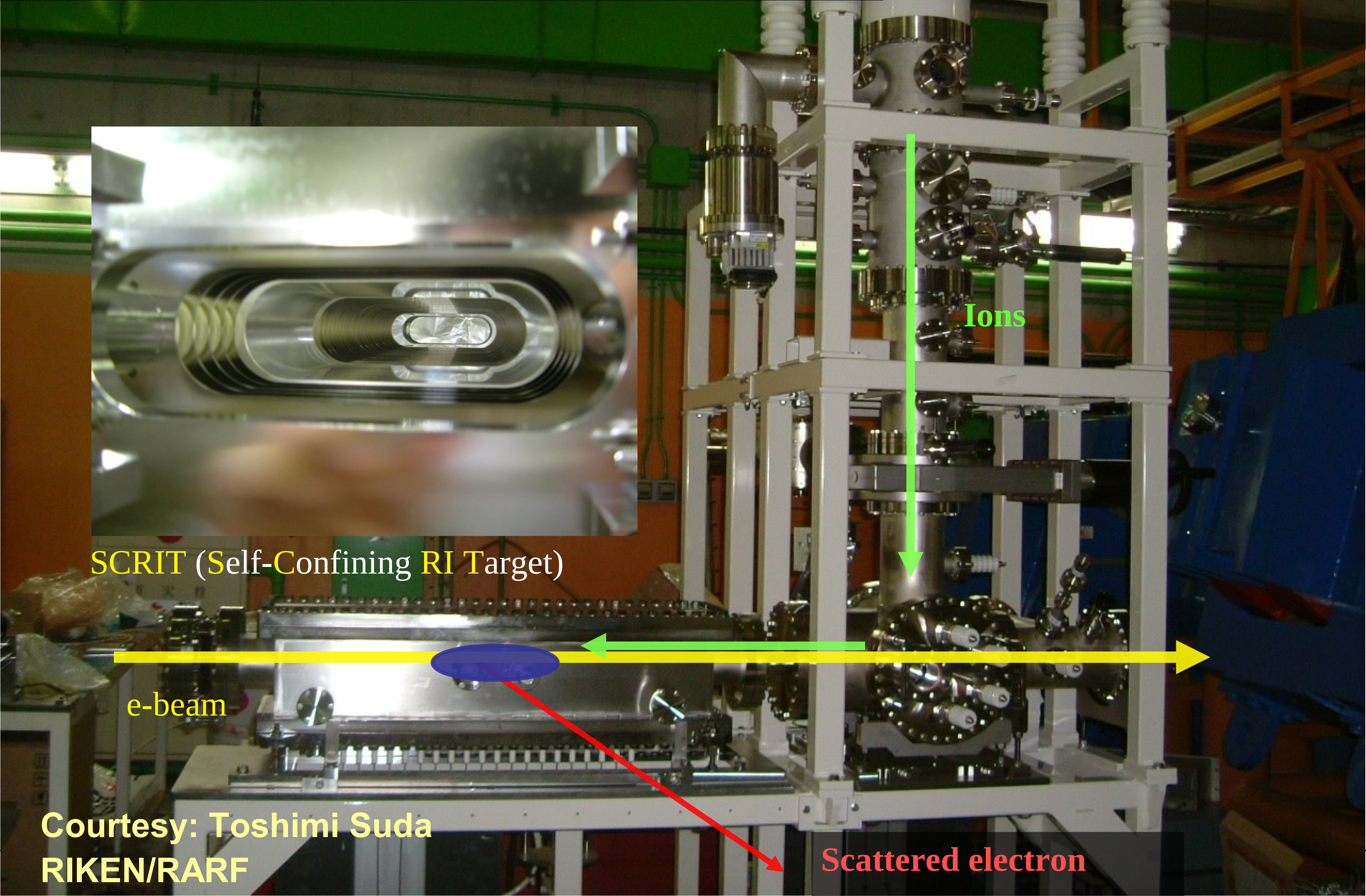
unstable nuclei ($T_{1/2}$< 1d)

890	Isotopes
1472	Isotopes

accessible for the first time !

Competing project: SCRIT for RARF

Test setup @ KSR Kyoto Univ. 100 MeV/100mA



Courtesy: Toshimi Suda
RIKEN/RARF

Bright future -
– a lot to do