Low-momentum transfer measurements with the ACTAR TPC active target

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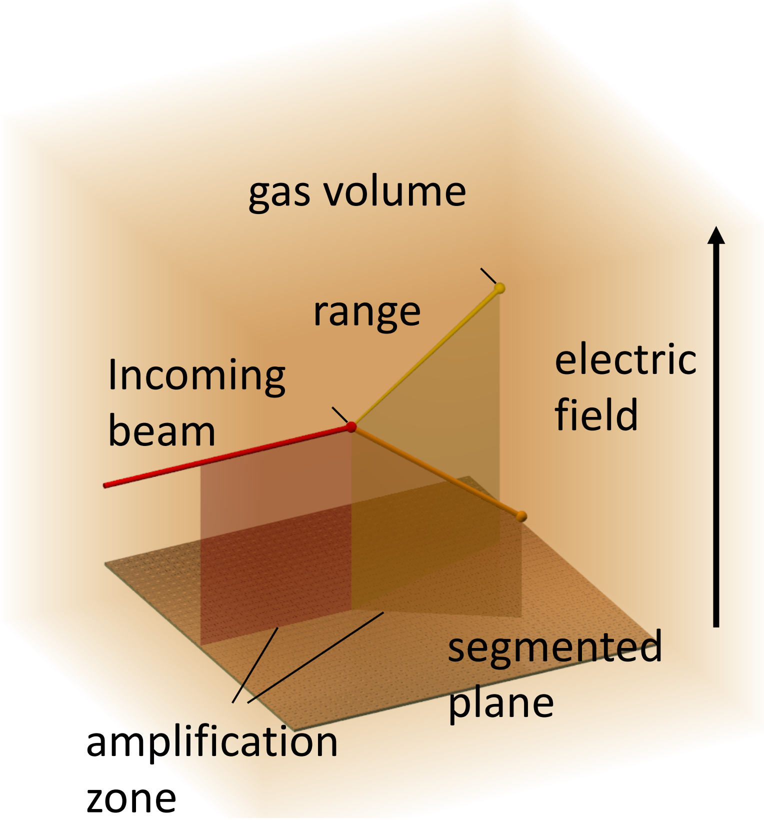
Active targets

Time-Projection Chamber (TPC)
+ gas is the target

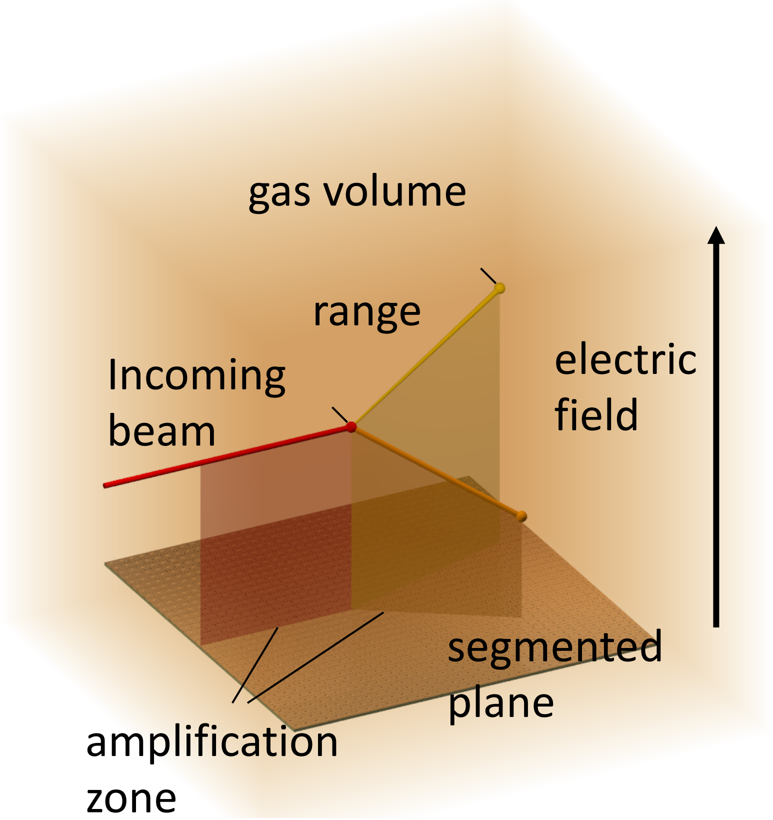
- Electrons produced by ionization drift to an amplification zone
- Signals collected on a segmented "pad" plane ⇒ 2d-image of the track
- 3rd dimension from the drift time of the electrons
- Information:
  - angles
  - energy (from range or charge)
  - particle identification



Active targets

Advantages

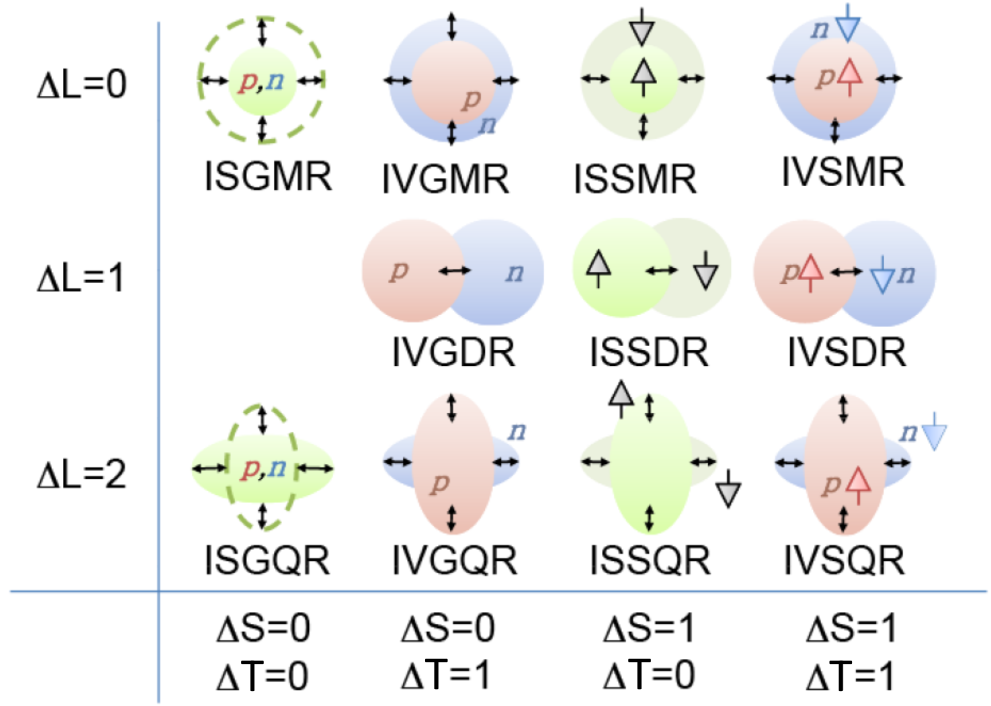
- Large target thickness
  → high luminosity
- Efficient:
  - 4π geometry
  - Low thresholds
- Extremely versatile
  - different gases and pressures
  - variable shape
  - auxiliary detectors

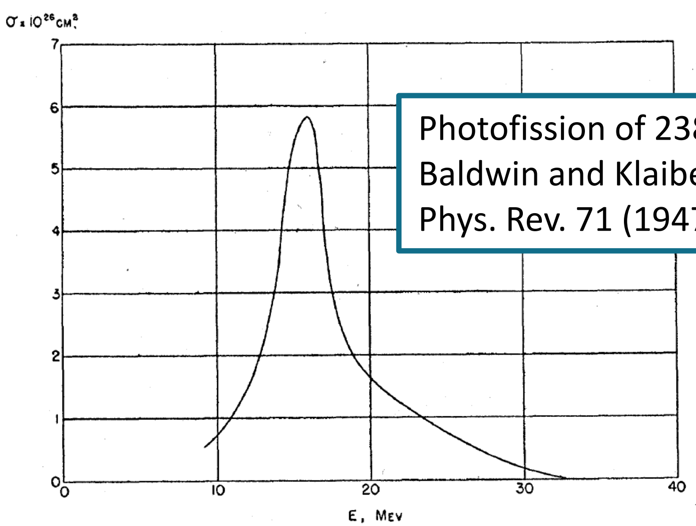


Collective excitations: Giant resonances

- Giant Resonances (GR) are nuclear collective excited states
- Many if not all nucleons are involved in the excitation
- They involve spin (S), isospin (T) and angular momentum (L)

- IVGDR known since 1947





Photofission of 238U
Baldwin and Klaiber
Phys. Rev. 71 (1947) 3

M. N. Harakeh and A. van der Woude,
Giant Resonances: Fundamental High-Frequency Modes of Nuclear Excitation
Oxford University Press

Collective excitations: Giant resonances

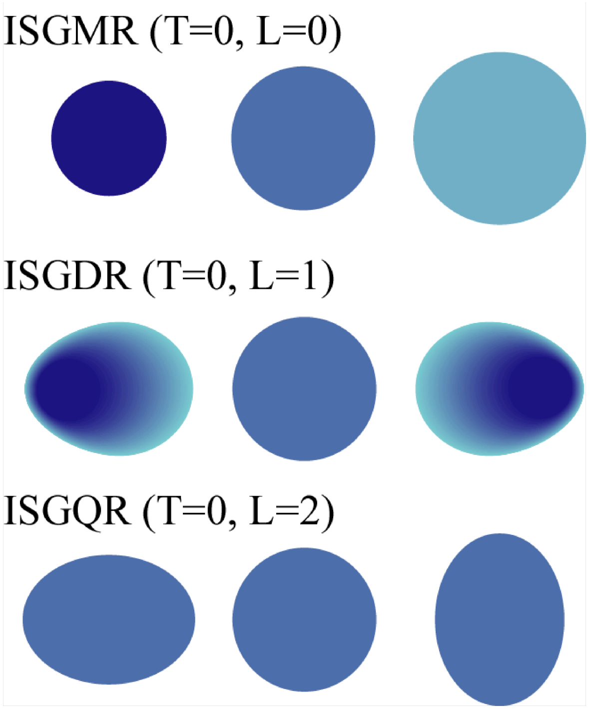
Why so important?

- **Robust test for self-consistent mean-field approaches based on density functionals**
  - GRs: harmonic oscillations, RPA response function derived from TDHF equations
  - GRs constrain the parameters of the functional to the nuclear dynamics
- **Provide information on features of finite nuclei and nuclear matter**
  Effective masses, neutron skin, vortex motions, **incompressibility**

Isoscalar modes

- Isoscalar modes are compression modes
  → tool to study incompressibility of nuclear matter K_∞
  through the nuclear incompressibility K_A

$$E_{ISGMR} = \hbar\sqrt{\frac{K_A}{m\langle r^2\rangle}}$$



K_∞ can be extracted from

- an expansion of K_A:
  $$K_A = K_{vol} + K_{surf}A^{-1/3} + K_{sym}\left(\frac{N-Z}{A}\right) + K_{Coul}\frac{Z^2}{A^{4/3}}$$
  by fitting data and assuming $K_{vol} = \lim_{A\to\infty} K_A = K_\infty$

- RPA calculations that provide K_∞ and E_{ISGMR}

  $K_\infty = 230 \pm 40$ MeV Kahn et al, Phys. Rev. Lett. 109 (2012) 092501

Equation of State

- K_∞ is an ingredient of the nuclear Equation of State (EoS)
- EoS is used to describe
  - heavy-ion collision
  - core-collapse supernovas
  - neutron star and neutron-star mergers
  - black holes…
- Constrained by
  - astrophysical observations
  - properties of nuclei
- Kahn et al, Phys. Rev. Lett. 109 (2012) 092501:
  - Use E_{GMR} vs. <u>derivative</u> of $K(\rho)$ at ρ_c instead of E_{GMR} vs. K_∞
  - **Measure E_{GMR} in nuclei far from stability to study the isospin dependence of $K(\rho)$**

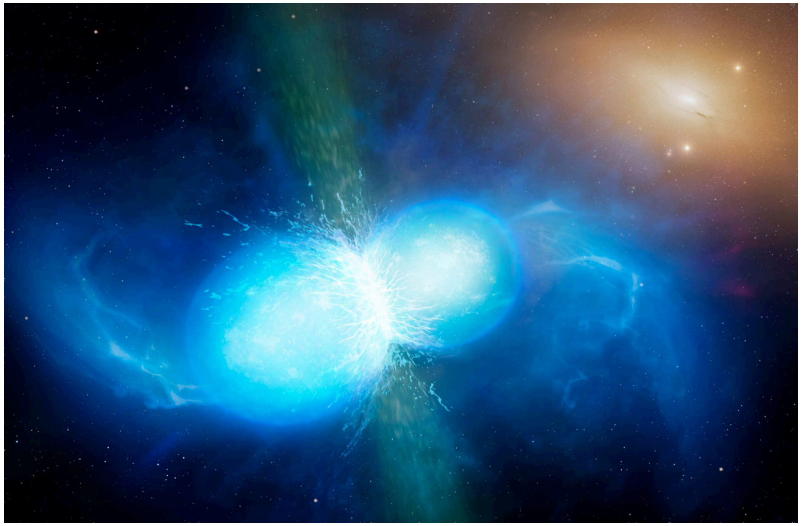
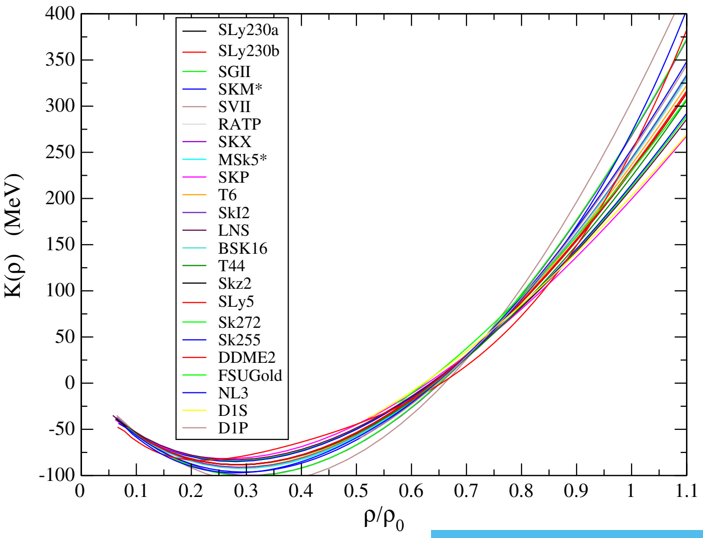


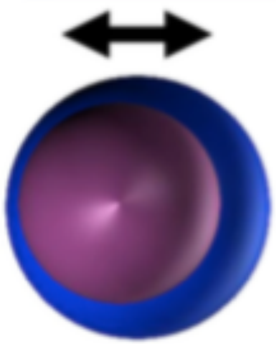
Image credit: Mark Garlick, University of Warwick



Soft modes: PDR

Low-energy dipole strength

- First observation in 1961
  γ rays from neutron capture
  G.A. Bartholomew, Annu. Rev. Nucl. Sci. 11 (1961) 259
- First use of "pygmy resonance" (PDR)
  J.S. Brzosko et al., Can. J. Phys 47 (1969) 2849
- Description as a collective excitation
  Mohan et al., Phys. Rev. C 3 (1971) 1740
  "Three-Fluid Hydrodynamical Model of Nuclei":
  Neutron excess oscillates against the N=Z core



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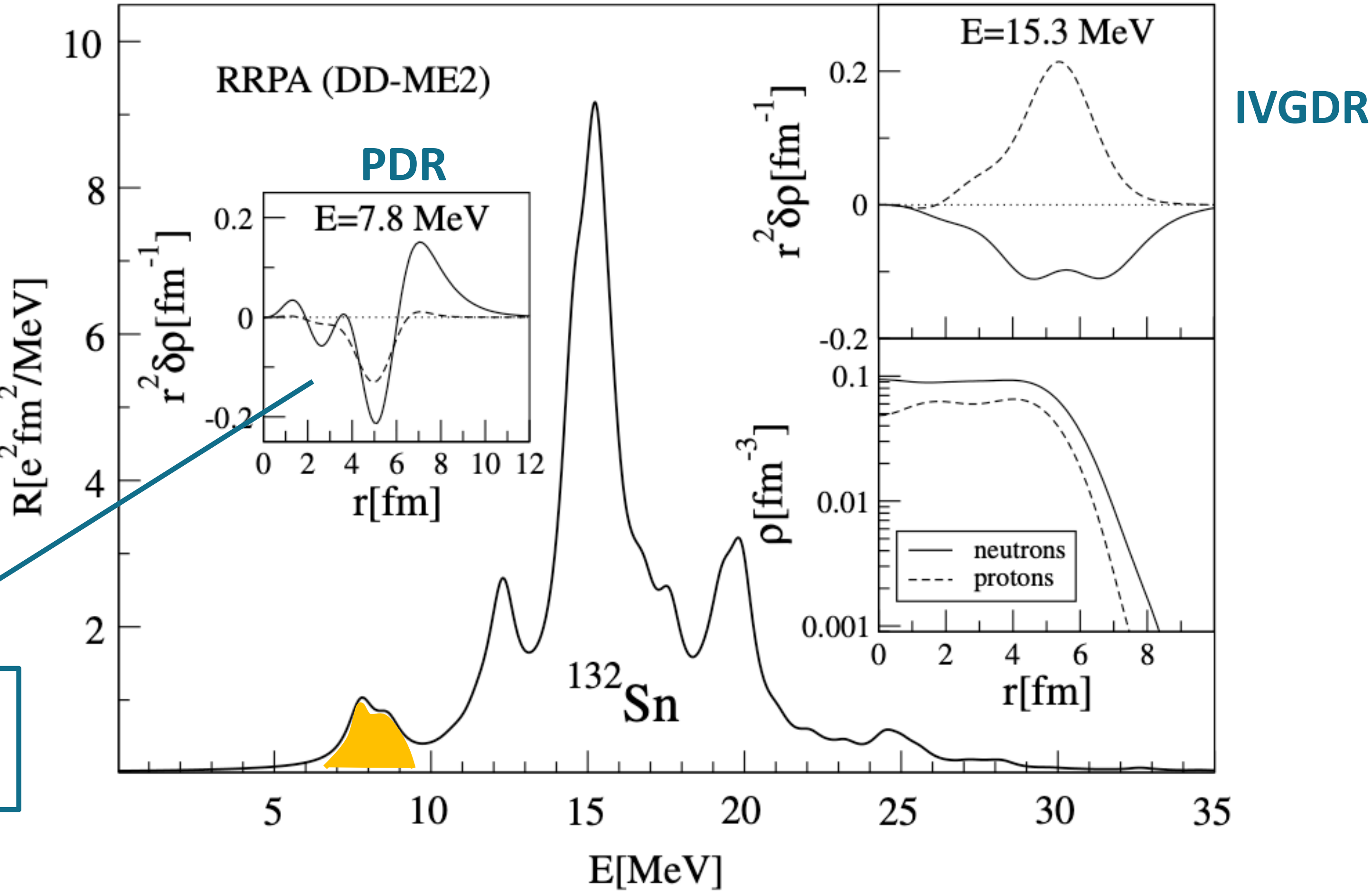
Soft modes: PDR

D. Vretenar et al., J. Phys. G 35 (2008) 014039



Core in phase +neutron skin

Soft modes: PDR

- Different experimental probes to investigate the nature of these states

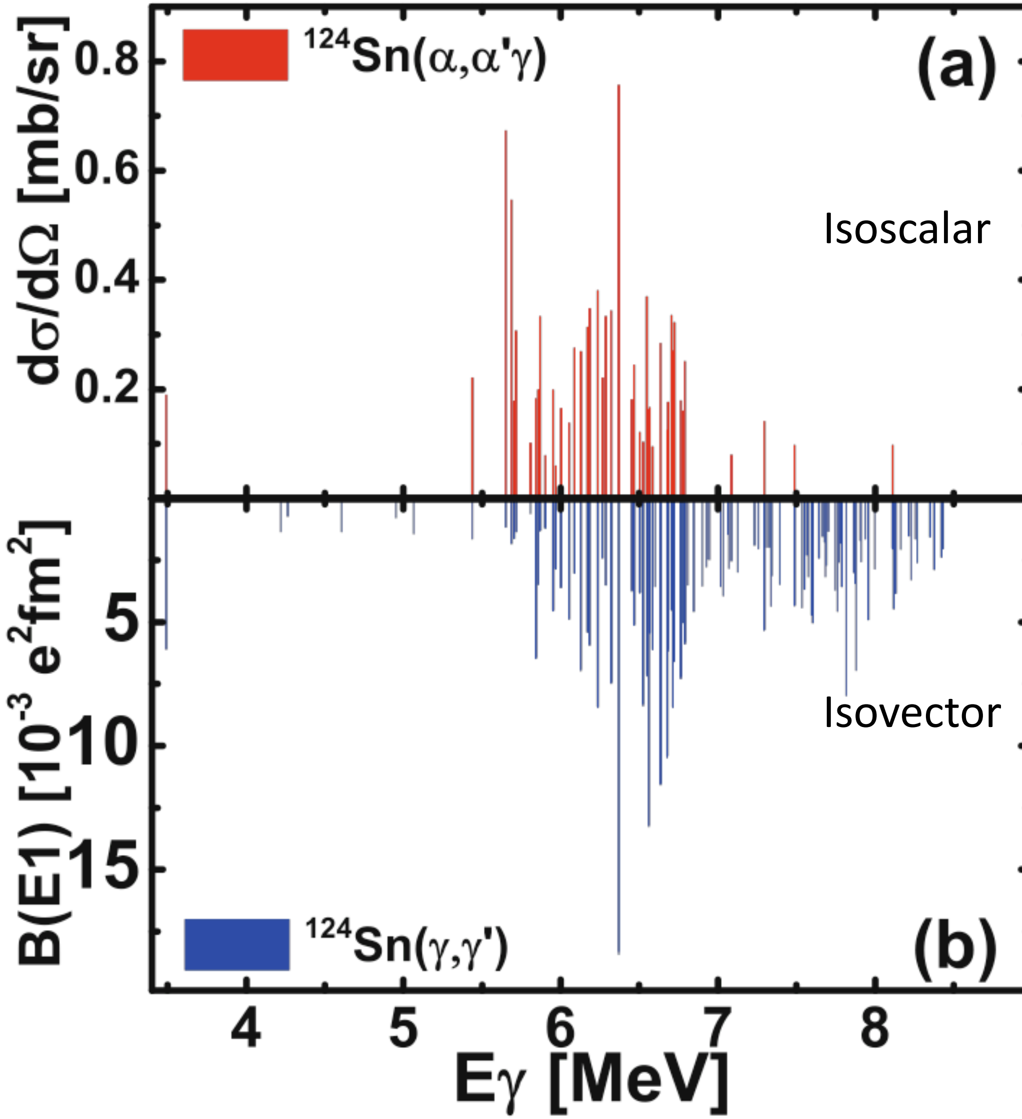


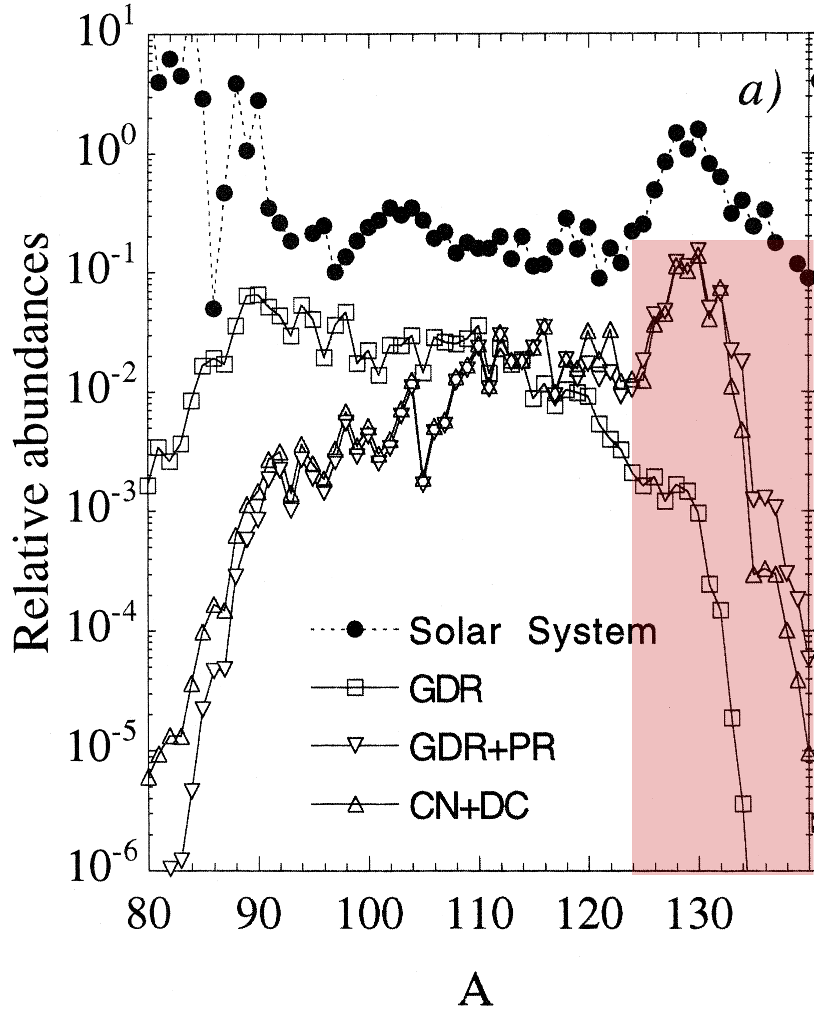
Figure A. Bracco et al., Eur. Phys. J. A 51 (2015) 99
Data from K. Govaert et al., Phys. Rev. C 57 (1998) 2229 and J. Endres et al., Phys. Rev. C 85 (2012) 064331

Soft modes: PDR

Impact: r-process abundances

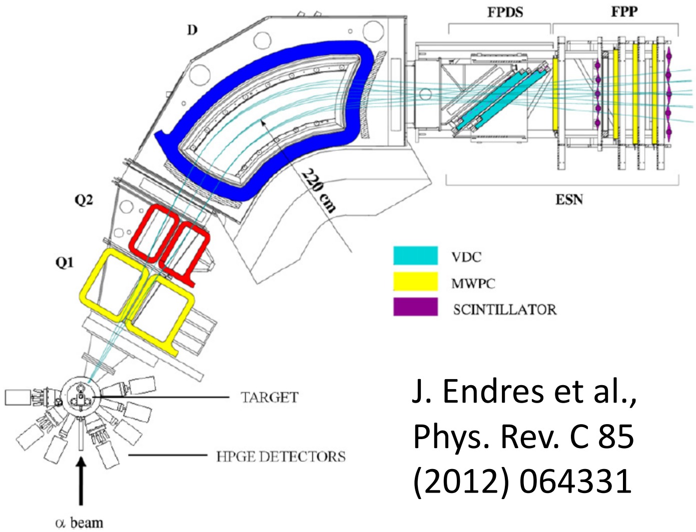
- Calculation for
  T = 10^9 K, $N_n = 10^{20}$ cm^{-3}, τ = 2.3 s
- Under some conditions, PDR can enhance production in some regions

S. Goriely,
Phys. Lett. B 436 (1998) 10



Experimental techniques (isoscalar)

- Inelastic scattering, multipole expansion
  Maximum cross section at very forward angles



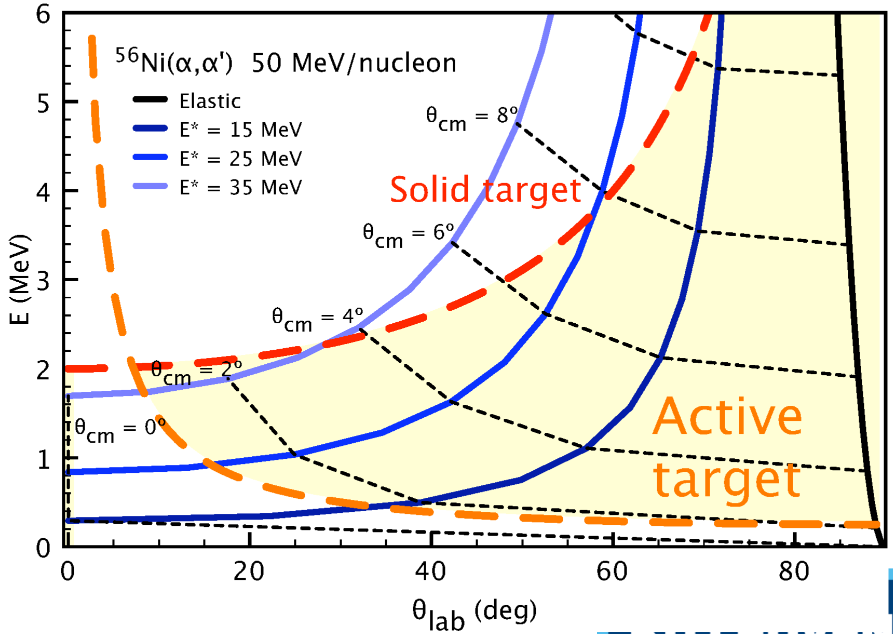
J. Endres et al., Phys. Rev. C 85 (2012) 064331

Stable nuclei

- Direct kinematics
  γ-ray coincidence
  to determine multipolarity

Unstable nuclei

- Inverse kinematics
  Low momentum transfer
  Very low energy of recoil nucleus



Low momentum-transfer in storage rings

Physics Letters B 763 (2016) 16–19

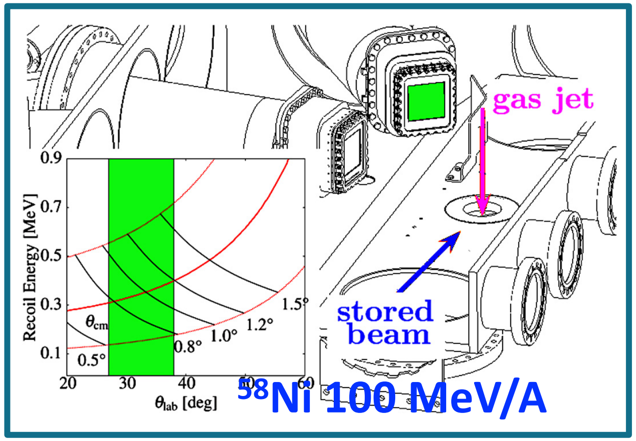
Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

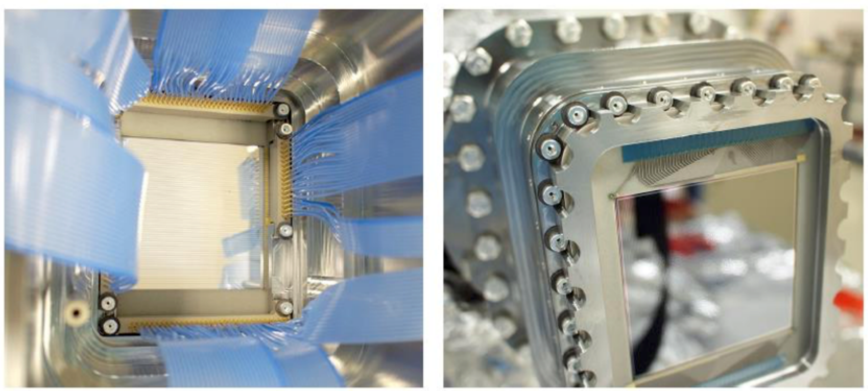
First measurement of isoscalar giant resonances in a stored-beam experiment

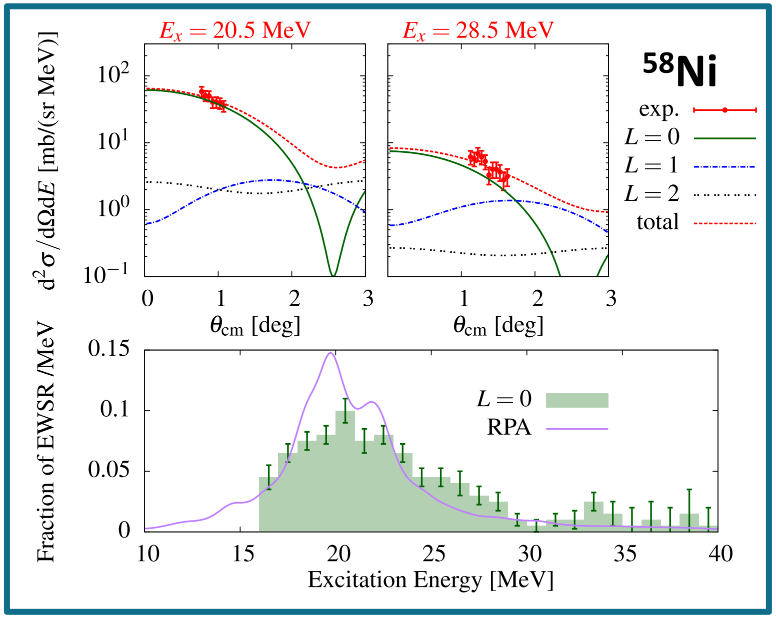
J.C. Zamora[a,*], T. Aumann[a,b], S. Bagchi[c,b], S. Bönig[a], M. Csatlós[d], I. Dillmann[b], C. Dimopoulou[b], P. Egelhof[b], V. Eremin[e], T. Furuno[f], H. Geissel[b], R. Gernhäuser[g], M.N. Harakeh[c], A.-L. Hartig[a], S. Ilieva[a], N. Kalantar-Nayestanaki[c], O. Kiselev[b], H. Kollmus[b], C. Kozhuharov[b], A. Krasznahorkay[d], Th. Kröll[a], M. Kuilman[c], S. Litvinov[b], Yu.A. Litvinov[b], M. Mahjour-Shafiei[h,c], M. Mutterer[b], D. Nagae[i], M.A. Najafi[c], C. Nociforo[b], F. Nolden[b], U. Popp[b], C. Rigollet[c], S. Roy[c], C. Scheidenberger[b], M. von Schmid[a], M. Steck[b], B. Streicher[b], L. Stuhl[d], M. Thürauf[a], T. Uesaka[j], H. Weick[b], J.S. Winfield[b], D. Winters[b], P.J. Woods[k], T. Yamaguchi[l], K. Yue[a,b,m], J. Zenihiro[j]



► Auxilliary vacuum side

► Ultra-high vacuum side





P. Egelhof (GSI), **EXL** Collaboration
H. Moeini et al., NIMA 634 (2011) 77

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Active targets: Maya

- Particles stopped inside the gas
- Mask to screen/collect electrons produced by the beam particles

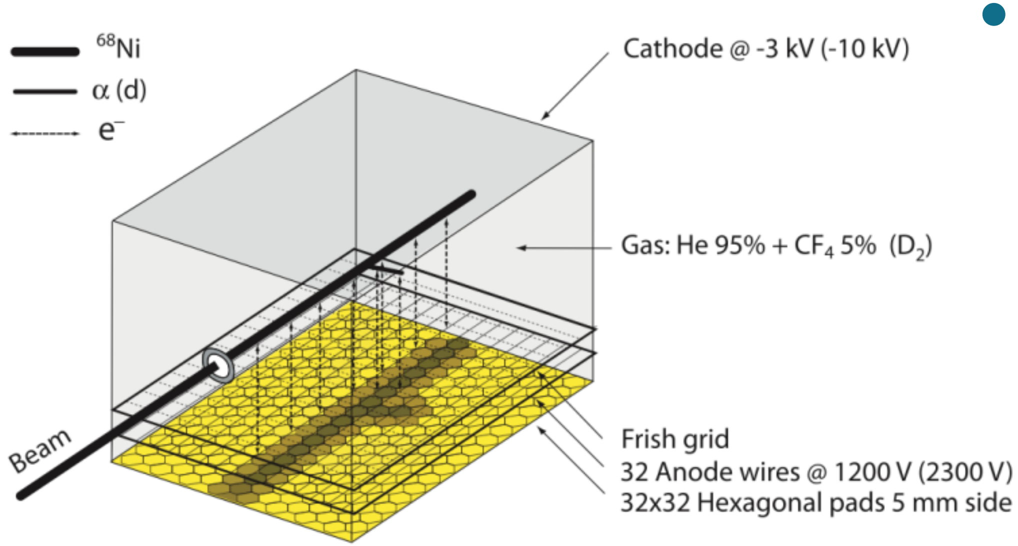


Figure: M. Vandebrouck, PRC 92 (2015) 024316

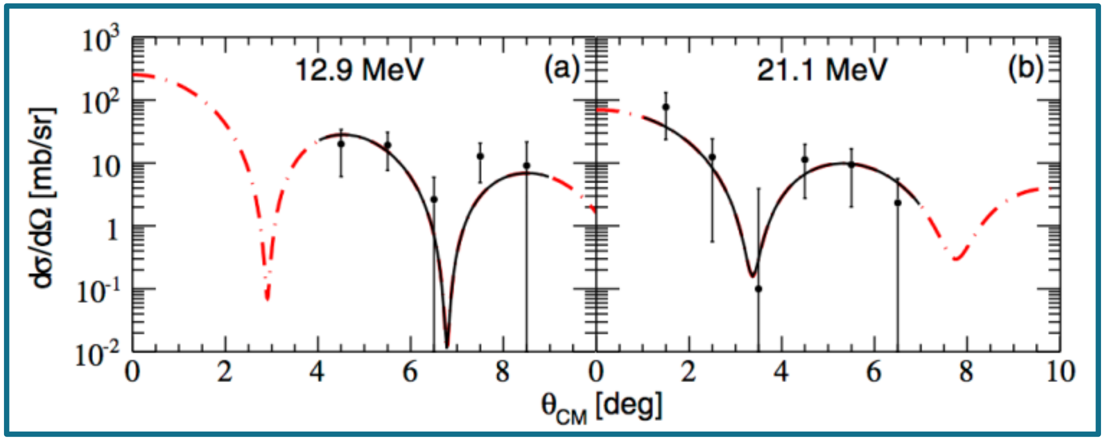
- ^{56}Ni(d,d') GMR and GQR
  C. Monrozeau et al., PRL 100 (2008) 042501
- ^{68}Ni(d,d') and (α,α')
  GMR, GQR and soft monopole
  M. Vandebrouck, PRL 113 (2014) 032504
  M. Vandebrouck, PRC 92 (2015) 024316
- ^{56}Ni(α,α') GMR and GDR
  S. Bagchi, PLB 751 (2015) 371

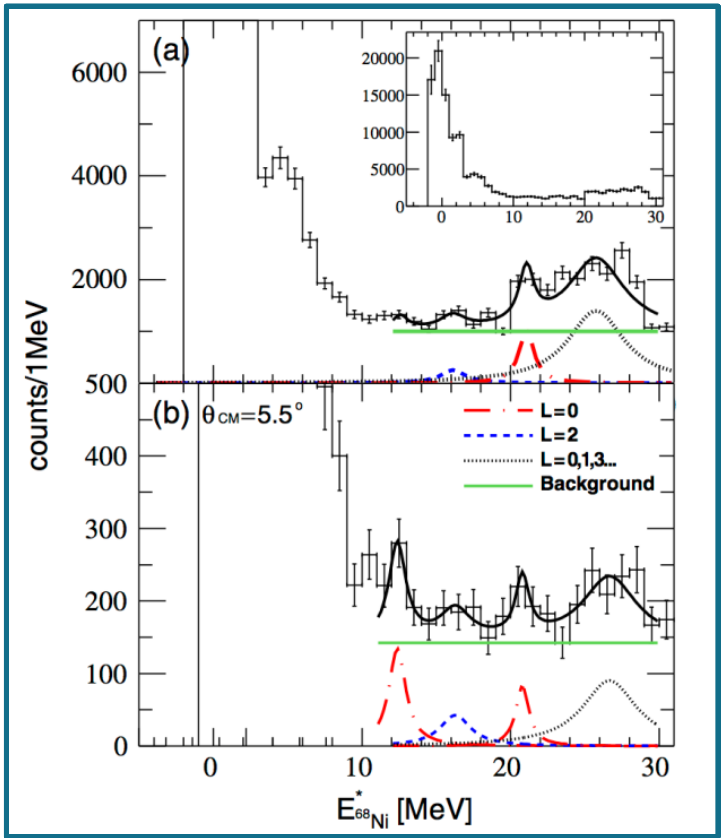
Active targets: Maya

^{56}Ni	50 MeV/A	Monrozeau et al. 2008	E_{ISGMR} = 19.3 ± 0.5 MeV E_{ISGQR} = 16.2 ± 0.5 MeV
^{56}Ni	50 MeV/A	Bagchi et al. 2015	E_{ISGMR} = 19.1 ± 0.5 MeV E_{ISGDR} = 17.4 ± 0.7 MeV
^{68}Ni	50 MeV/A	Vandebrouck et al. 2015	E_{ISGMR} = 21.1 ± 1.9 MeV E_{ISGQR} = 15.9 ± 1.3 MeV

Example ^{68}Ni (α,α')

- Beam intensity 4x10^{4} pps, purity 75%
- He + 5% CF_4 pressure 500 mb
- Recoil threshold 600 keV

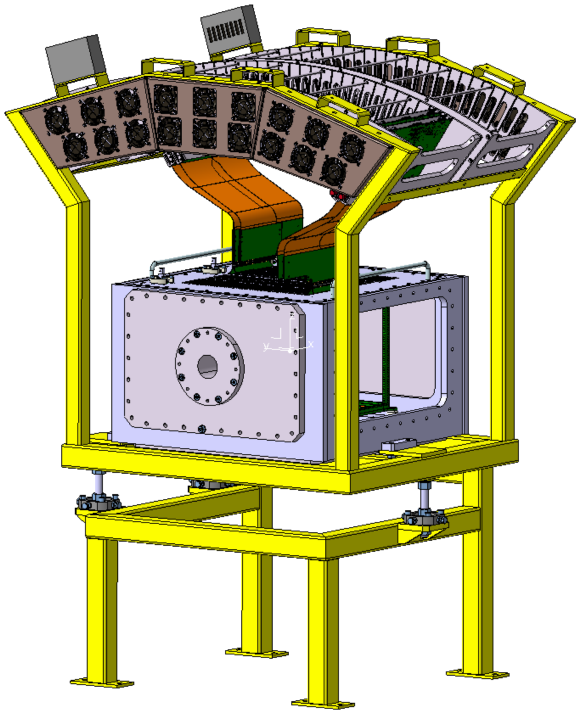




M. Vandebrouck, PRL 113 (2014) 032504

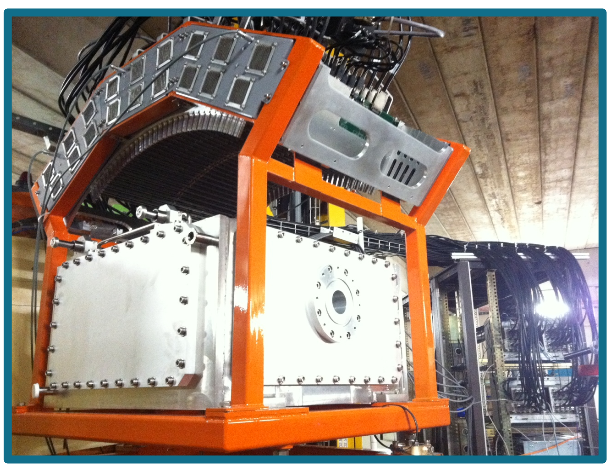
Beyond Maya: ACTAR TPC

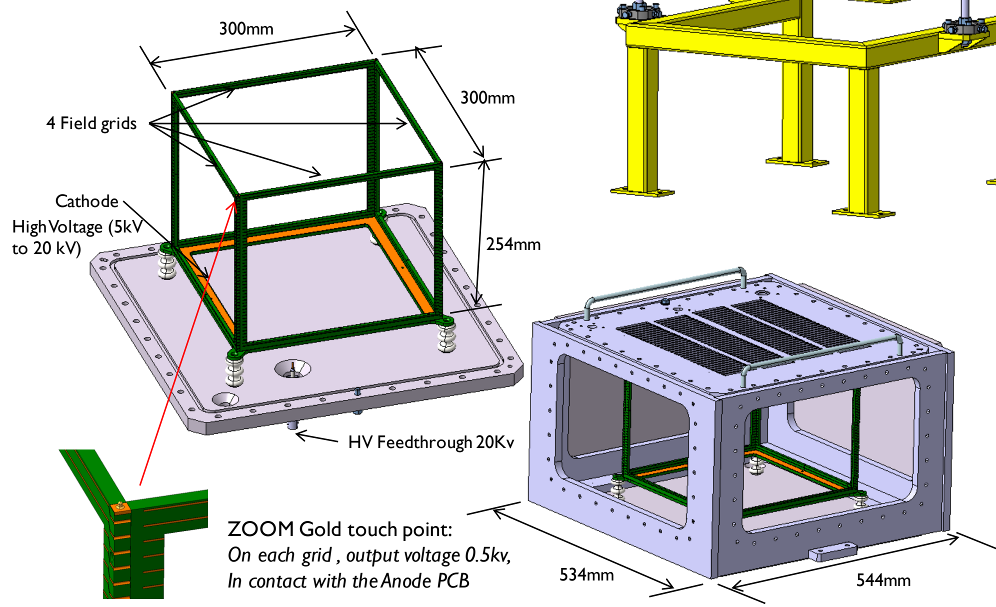
Work of P. Gangnant, GANIL



Improvements

- Multi-particle detection
- Low energy threshold
- Spatial resolution (angular and range)
- Reconstruction efficiency
- New electronics (16k channels)
- Energy dynamics
  - pad polarization
  - electrostatic mask





Isoscalar resonances in ^{68}Ni

PhD of Alex Arokiaraj (KU Leuven)

- Measurement at LISE (GANIL)
- ^{58,68}Ni at 49 MeV/nucleon, ≈10^4 pps inelastic scattering on ^{4}He
- 98% He + 2% CF_4
  400 mbar
  2.5×10^{20} at/cm^2
- Resolution ≈500 keV

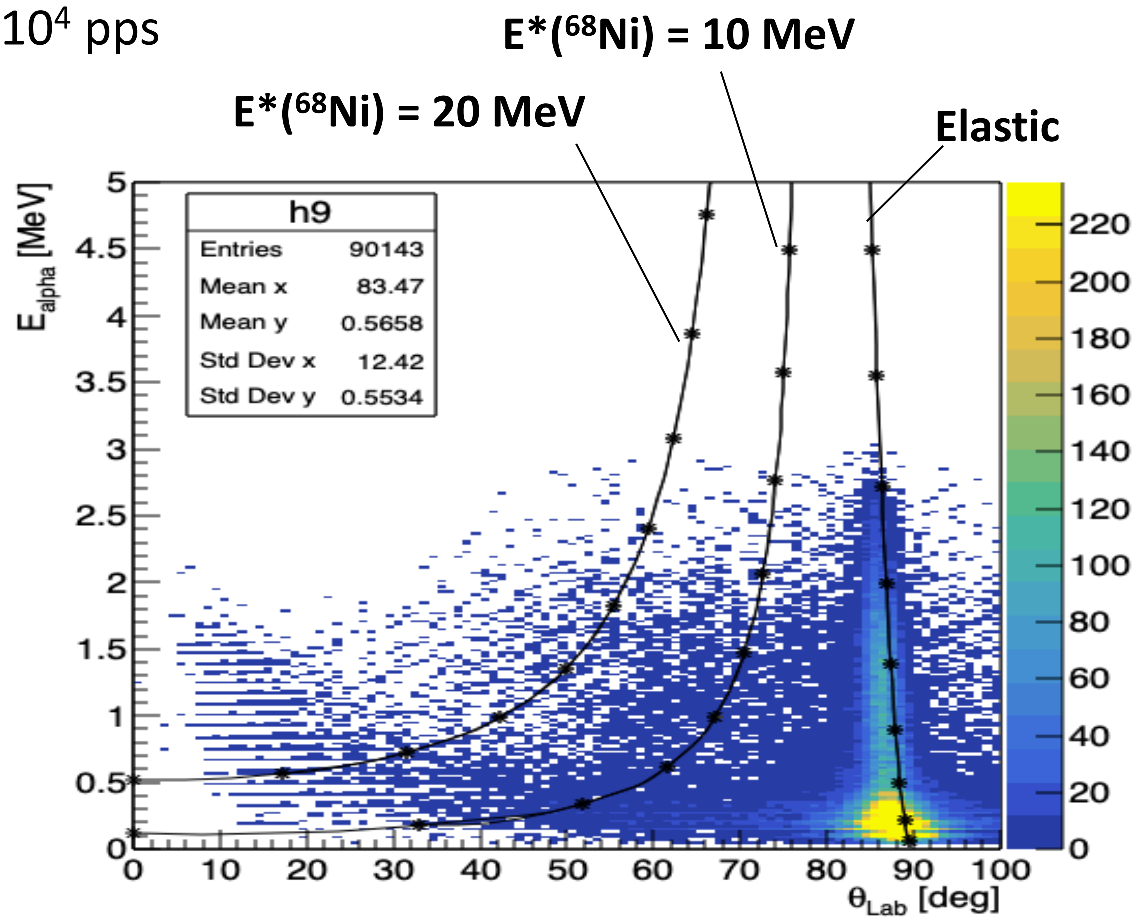
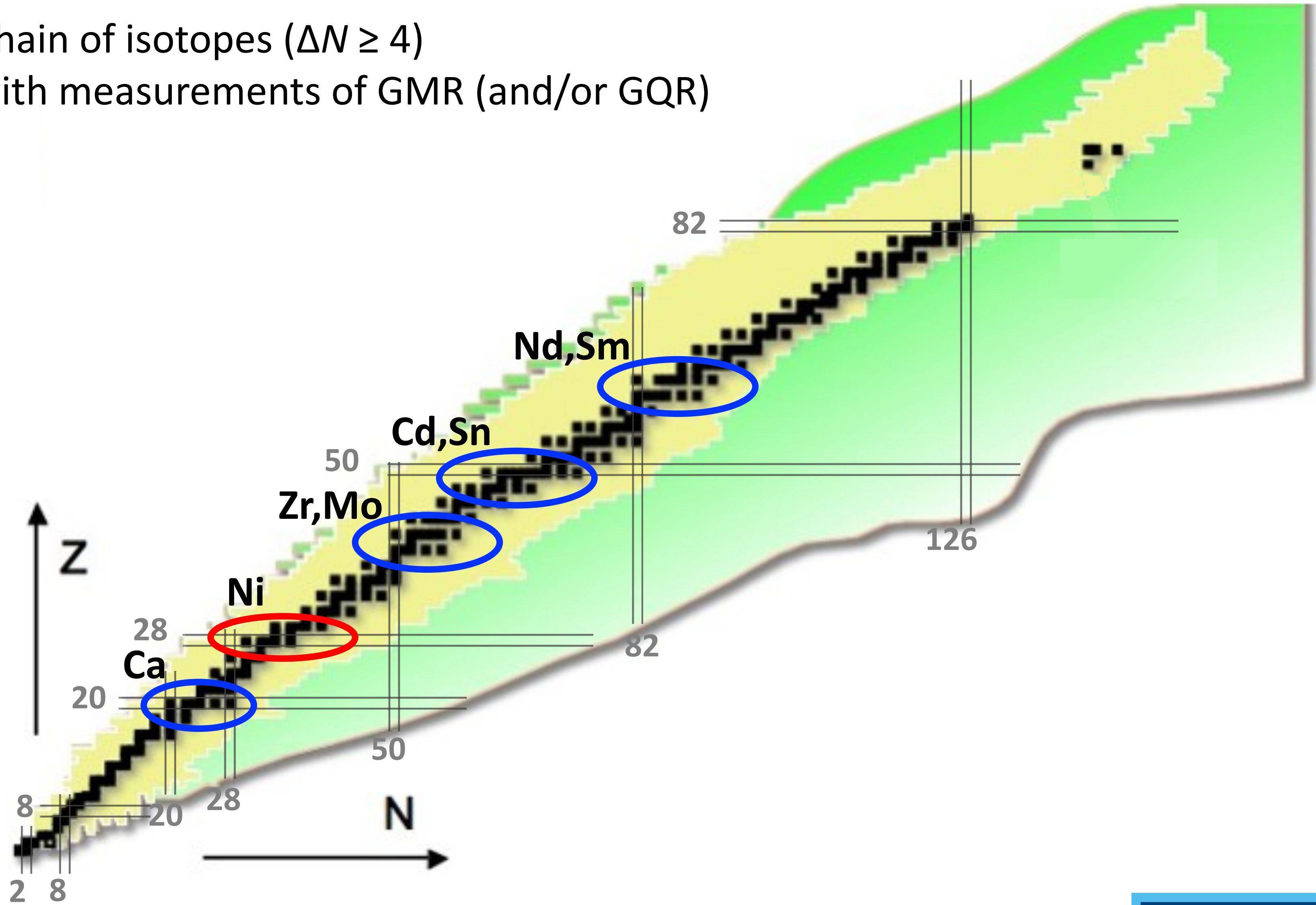


Figure: Marine Vandebrouck

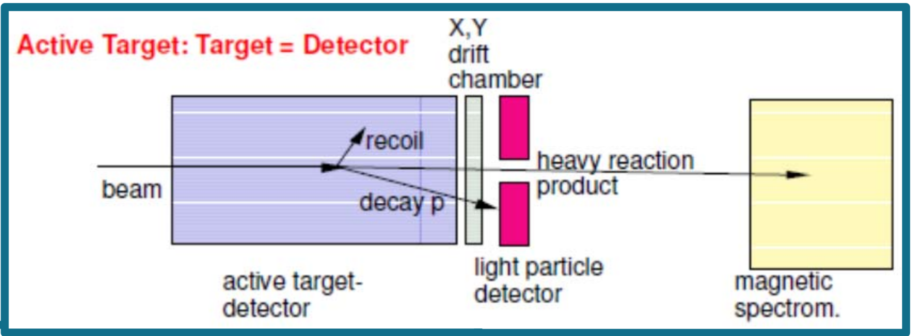
Where do we go from here

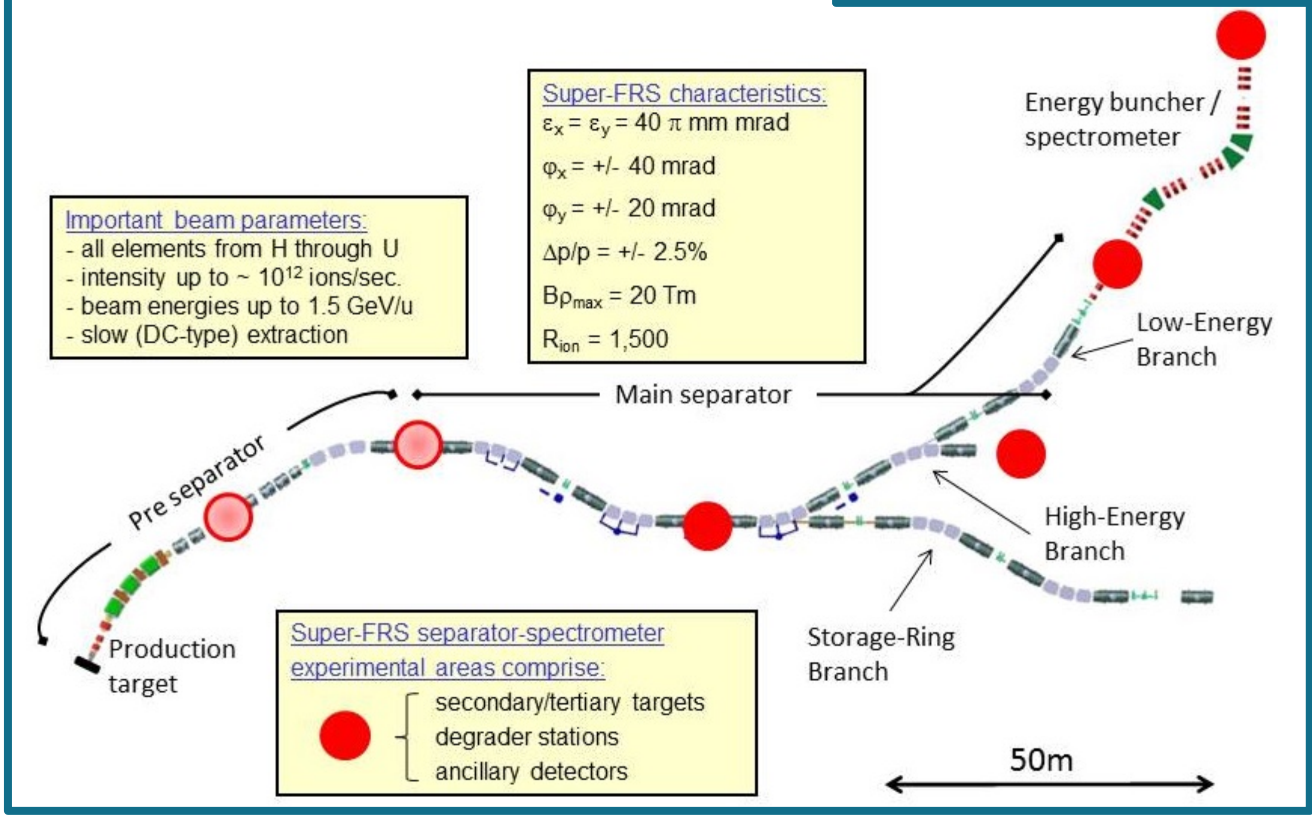
- Chain of isotopes ($\Delta N \geq 4$) with measurements of GMR (and/or GQR)



Active target in NUSTAR?

Maximum energy ≈200 MeV/nucleon
→ $B\rho(^{132}Sn)$ = 5.35 Tm

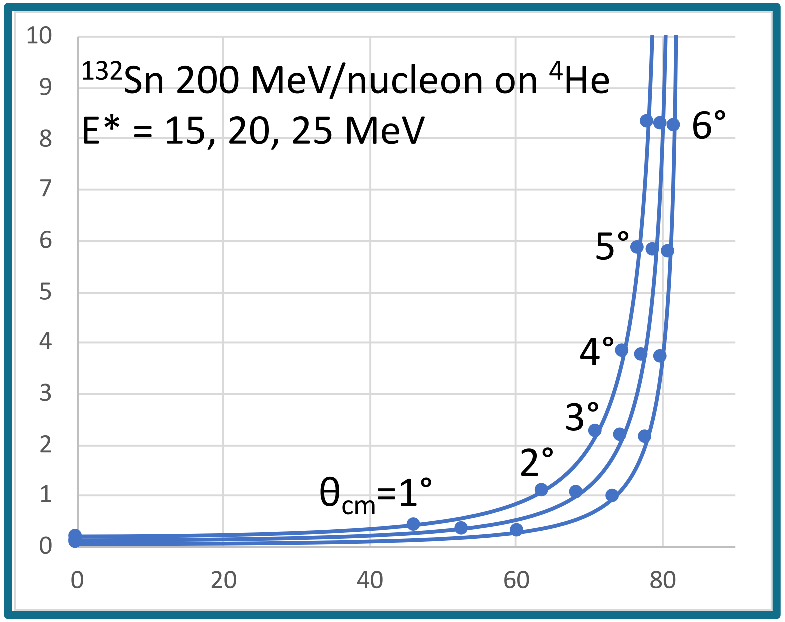


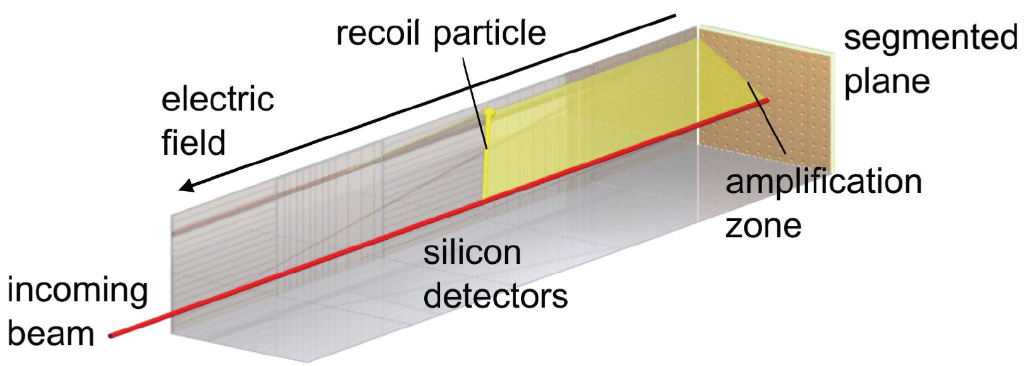


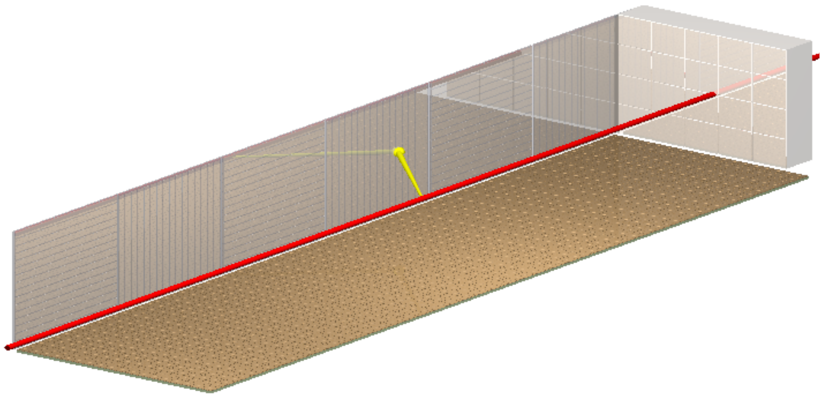
CDR of Super-FRS (Nov 2016)

Active target in NUSTAR?

- Elongated geometry (1m?)
- Track reconstruction in gas
- Particle angles from tracks
- Particle energy from ancillary detectors
- Decay particles at forward angles







Summary

Collective modes (still) very important for nuclear research and beyond

- GRs: constraints on density functionals
- IS-GRs (compression modes): related to incompressibility and Equation of State of nuclear matter
  → nuclear physics, astrophysics implications
- Soft modes not well understood:
  Neutron skin?
  Nature of excitations?

Opportunities at NUSTAR/FAIR

- Maximum energy ≈200 MeV/nucleon
- Location at Super-FRS, Low-Energy Branch…
- High luminosity, complete kinematic reconstruction