

Investigation of Giant Resonances in Inverse Kinematics using Storage Rings

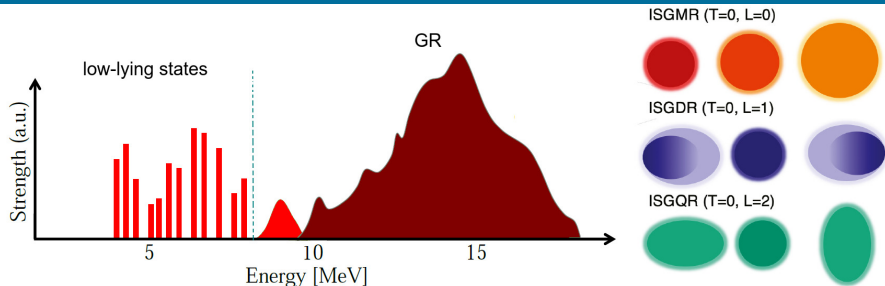
Juan Carlos Zamora

University of de Sao Paulo

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Why giant resonances are important?



	ISOSPIN	SPIN
$L=0$	IS/IV	flip/non flip
$L=1$	"	"
$\vdots$		
$\vdots$		

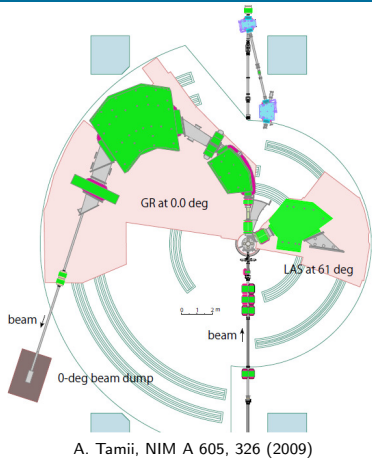
- Collective motion of nucleons
- Located at energies above particle separation
- Exhaust large fraction of EWSR
- Effects of deformation, neutron excess...
- Astrophysical implications:

EoS: A. Carbone et al. PRC 81, 041301(R) (2010)

Neutron stars: P.-G. Reinhard PRC 81, 051303(R) (2010)

Nucleosynthesis S.Goriely PLB 436, 10 (1998)

Experimental probes (strong interaction)



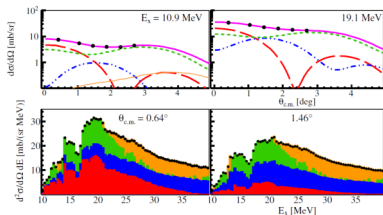
Inelastic scattering
at very forward angles
 $E_B \sim 100 \text{ MeV/u}$

(p, p') : IS/IV

(α, α') : IS

$$\left(\frac{d^2\sigma}{d\Omega dE} \right)^{\text{exp}} = \sum_L a_L(E_x) \left(\frac{d^2\sigma}{d\Omega dE} \right)^{\text{theo}}$$

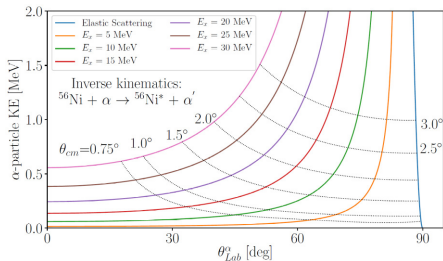
Zamora et al., in preparation



Measurements with spectrometers
KVI, RCNP, TAMU...

Experiments in inverse kinematics

- Suitable for unstable beams
- Reaction channels separated by kinematics
- $\theta_{\text{cm}} \neq \theta_{\text{lab}}$
- Low energy recoils (~ 300 keV)

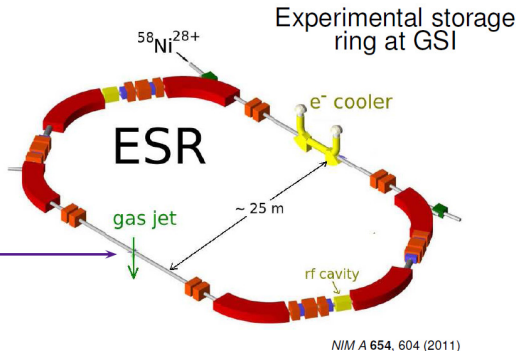
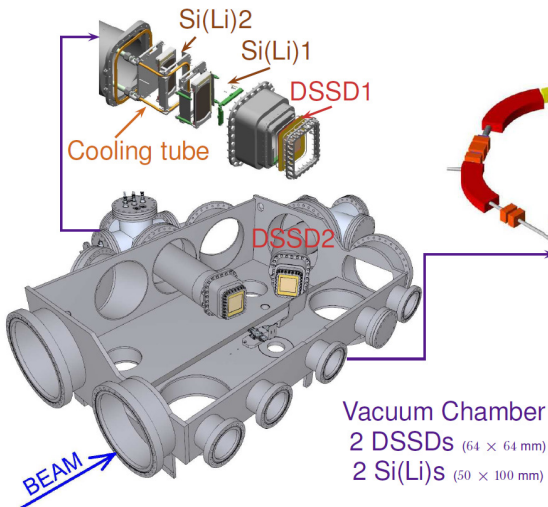


Two possible techniques:

- ✓ Active Target
- ✓ Storage Ring
 - ▶ Windowless target
 - ▶ In-ring detection

Experiments at ESR

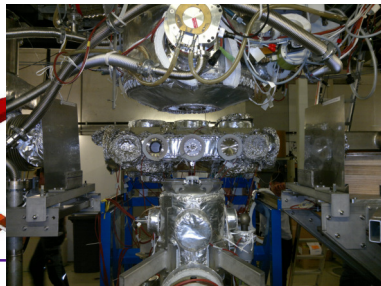
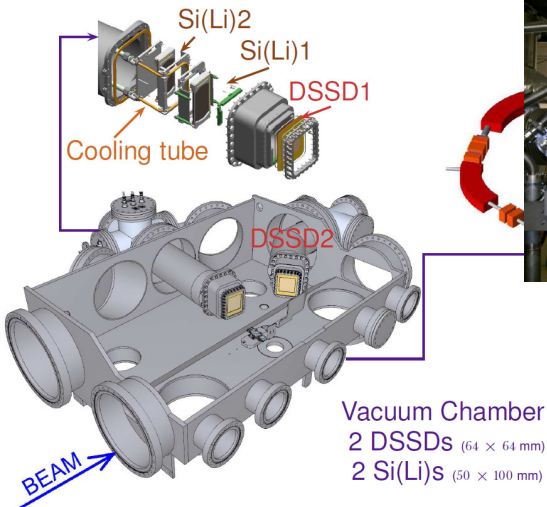
M. Mutterer, Phys. Scr., 014053 (2015)



- ✓ UHV compatible elements
- ✓ DSSDs are active windows

Experiments at ESR

M. Mutterer, Phys. Scr., 014053 (2015)

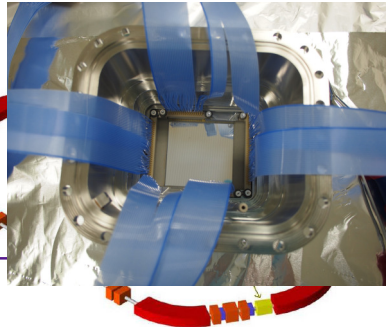
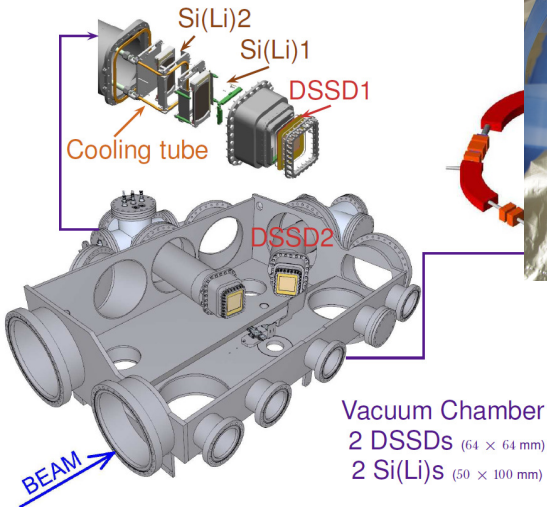


NIM A 654, 604 (2011)

- ✓ UHV compatible elements
- ✓ DSSDs are active windows

Experiments at ESR

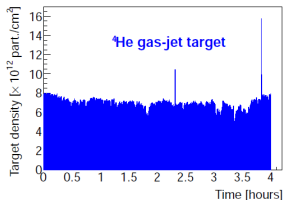
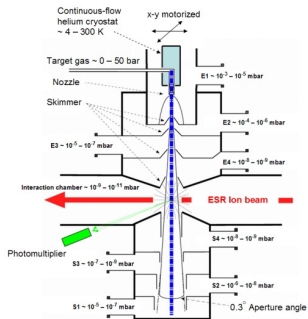
M. Mutterer, Phys. Scr., 014053 (2015)



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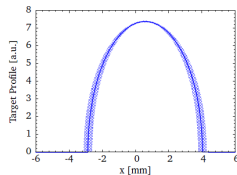
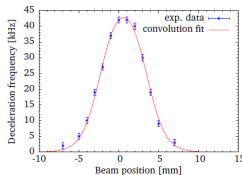
- ✓ UHV compatible elements
- ✓ DSSDs are active windows

Gas-jet target



- Windowless
- Temperature ~ 12 K
- Speed ~ 350 m/s
- Density ~ 10^{12} part./cm²

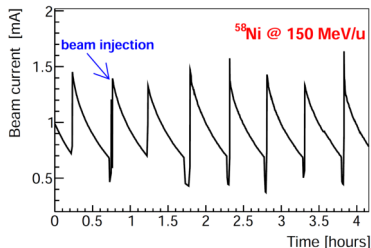
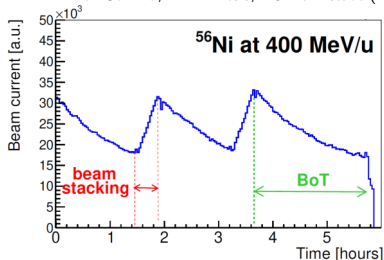
Target Profile (no halo)



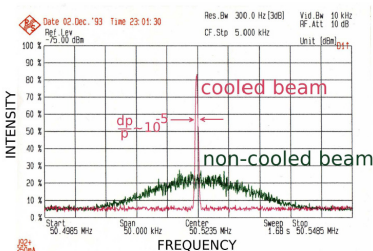
$$d(x) = \int_{-\infty}^{\infty} t(x')b(x-x')dx'$$

Stored beams

⁵⁶Ni: M. von Schmid, PhD Thesis, TU Darmstadt (2015)



- Electron cooling
- Stored ⁵⁸Ni beam: 100 and 150 MeV/u
- $\sim 10^8$ part. stored
- Revolution frequency $\sim$ MHz
- $\mathcal{L} \propto (n_B)(f_{\text{rev}})(n_T) \sim 10^{26} \text{ cm}^{-2} \text{ s}^{-1}$

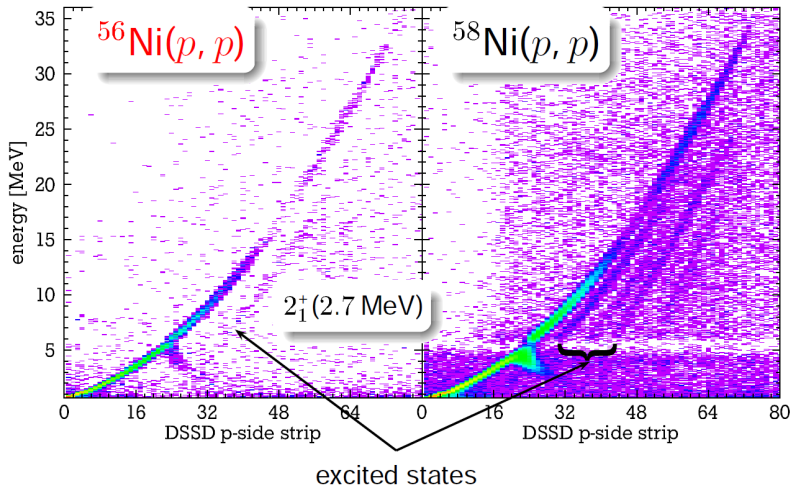


M. Steck, Storage Rings Lecture (2011)

Results

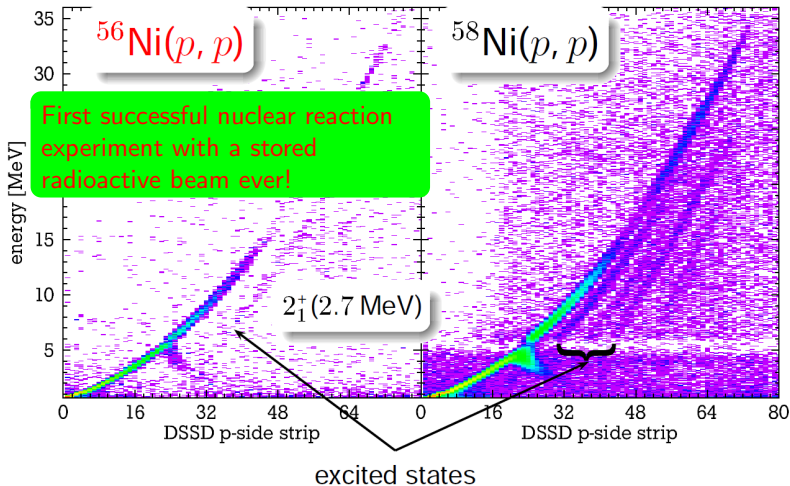
Proton scattering at 400 MeV/u

(courtesy of M. von Schmid, TU Darmstadt)



Proton scattering at 400 MeV/u

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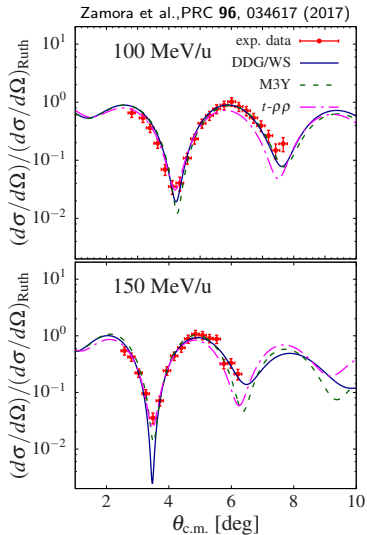
Cross section fitted with Glauber multiple-scattering theory

$^{56}\text{Ni}(p, p)$

- Density parametrization:
Symmetrized Fermi
- RMS point-matter radius
 $R_m \approx 3.6$ fm

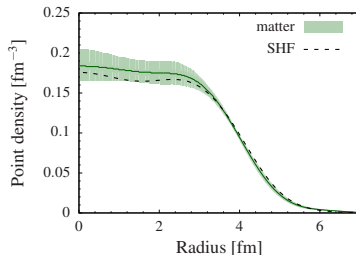
Elastic scattering (matter radius)

$^{58}\text{Ni}(\alpha, \alpha)$



Optical limit of Glauber Theory

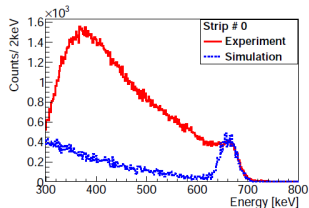
$$f_{NN}(\mathbf{q} = 0) = \frac{k_{NN}}{4\pi} \sigma_{NN}(i + \alpha_{NN})$$



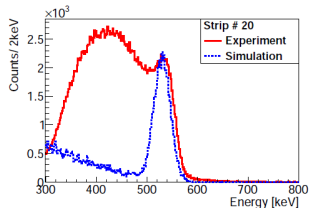
$$\sqrt{\langle r_m^2 \rangle} = 3.70(7) \text{ fm}$$

High production of δ rays!!

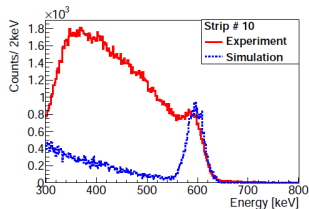
Strip number 0, $\theta_{\text{lab.}} \approx 27.5^\circ$



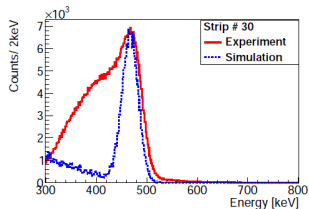
Strip number 20, $\theta_{\text{lab.}} \approx 33.9^\circ$



Strip number 10, $\theta_{\text{lab.}} \approx 30.7^\circ$

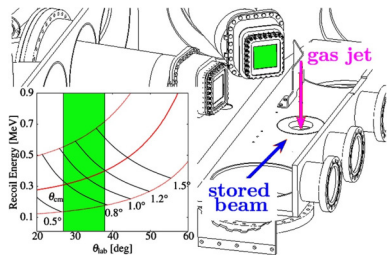


Strip number 30, $\theta_{\text{lab.}} \approx 37.1^\circ$

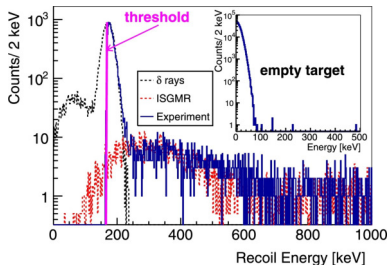
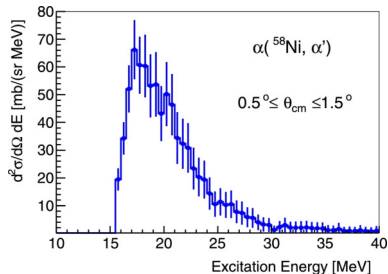


First giant resonances experiment with a stored beam

$^{58}\text{Ni}(\alpha, \alpha')$



Zamora et al. Phys. Lett. B **763**, 16 (2016)

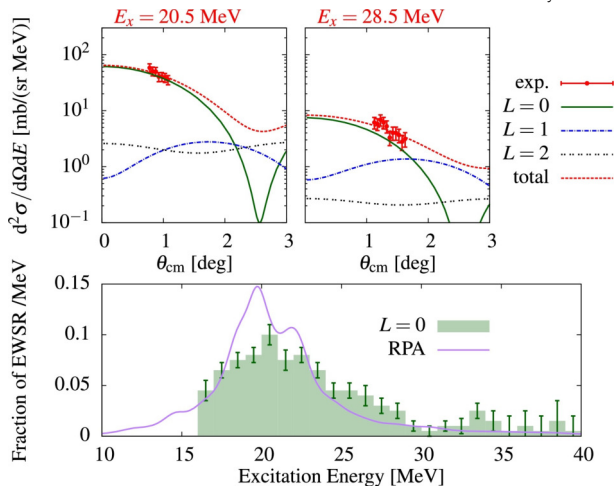


- α particles at 200-600 keV
- Unexpected high δ -rays production
- Center of mass angles $[0.5^\circ, 1.5^\circ]$
- Simultaneous normalization using elastic scattering

First giant resonances experiment with a stored beam

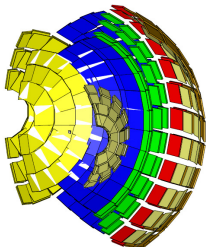
$^{58}\text{Ni}(\alpha, \alpha')$

Zamora et al. Phys. Lett. B **763**, 16 (2016)

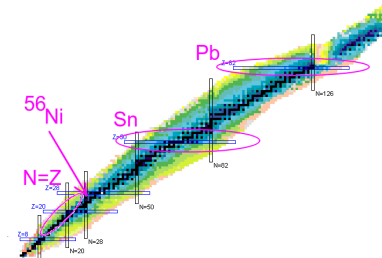
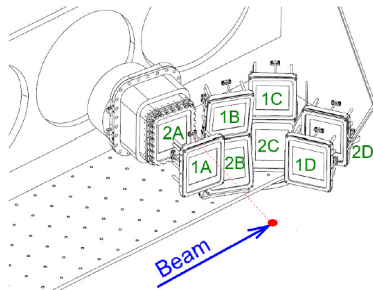


Extension of the technical concept

- ^{56}Ni : new detectors covering $\theta_{\text{cm}} > 2$ deg/ tracking
- Sn/Pb isotopes: Asymmetric nuclear matter (EoS)
- $N = Z$ nuclei: α -clustering with astrophysical implications
- Light nuclei: $E1$ response



EXL: EXotic nuclei studied in Ligh ion induced reactions at storage rings



Summary

Technical concept

- Excellent performance of the UHV capable detection system. The operation of the DSSD active windows was stable with low noise conditions.

Proof of principle

- First time GRs are being studied via an experiment with stored beam. The ISGMR in ^{58}Ni was extracted
- Excellent results for the matter radius obtained from elastic scattering data

Perspectives

- New detectors covering $\theta_{\text{cm}} > 2^\circ$ are needed to extract the ISGDR and ISGQR components. An extended setup will enable unique studies at FAIR

Thank you for your attention!

S. Bagchi¹, S. Bönig², M. Csatlós³, I. Dillmann⁴, C. Dimopoulou⁴, P. Egelhof⁴, V. Eremin⁵, T. Furuno⁶, H. Geissel⁴, R. Gernhäuser⁷, M. N. Harakeh¹, A.-L. Hartig², S. Ilieva², N. Kalantar-Nayestanaki¹, O. Kiselev⁴, H. Kollmus⁴, C. Kozhuharov⁴, A. Krasznahorkay³, T. Kröll², M. Kuilman¹, S. Litvinov⁴, Yu. A. Litvinov⁴, M. Mahjour-Shafiei^{1,8}, M. Mutterer⁴, D. Nagae⁹, M.A. Najafi¹, C. Nociforo⁴, F. Nolden⁴, U. Popp⁴, C. Rigollet¹, S. Roy¹, C. Scheidenberger⁴, M. von Schmid², M. Steck⁴, B. Streicher^{2,4}, L. Stuhl³, M. Takechi⁴, M. Thürauf², T. Uesaka¹⁰, H. Weick⁴, J. S. Winfield⁴, D. Winters⁴, P. J. Woods¹¹, T. Yamaguchi¹², K. Yue^{2,4,13}, J.C. Zamora², J. Zenihiro¹⁰

¹ KVI-CART, Groningen

² Technische Universität Darmstadt

³ ATOMKI, Debrecen

⁴ GSI, Darmstadt

⁵ Ioffe Physico-Technical Institute, St.Petersburg

⁶ Kyoto University

⁷ Technische Universität München

⁸ University of Tehran

⁹ University of Tsukuba

¹⁰ RIKEN Nishina Center

¹¹ The University of Edinburgh

¹² Saitama University

¹³ Institute of Modern Physics, Lanzhou

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