INFN
Istituto Nazionale
di Fisica Nucleare

Experimental studies on neutron rich Ni isotopes

EGAN
European Gamma and Ancillary detectors Network

T. Marchi

GSI, June 23 – 26 2014

Experimental studies on neutron rich Ni isotopes

Introduction

- **Discovery of the Ni isotopes**
- **Shell evolution along Ni isotopic chain, towards ^{78}Ni.**

Selected experiments on even-even neutron-rich Ni isotopes

- **^{70}Ni: Enhanced collectivity and core polarization**
- **Focus on ^{74}Ni Coulex at NSCL and RIKEN**
- **Partial conclusion on core polarization**

Near Future Perspectives at the European scale

T. Marchi

GSI, June 23 – 26 2014

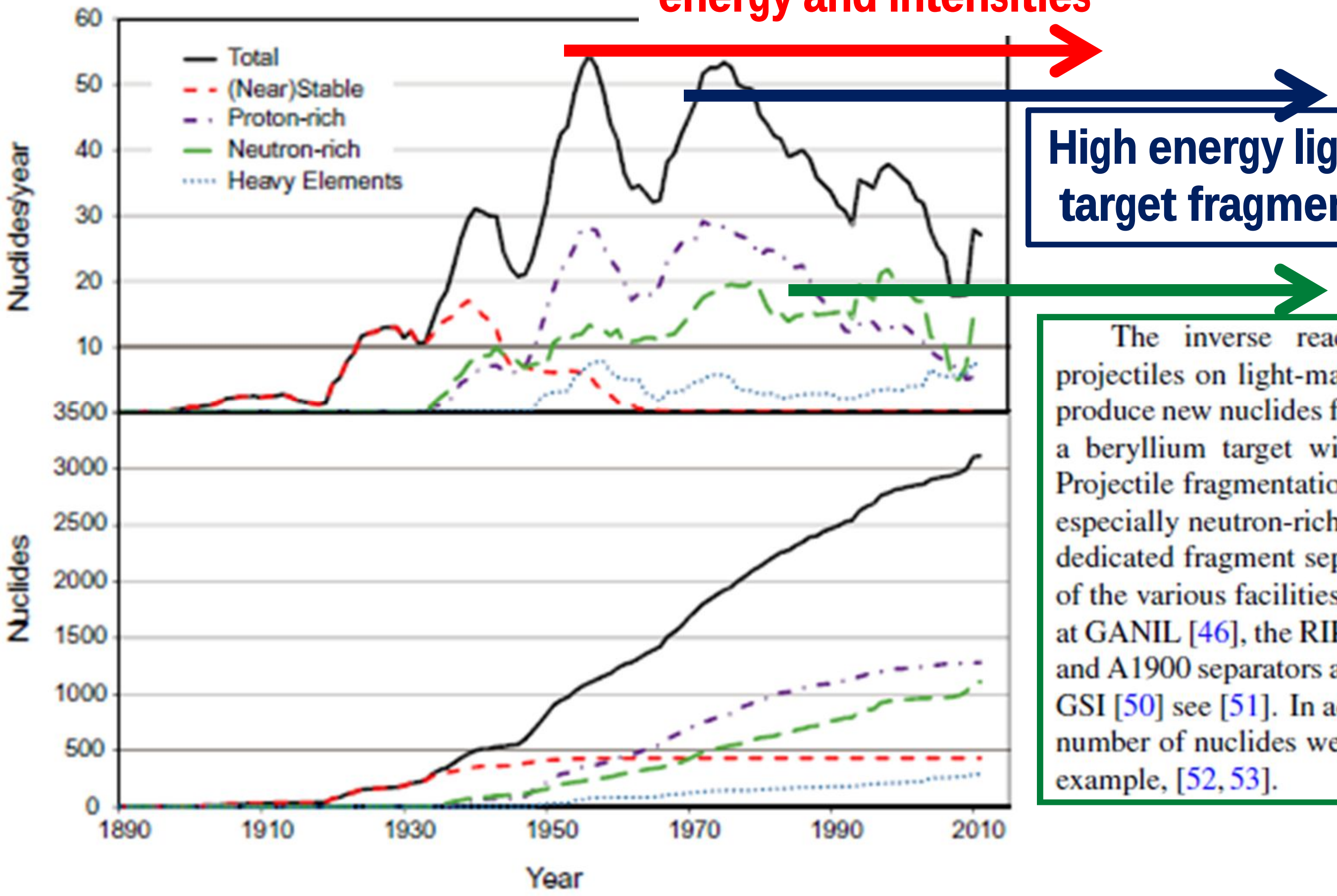
Discovery of Ni isotopes

IOP Publishing — Reports on Progress in Physics
Rep. Prog. Phys. 76 (2013) 056301 (14pp) — doi:10.1088/0034-4885/76/5/056301

Current status and future potential of nuclide discoveries

M Thoennessen

Rep. Prog. Phys. 76 (2013) 056301

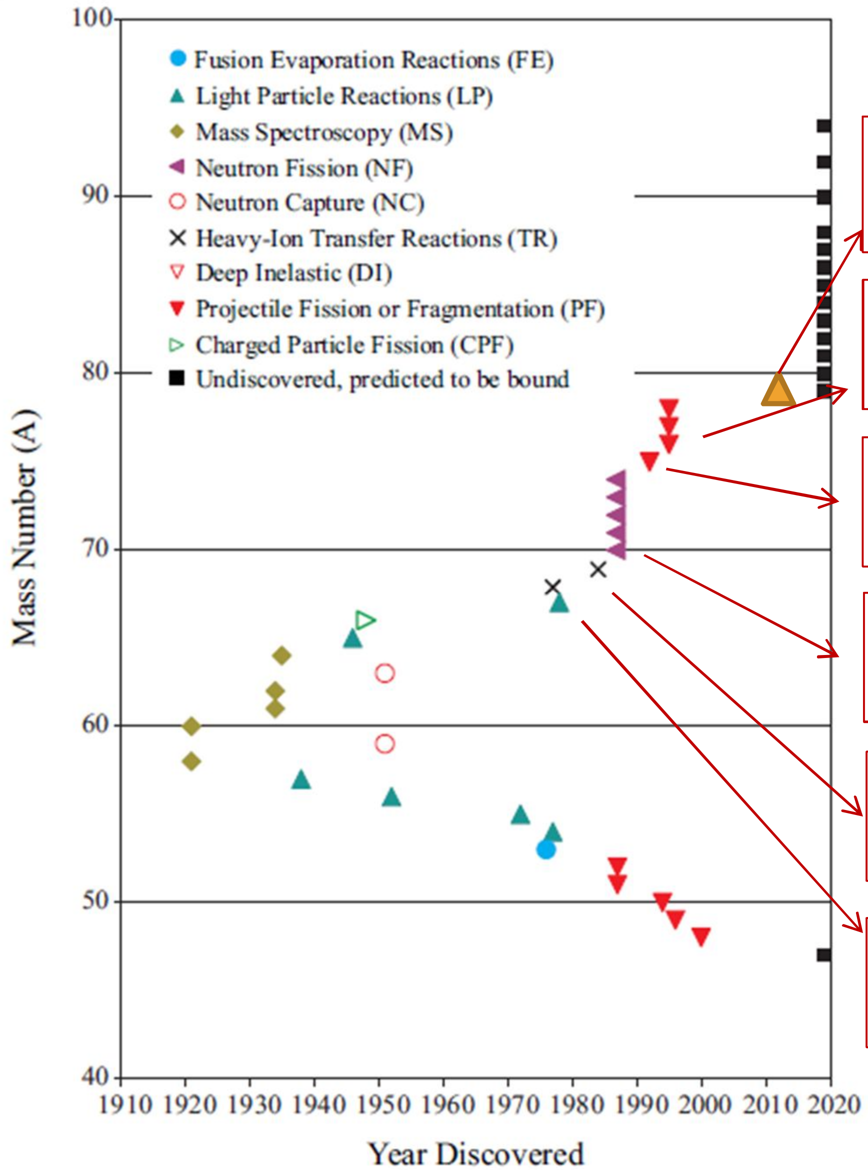


High energy light beams: target fragmentation/fission. (ISOL)

The inverse reaction, the fragmentation of heavy projectiles on light-mass targets was successfully applied to produce new nuclides for the first time in 1979 by bombarding a beryllium target with 205 MeV/nucleon ^{40}Ar ions [45]. Projectile fragmentation began to dominate the production of especially neutron-rich nuclei starting in the late 1980s when dedicated fragment separators came online. For an overview of the various facilities, for example, the LISE3 spectrometer at GANIL [46], the RIPS separator at RIKEN [47], the A1200 and A1900 separators at NSCL [48, 49], and the FRS device at GSI [50] see [51]. In addition to these separators a significant number of nuclides were discovered at storage rings, see, for example, [52, 53].

Discovery of Ni isotopes

[K. Garofali, R. Robinson, M. Thoennessen At. Data and Nucl. Data Tables. 2012;98(2)]



^{79}Ni: T.Ohnishi et al, J.Phys.Soc.Jpn. 79, 073201 (2010) RIKEN ^{238}U fragmentation

$^{76-78}$Ni: Engelmann et al, 1995 GSI
^{238}U fragmentation 750 AMeV projectile fission

^{75}Ni: Weber et al., Z. Phys A 343 (1992)
GSI ^{86}Kr fragmentation 500 AMeV

$^{70-74}$Ni: Armbruster et al., Europhys Lett 4 (1987)
Grenoble: thermal neutron induced fission of ^{235}U

^{69}Ni: Dessagne et al., NPA 426 (1984)
Orsay MP tandem ^{70}Zn(^{14}C,^{15}O)^{69}Ni

^{68}Ni: T.S. Bhatia et al, Z. Phys. A 164 (1971)
Heidelberg MP Tandem. ^{18}O+^{70}Zn @ 81-84 MeV

Isotope observation is just the beginning...

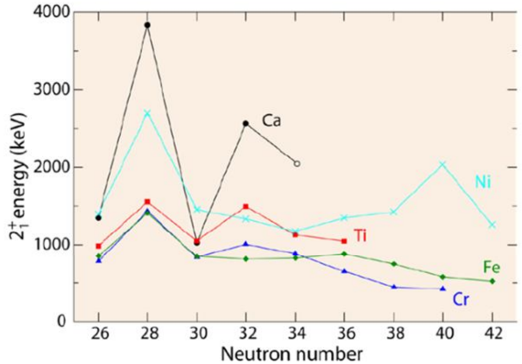
Nuclear Physics News International

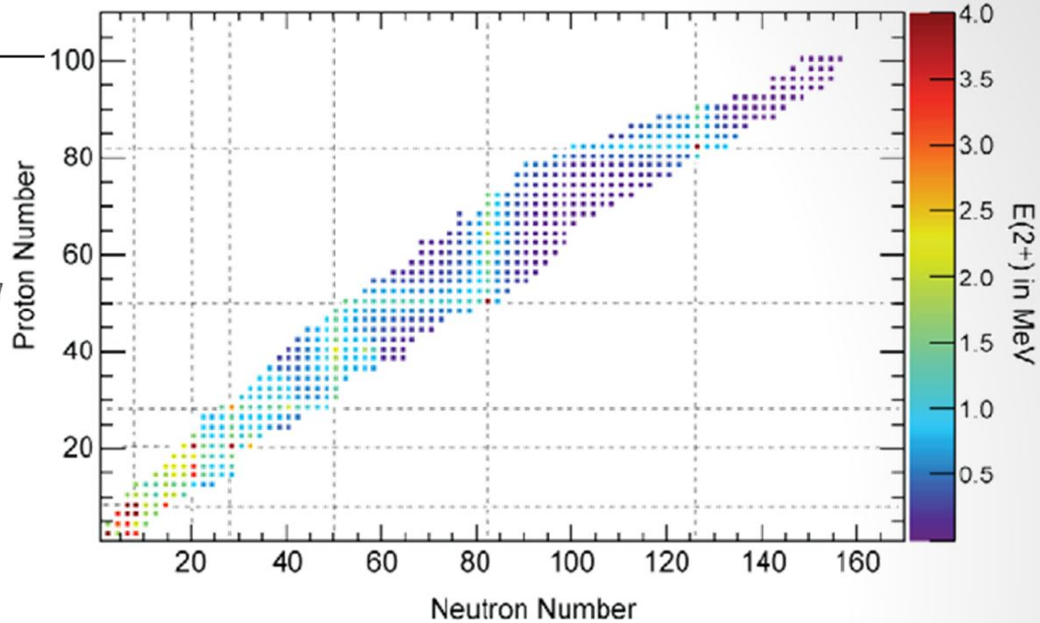
[A. Gade, Nucl Phys News 23-4 (2013) 10]

feature article

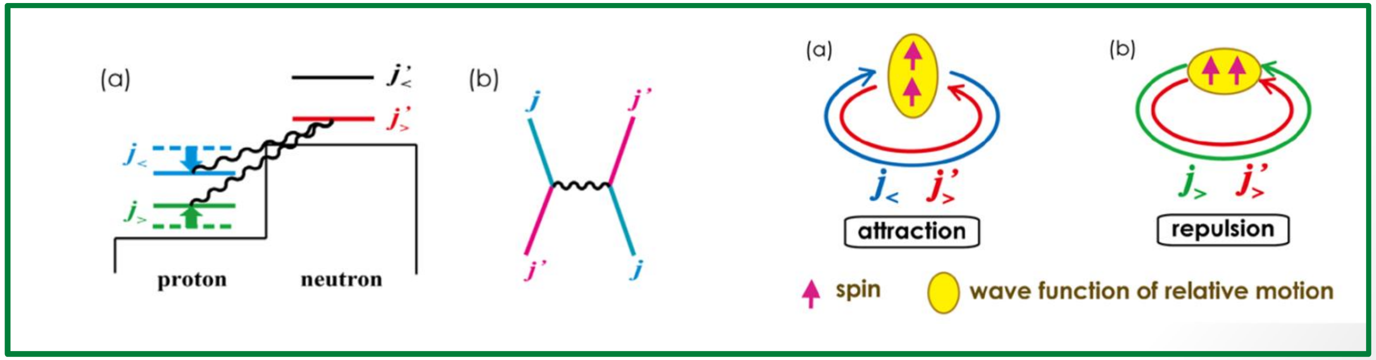
Excitation Energies in Rare Isotopes as Indicators of Shell Evolution

ALEXANDRA GADE
National Superconducting Cyclotron Laboratory and Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan, USA

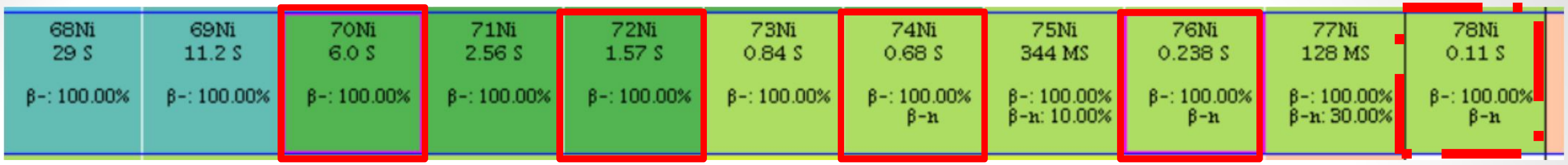




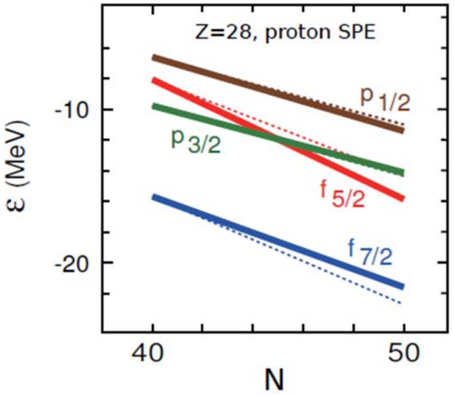
[T. Otsuka, A. Schwenk, Nucl Phys News 22-4 (2012) 12]

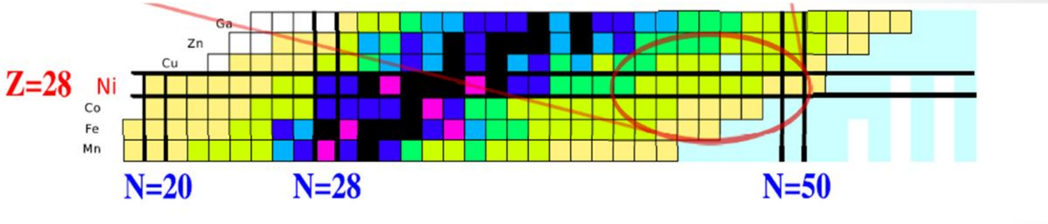


Evolution of Ni shells



[T. Otsuka, Phys Rev Lett 104.012501]





Neutron ESPE for N=50 isotones and for Ni isotopes

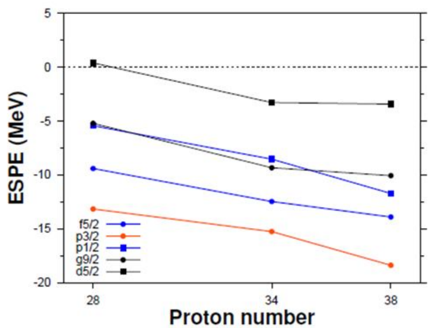


FIG. 3: Evolution of the neutron effective single particle energies with the proton number at $N = 50$.

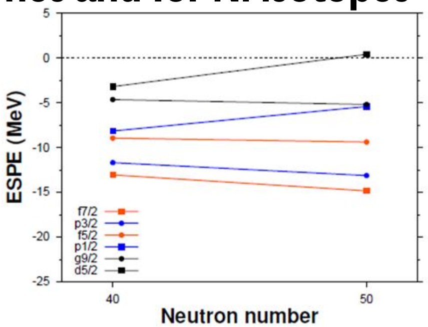
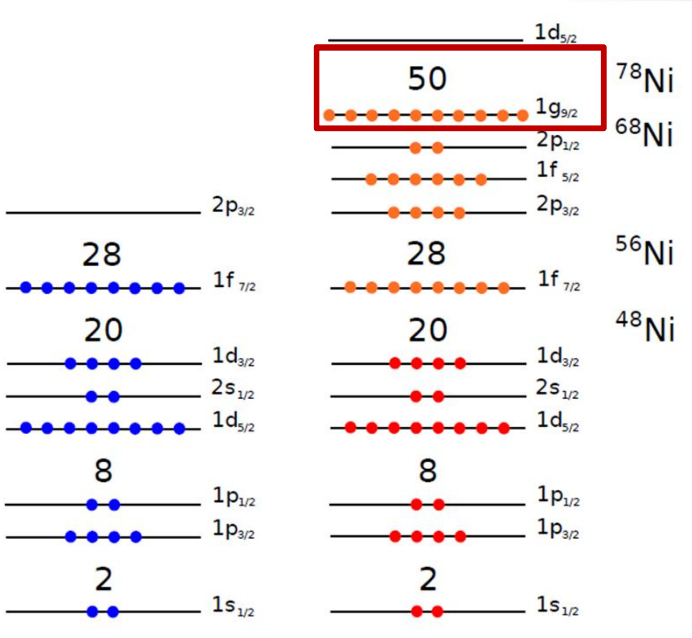
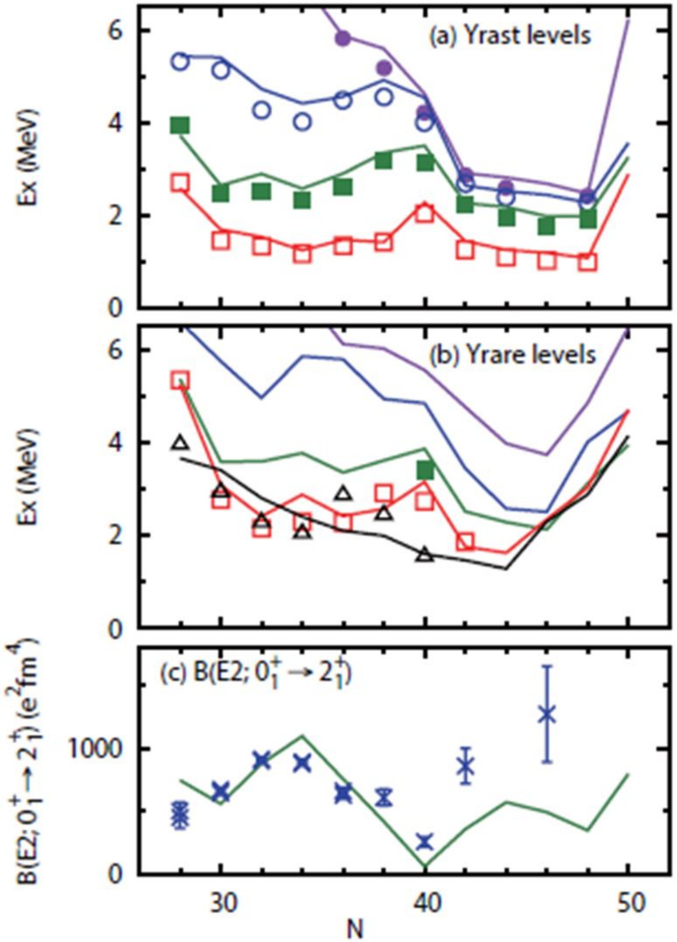


FIG. 4: Evolution of the neutron effective single particle energies between ^{68}Ni and ^{78}Ni.

[K. Sieja and F. Nowacki, Phys Rev C 85, 051301]



Type 2 shell evolution



[Y. Tsunoda eta l, PRC 89 (2014) 031301(R)]

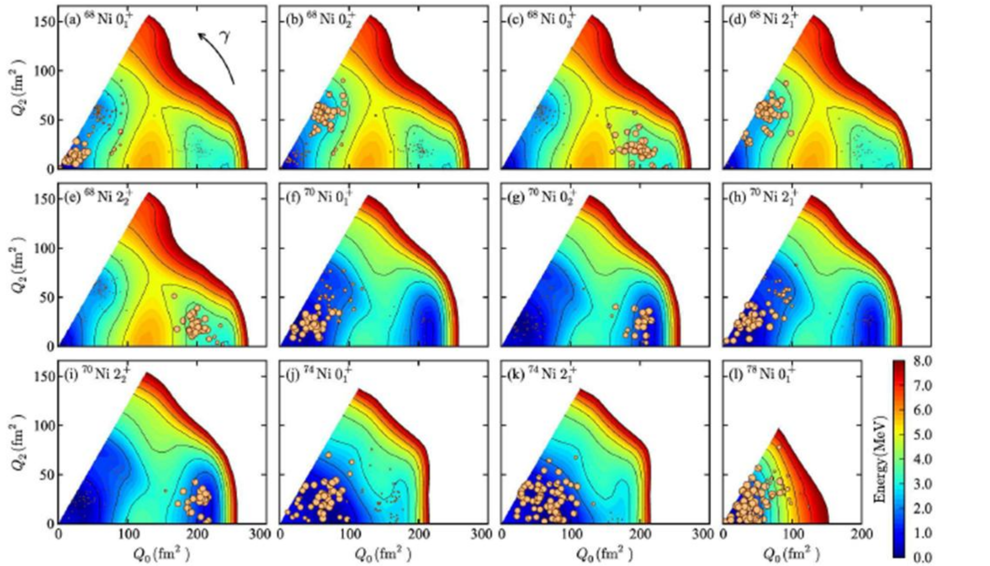


FIG. 3. (Color online) Potential energy surfaces (PES) of Ni isotopes, coordinated by usual Q_0 and Q_2 (or γ). The energy relative to the minimum is shown by contour plots. Circles on the PES represent shapes of MCSM basis vectors (see the text).

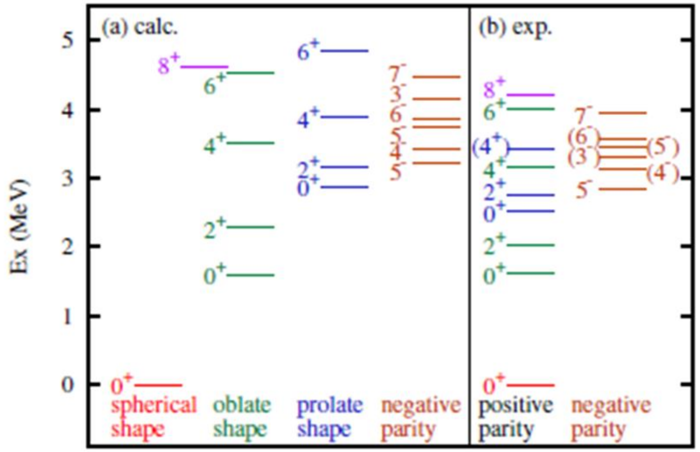
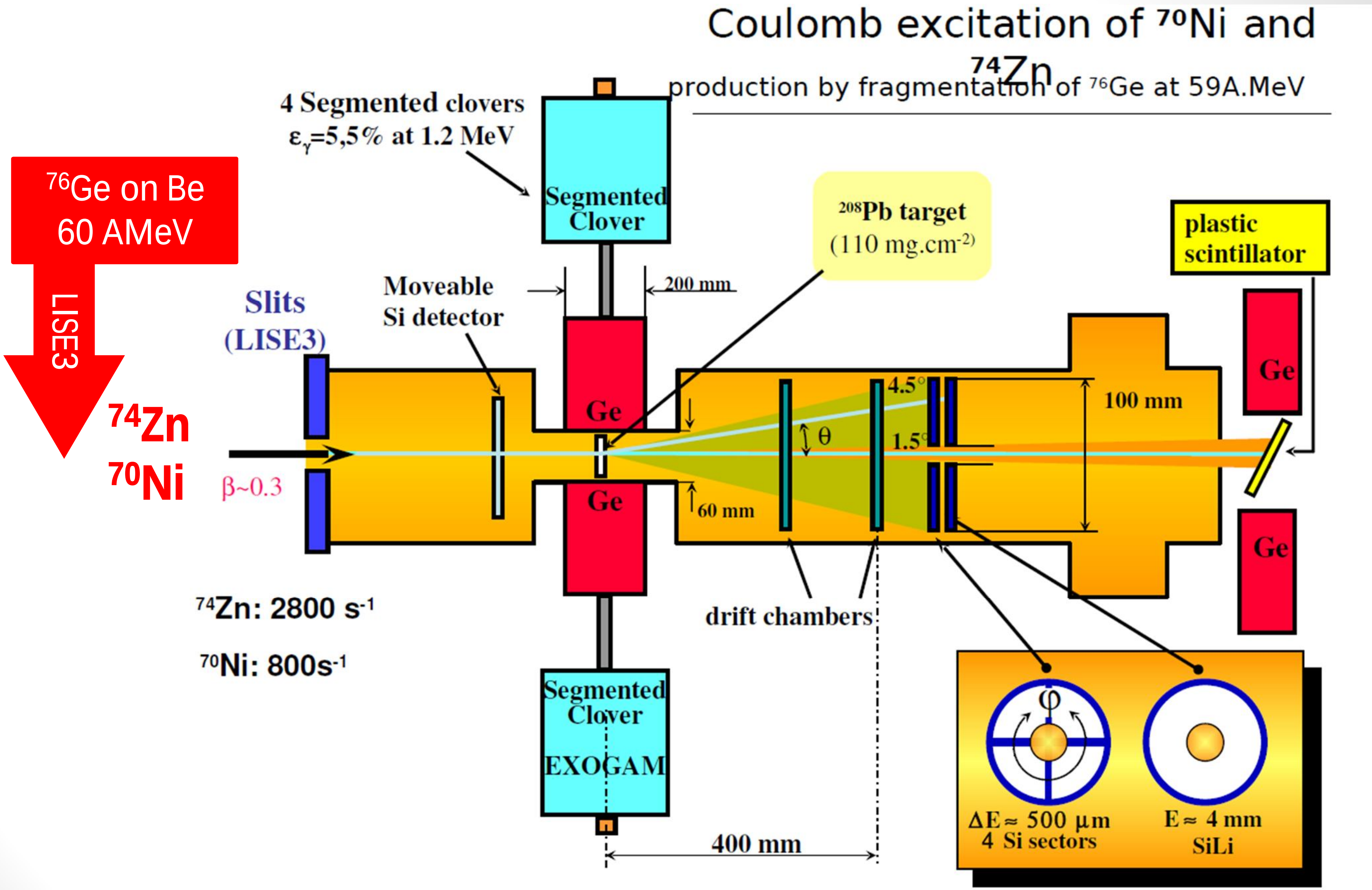


FIG. 2. (Color online) Energy levels of ^{68}Ni by present calculation (left panel) and by experiment (right panel) [19–21].

Enhanced core polarization in ^{70}Ni



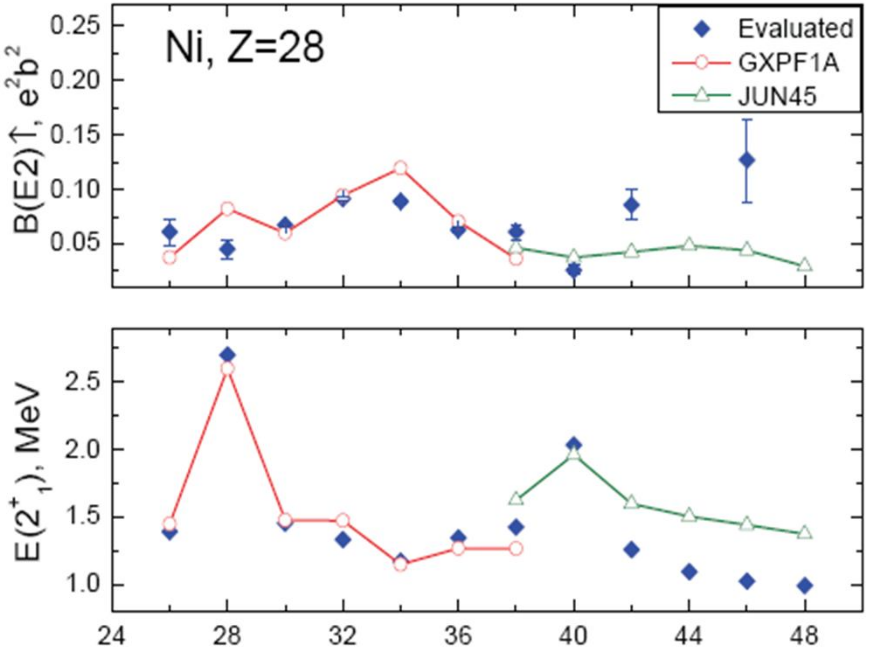
[Transparency by F. Azaiez, nipne seminar 2007]

Enhanced core polarization in ^{70}Ni

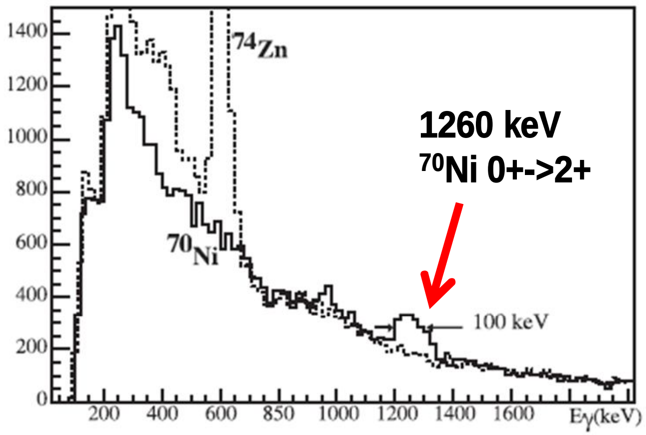
PRL 96, 232501 (2006) PHYSICAL REVIEW LETTERS week ending 16 JUNE 2006

Enhanced Core Polarization in ^{70}Ni and ^{74}Zn

O. Perru,[1] O. Sorlin,[1,9] S. Franchoo,[1] F. Azaiez,[1] E. Bouchez,[2] C. Bourgeois,[1] A. Chatillon,[2] J. M. Daugas,[3] Z. Dlouhy,[4] Zs. Dombrádi,[5] C. Donzaud,[1] L. Gaudefroy,[1] H. Grawe,[6] S. Grévy,[7] D. Guillemaud-Mueller,[1] F. Hammache,[1] F. Ibrahim,[1] Y. Le Coz,[2] S. M. Lukyanov,[8] I. Matea,[9,*] J. Mrazek,[4] F. Nowacki,[10] Yu.-E. Penionzhkevich,[8] F. de Oliveira Santos,[9] F. Pougheon,[1] M. G. Saint-Laurent,[9] G. Sletten,[11] M. Stanoiu,[1] C. Stodel,[9] Ch. Theisen,[2] and D. Verney[1]



W LETTERS week ending 16 JUNE 2006



Isotope	N_n (10^8)	N_γ	ϵ_{geom}	ϵ_{ang}	$B(E2)_{rel}$ (e^2 fm^4)
^{76}Ge	2.19(2)	6450(150)	0.78	1.06	2680(80)[a]
^{74}Zn	2.78(8)	5630(140)	0.74	1.06	2040(150)
^{70}Ni	1.58(14)	675(90)	0.75	0.98	860(140)

[a]Ref. [20].

^{74}Ni from 74Co β-decay

C. Mazzocchi et al. / Physics Letters B 622 (2005) 45–54

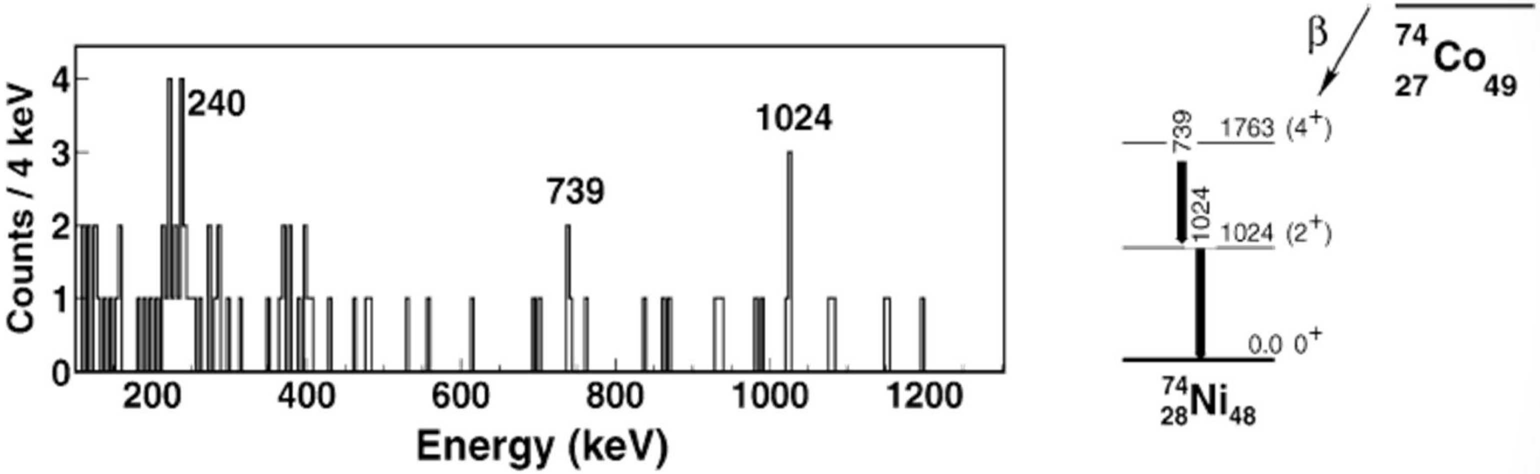
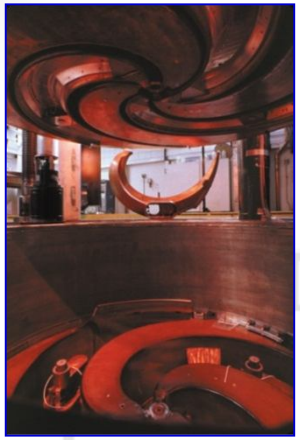
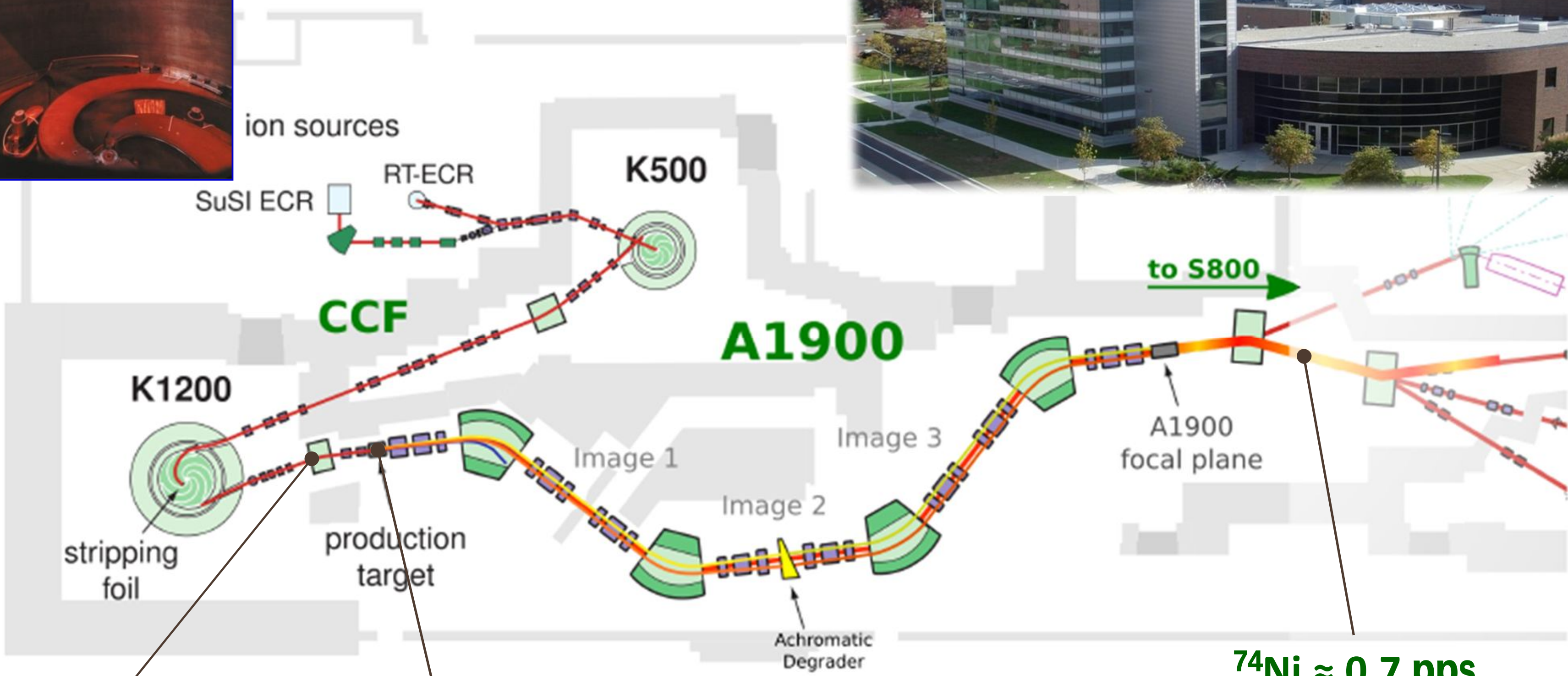


Fig. 2. Left-hand side: β-coincident γ-ray spectrum correlated with an implanted ^{74}Co ion. The correlation time amounted to 100 ms. The γ lines are labeled with their energy in keV. See text for details. Right-hand side: decay scheme of $^{74}Co \rightarrow {}^{74}Ni$.

Radioactive ion beam production at NSCL





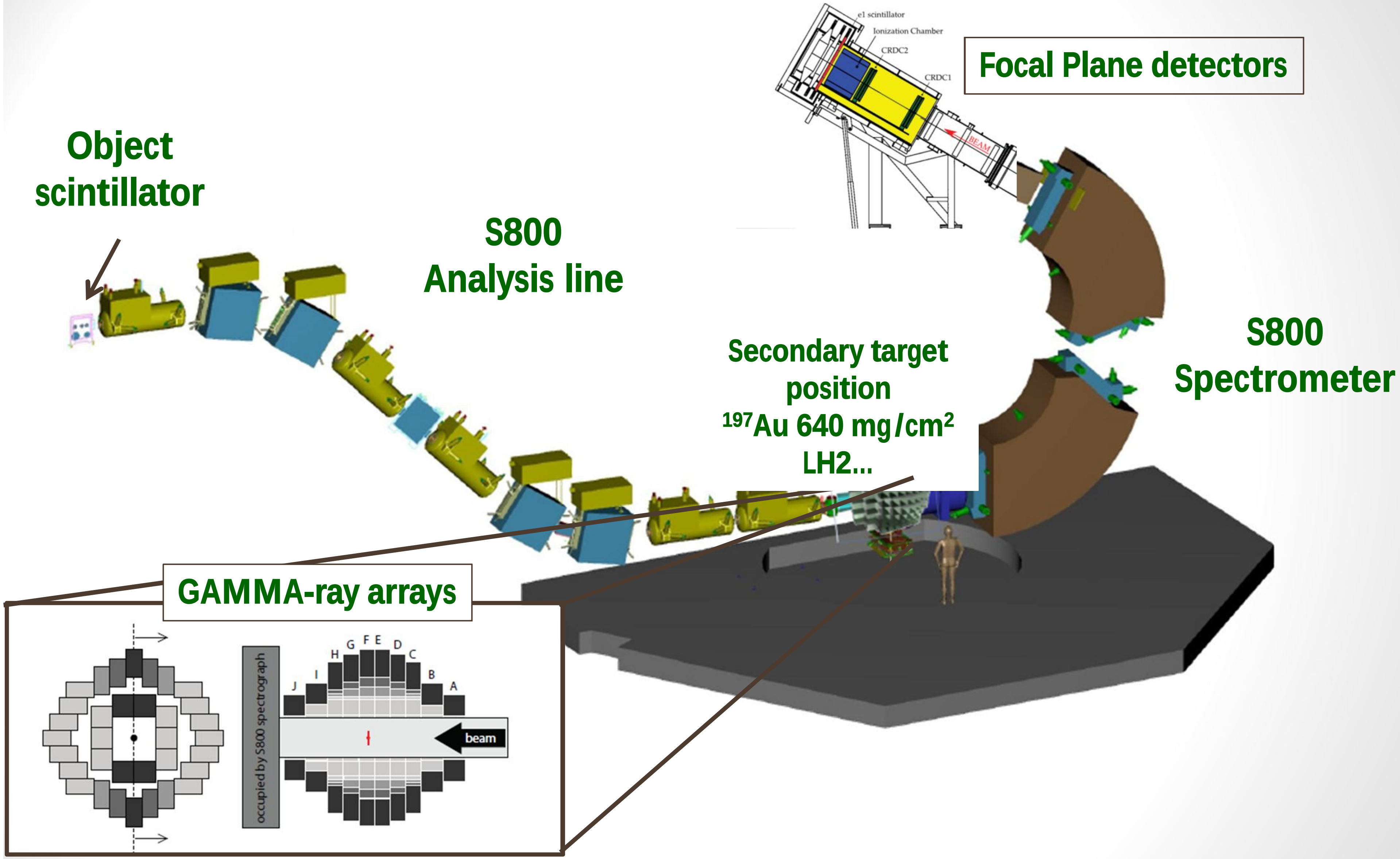
$^{86}Kr^{34+}$ @ 140 AMeV

^{9}Be 399 mg/cm^2

$^{74}Ni \approx 0.7$ pps

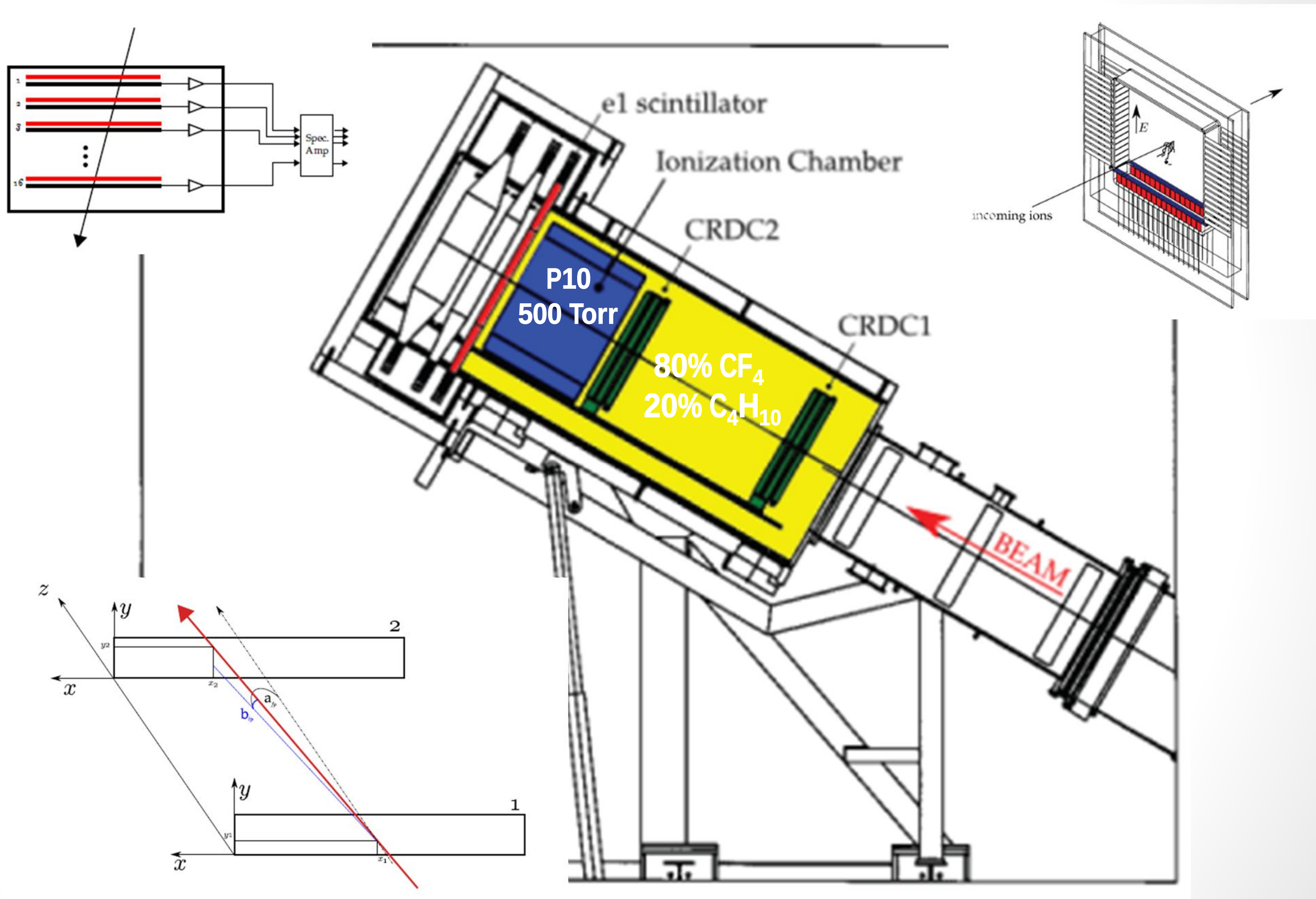
dp/p = 3%

Experimental setup

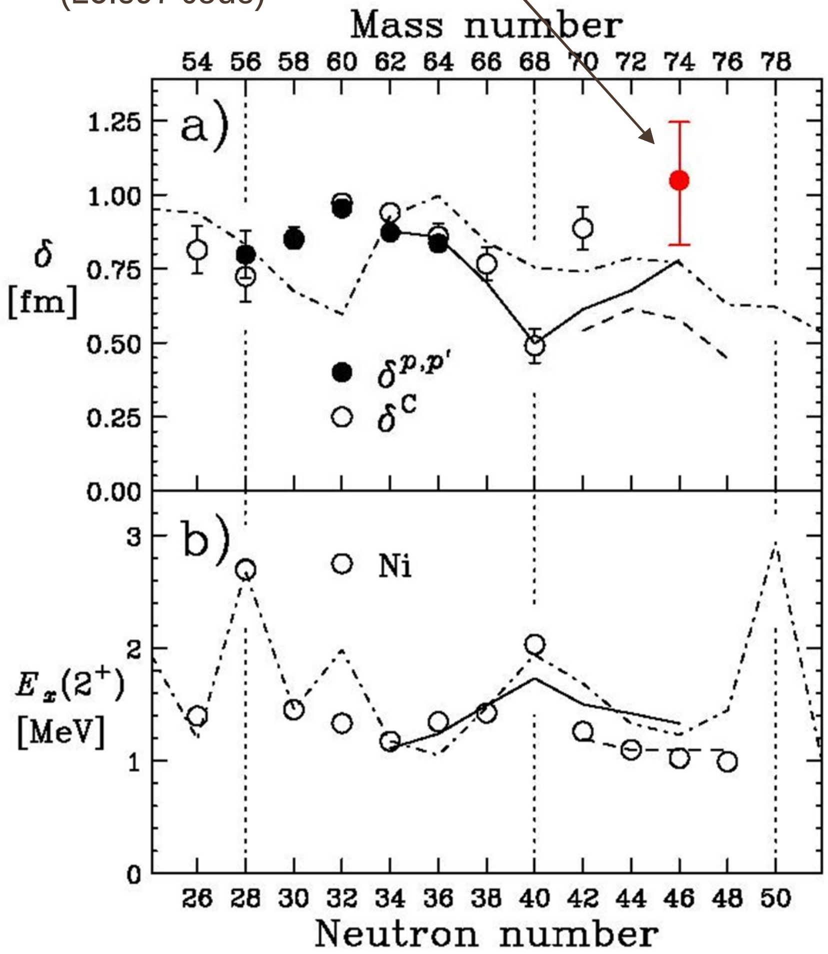


S800 Focal Plane Detectors

[D. Bazin et al., NIM B 204, 629 (2003)]



δ(p,p') extracted from proton inelastic scattering cross section using distorted wave theory. (ECIS97 code)

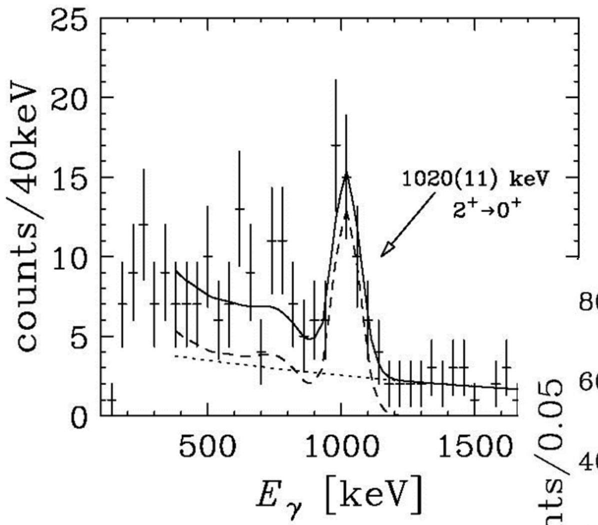


$$\delta^C = \beta_2^C R = \frac{4\pi}{3ZeR}\sqrt{B(E2; 0^+ \rightarrow 2^+)}$$

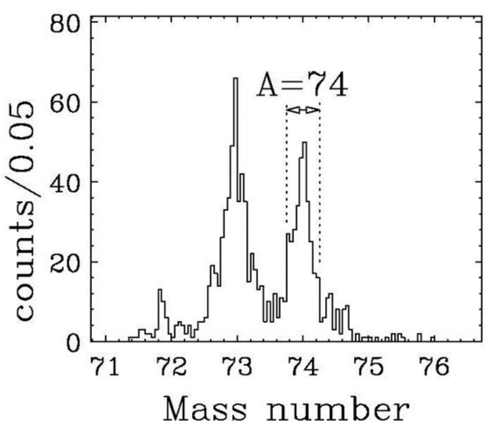
Assuming comparable deformation lengths also for the neutron rich part of the chain:

$$\delta^{(p,p')} \approx \delta^C$$

B(E2) = 1270(380) e^{2}fm^4

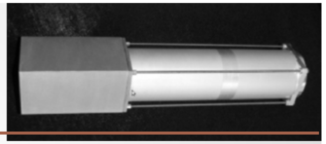


N=46

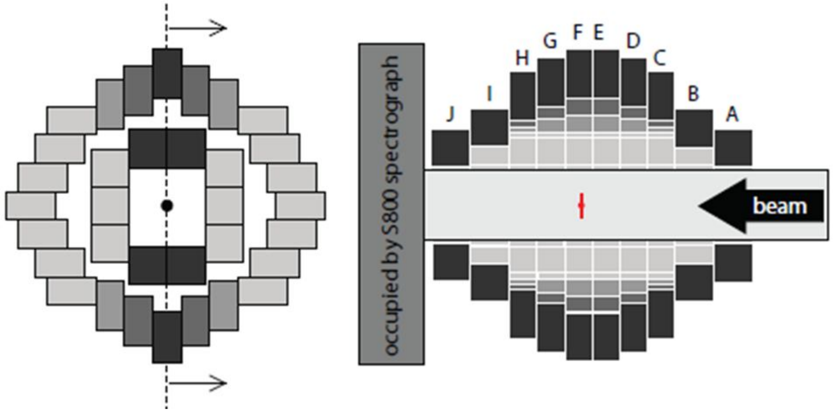


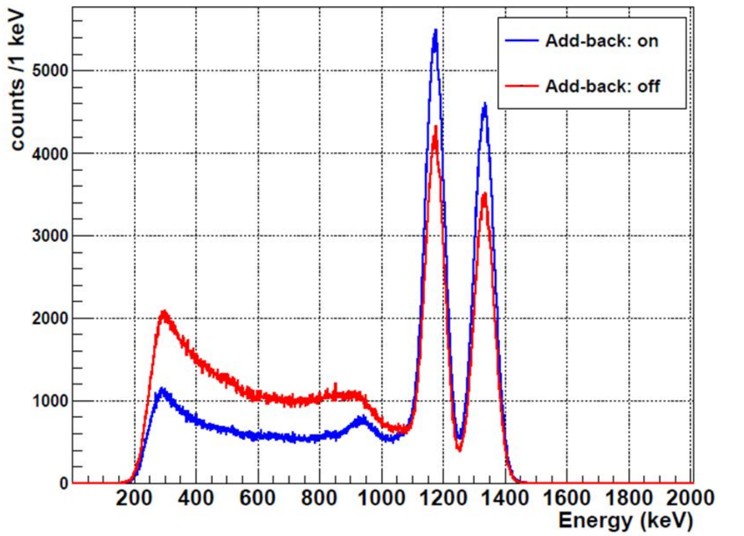
[N. Aoi et al, Phys. Lett. B 602, 302 (2010)]
[B. Pritychenko et al, At. Dat. And Nucl. Dat. Tab. 98, 4 (2012) 798]

^{74}Ni CAESAR scintillator array

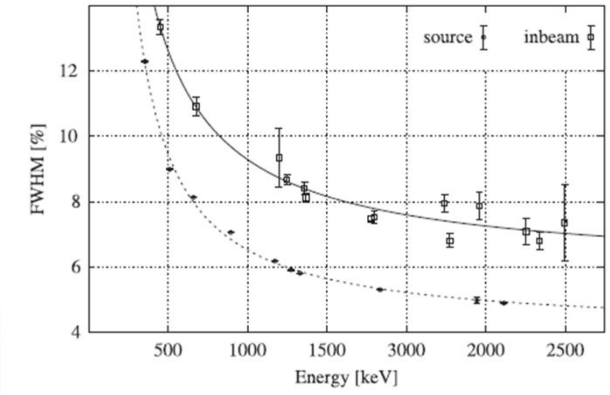


[D. Weisshaar et al., NIM A 624, 615 (2010)]

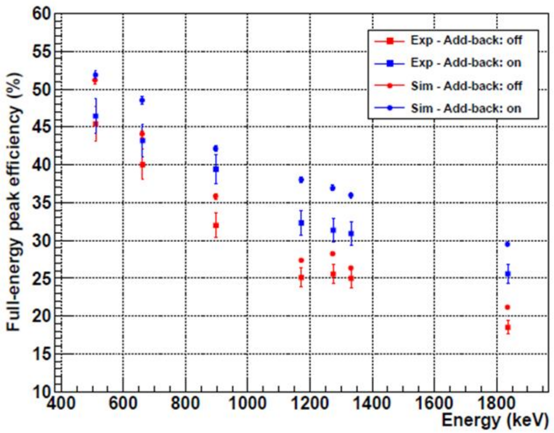




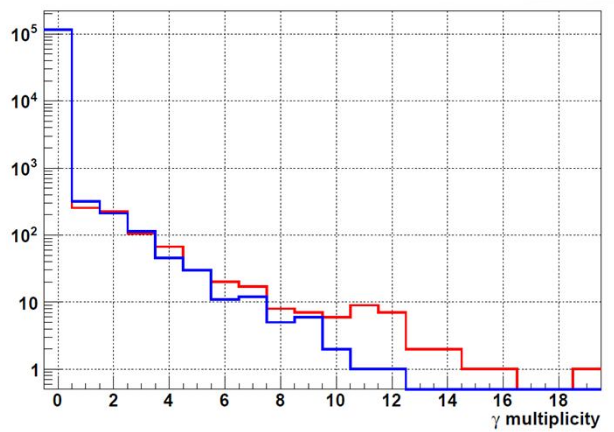
CAESAR Resolution



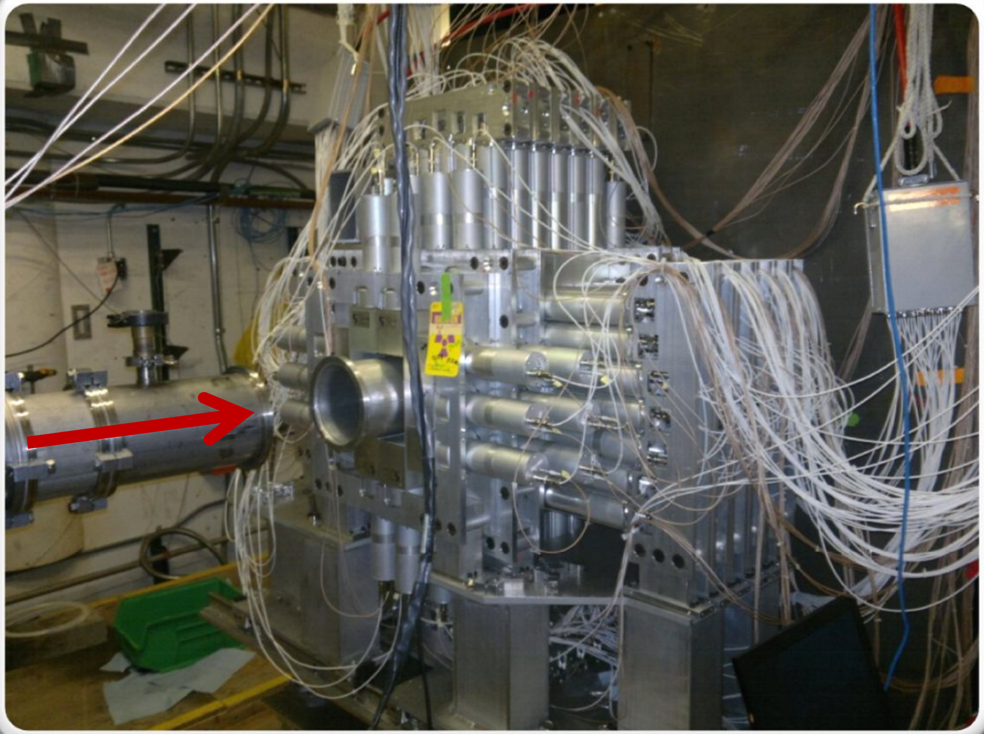
CAESAR Efficiency



Experimental gamma-rays multiplicity



The S800 spectrometer and the CAESAR array

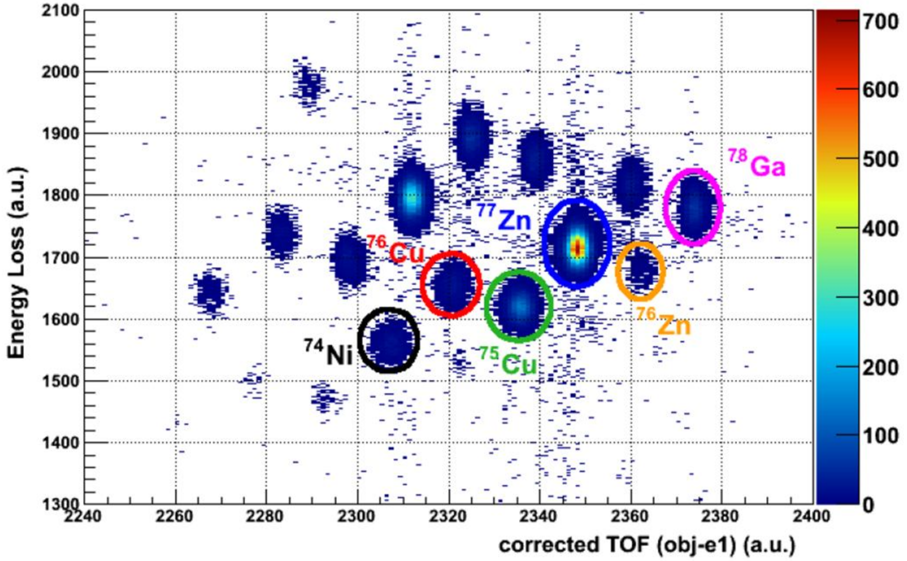


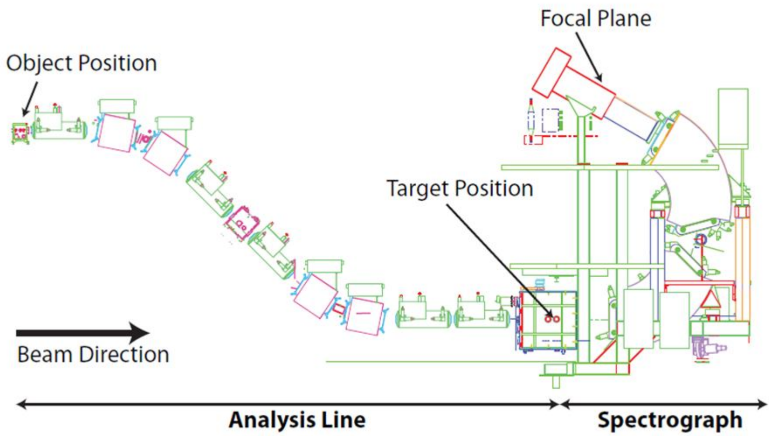
CAESAR array

CAESAR array + S800 spectrometer

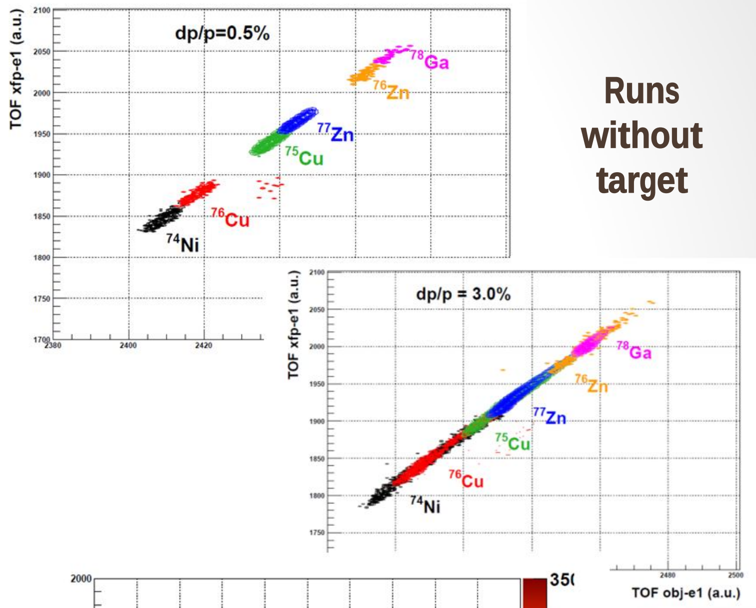
^{74}Ni Beam Tagging and Particle Identification

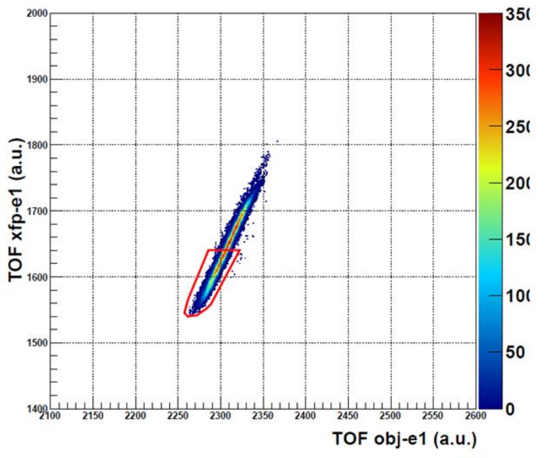
Focal plane PID





Beam Tagging

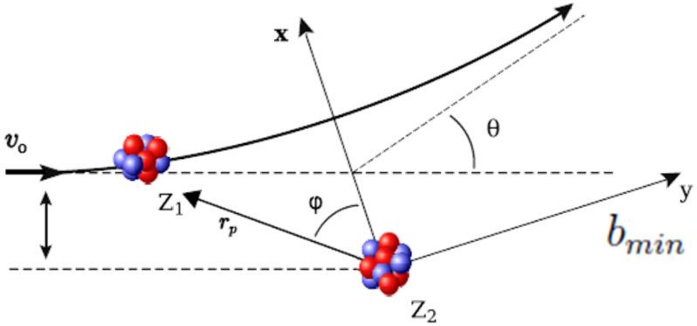




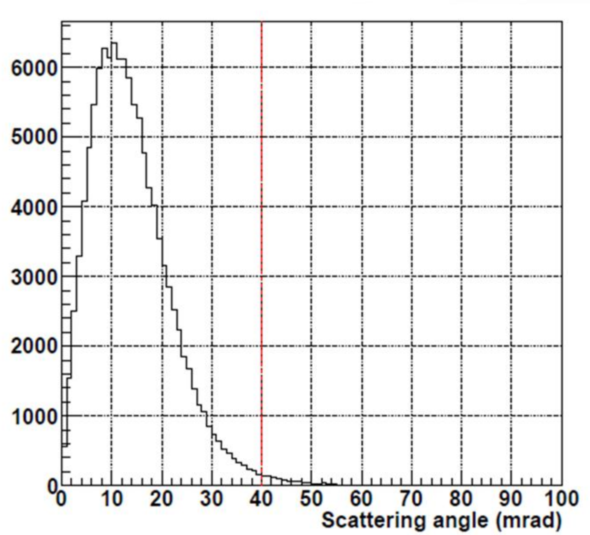
^{74}Ni Data analysis: particle and gamma ray time gates

Impact parameter selection:

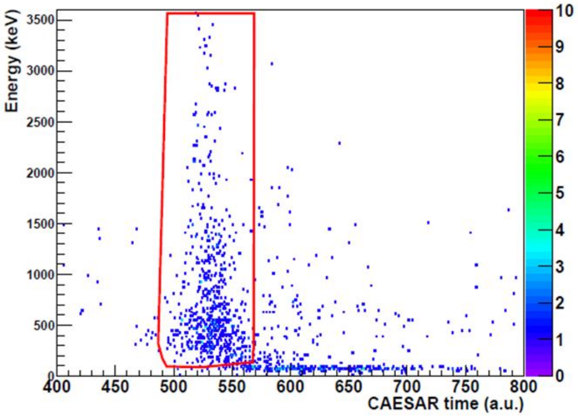
$$R_{int} = r_0(A_p^{1/3} + A_t^{1/3}) + 2\text{ fm}$$

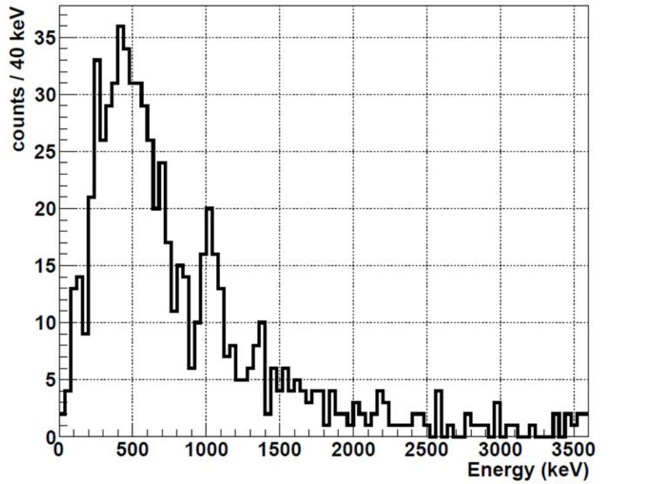


$$b_{min} = \frac{a_0}{\gamma}\cot\left(\frac{\theta^{CM}_{max}}{2}\right)$$



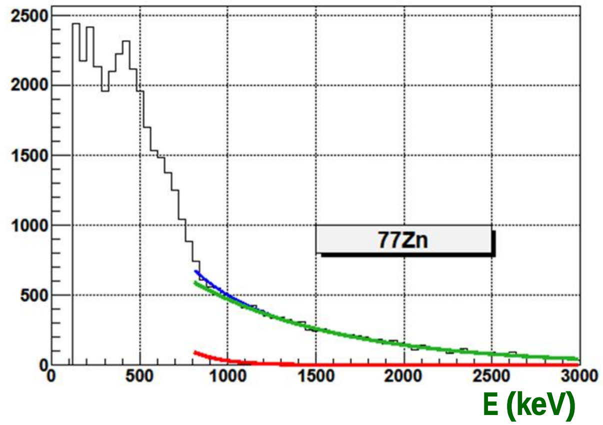
Energy-time gamma-rays gate:

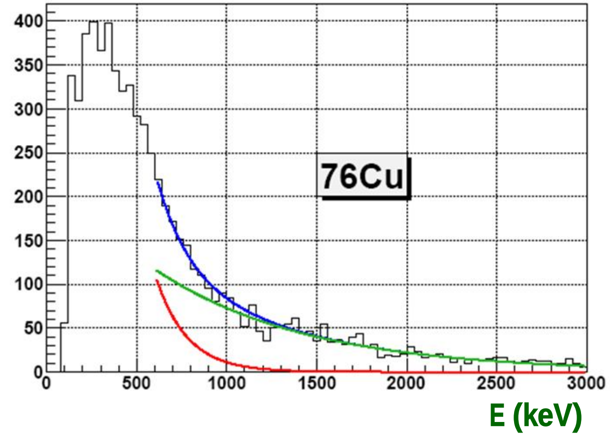




Two main issues

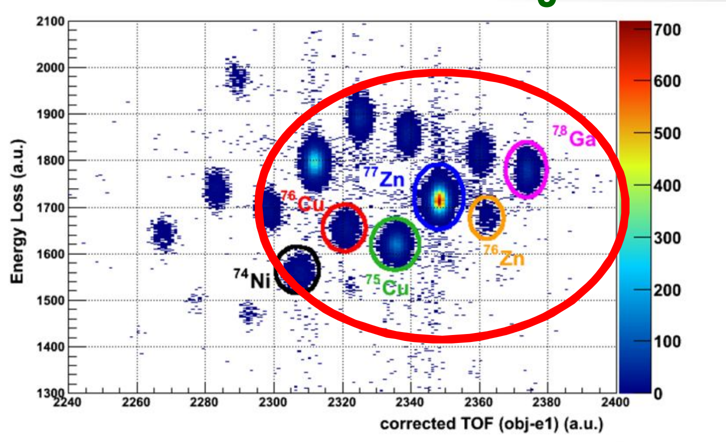
Background modeling



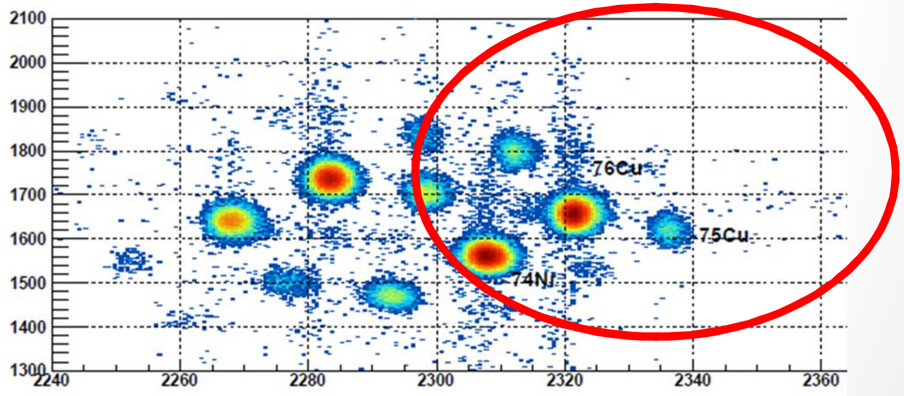


Beam contamination

Ungated PID



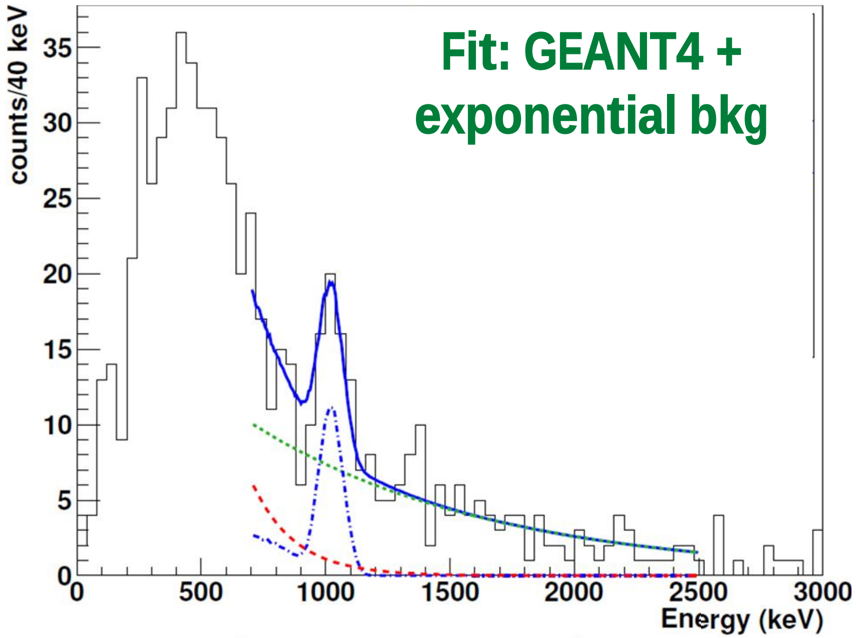
Gated PID



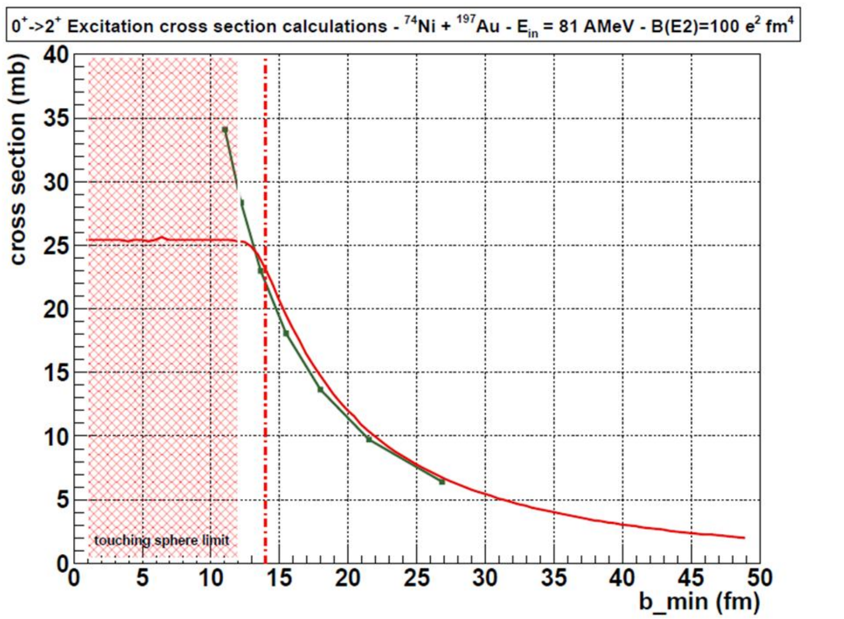
EPAX: 76Cu 1p-1n K.O. : σ = 29 mb

→ $N_{K.O.}$ =18±9 → N_{γ} = 9 ±5

^{74}Ni Event by event analysis and gamma-ray spectra



N_B	$(34.8 \pm 0.1) \cdot 10^4$
$N^{\gamma}_{0+\to 2+}$	108 ± 27
N_T	$(1.94 \pm 0.01) \cdot 10^{21}$



[A. Winther and K. Alder, Nucl. Phys. A319, 518 (1979)]

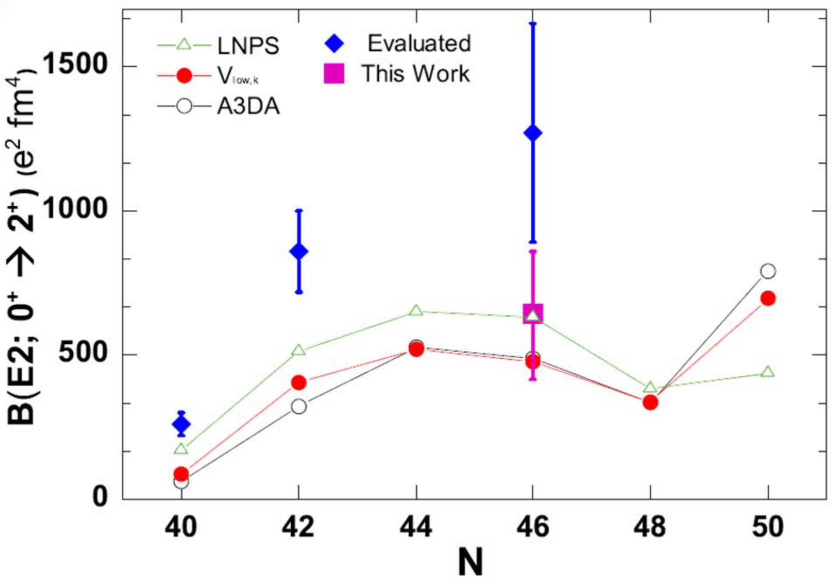
$$\sigma_{\pi\lambda} \approx \left(\frac{Z_1 e^2}{\hbar c}\right)^2 \frac{B(\pi\lambda, 0 \to \lambda)}{e^2} \pi b_{min}^{2(1-\lambda)} \times \begin{cases} (\lambda-1)^{-1} & \text{for } \lambda \geq 2 \\ 2\ln\left(\frac{b_{max}}{b_{min}}\right) & \text{for } \lambda = 1 \end{cases}$$

→ $N_\gamma = 99 \pm 28$

$$\sigma_{0+\to 2+} = \frac{N^{\gamma}_{2+\to 0+}}{N_B \quad N_T}$$

$= 148^{+50}_{-52}$ mb ⇨ $B(E2; 0^+ \to 2^+) = 642^{+216}_{-226}\ e^2\,fm^4$

Results



	p	ν	
LNPS	*pf*	*p*, $f_{5/2}$, $g_{9/2}$ $d_{5/2}$	[1]
V_{low_k}	$f_{7/2}$, $p_{3/2}$	*p*, $f_{5/2}$, $g_{9/2}$,$d_{5/2}$	[2]
A3DA	*pf* $g_{9/2}d_{5/2}$		[3]

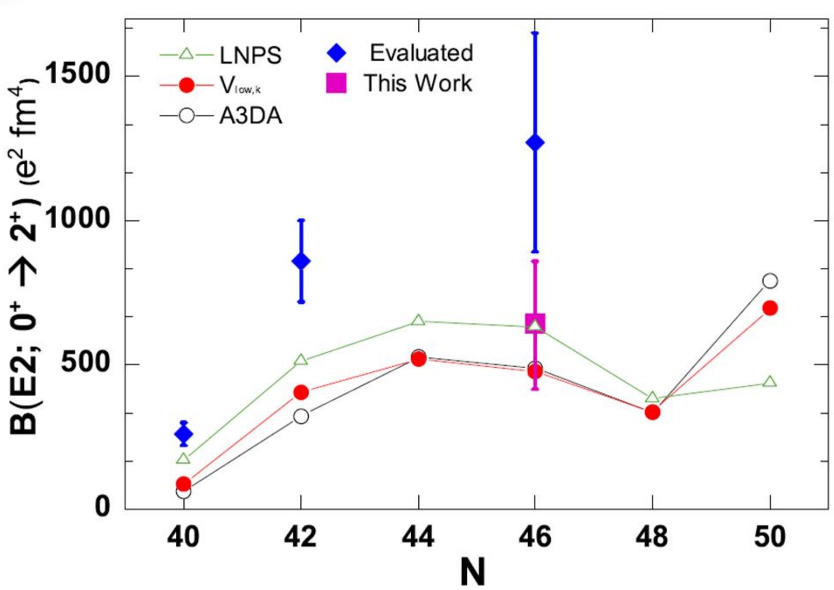
[1] K. Sieja, F. Nowacki, Phys Rev C 85, 051301(R) (2012)
K. Sieja, F. Nowacki, arXiv:1201.0373v1 (2012)
S. M. Lenzi et al, Phys Rev C 82, 054301 (2010)
[2] L. Coraggio, PRC 89, 024319 (2014)
L. Coraggio et al., Prog. Part. Nucl. Phys 62, 135 (2009)
[3] N. Shimizu et al., Progr Theor Exp. Phys, 01A205 (2012)
Y. Tsunoda et al., PRC 89, 031301(R) (2014)

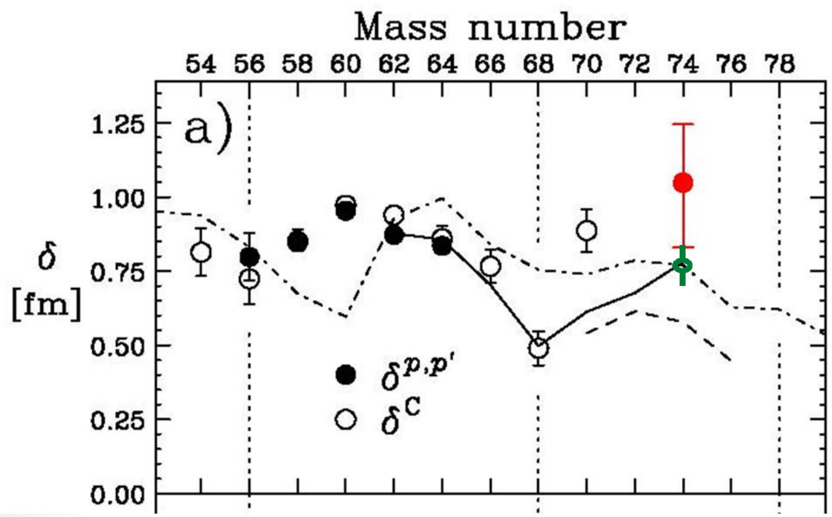
The B(E2; $0^+ \rightarrow 2^+$) value obtained in the intermediate energy Coulomb excitation provides new important information for the understanding of the Ni isotopic chain towards the ^{78}Ni doubly magic nucleus.

1-The collectivity enhancement suggested by the (p,p') experiment seems quenched when using purely electromagnetic probes;

2-The obtained values can be used to benchmark the Model Space and Interactions used for Shell Model Calculations far from stability.

^{74}Ni Discussion and outlook





Inelastic scattering data compared to Coulex results allow to disentangle the proton/neutron excitation matrix elements. For the ^{74}Ni isotope, their difference could be an indication of the relative proton/neutron cores polarization leading to different deformation. A higher degree of accuracy is needed to constrain the B(E2) error bar and provide quantitative Mn/Mp ratio information.

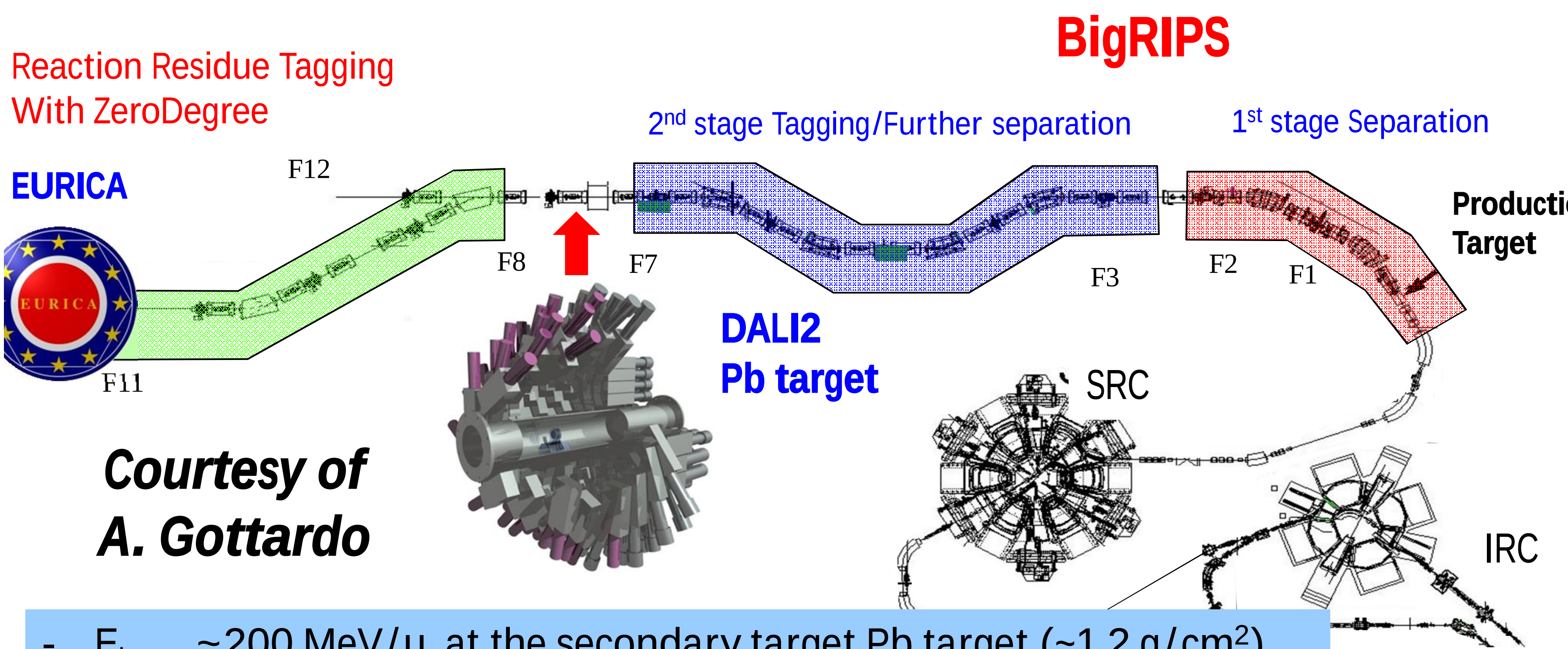
$$B(E\lambda, J_i \rightarrow J_f) = \frac{|M_p|^2}{2J_i + 1} .$$

$$\frac{M_n}{M_p} = \frac{b_p}{b_n}\left(\frac{\delta_{(p,p')}}{\delta_{\mathrm{em}}}\left(1 + \frac{b_n}{b_p}\frac{N}{Z}\right) - 1\right)$$

Exp	2.4±0.8
LNPS	1.8

^{73,74,75}Ni coulex at RIKEN

Double experiment: in beam with DALI2 + decay spectroscopy with WASABI-EURICA



- E_{beam} ~200 MeV/u at the secondary target Pb target (~1.2 g/cm^2)
- Beam centered on ^{72}Fe: lower ^{74}Ni transmission

^{238}U 345 MeV/u 9 pnA → **^{9}Be target** → **fission 0.4 μb** → **BigRIPS: transmission 1.4% from LISE**

^{74}Ni: 15 pps

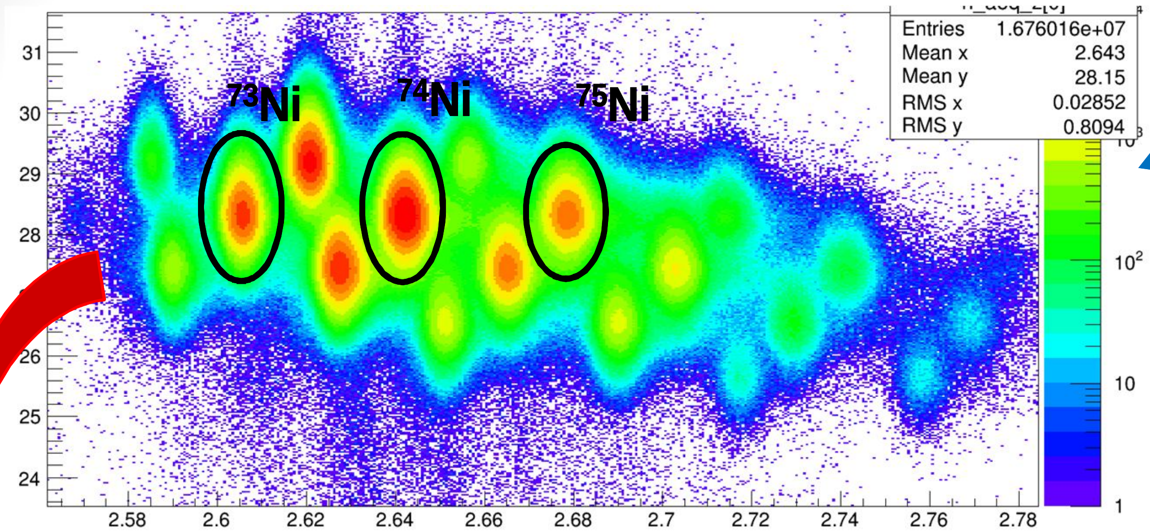
^{73}Ni: 10 pps

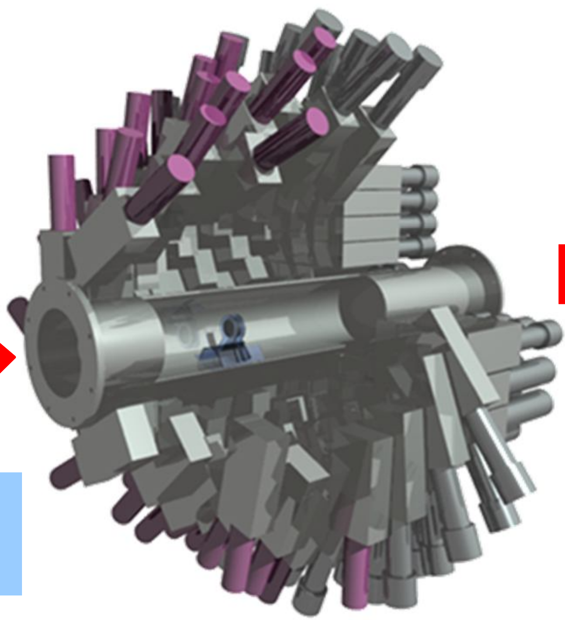
^{75}Ni: 3 pps

73-74-75Ni coulex @ RIKEN

Courtesy of A. Gottardo

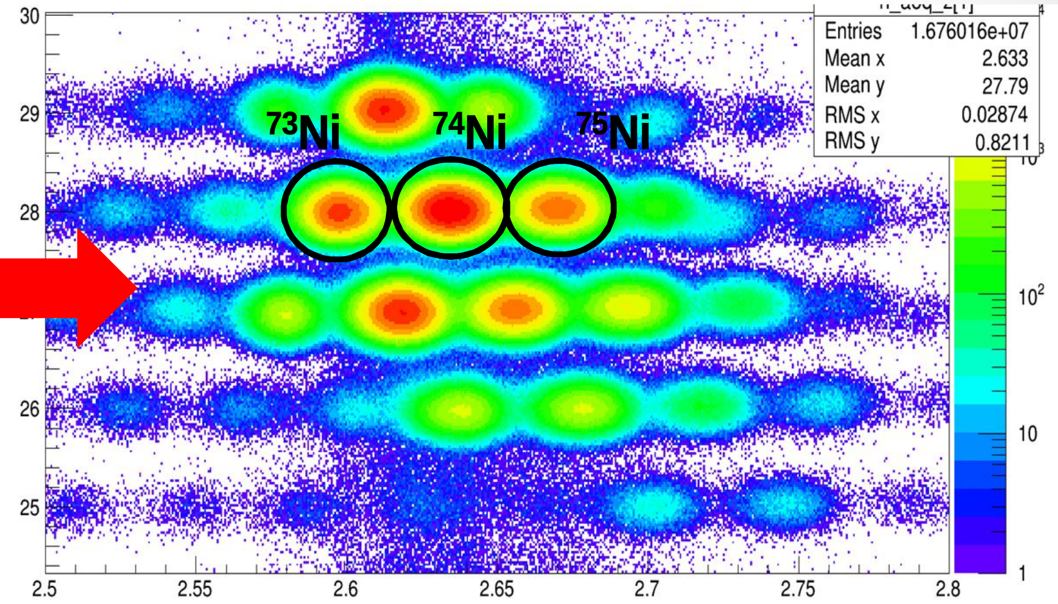
ID plot before coulex Pb target





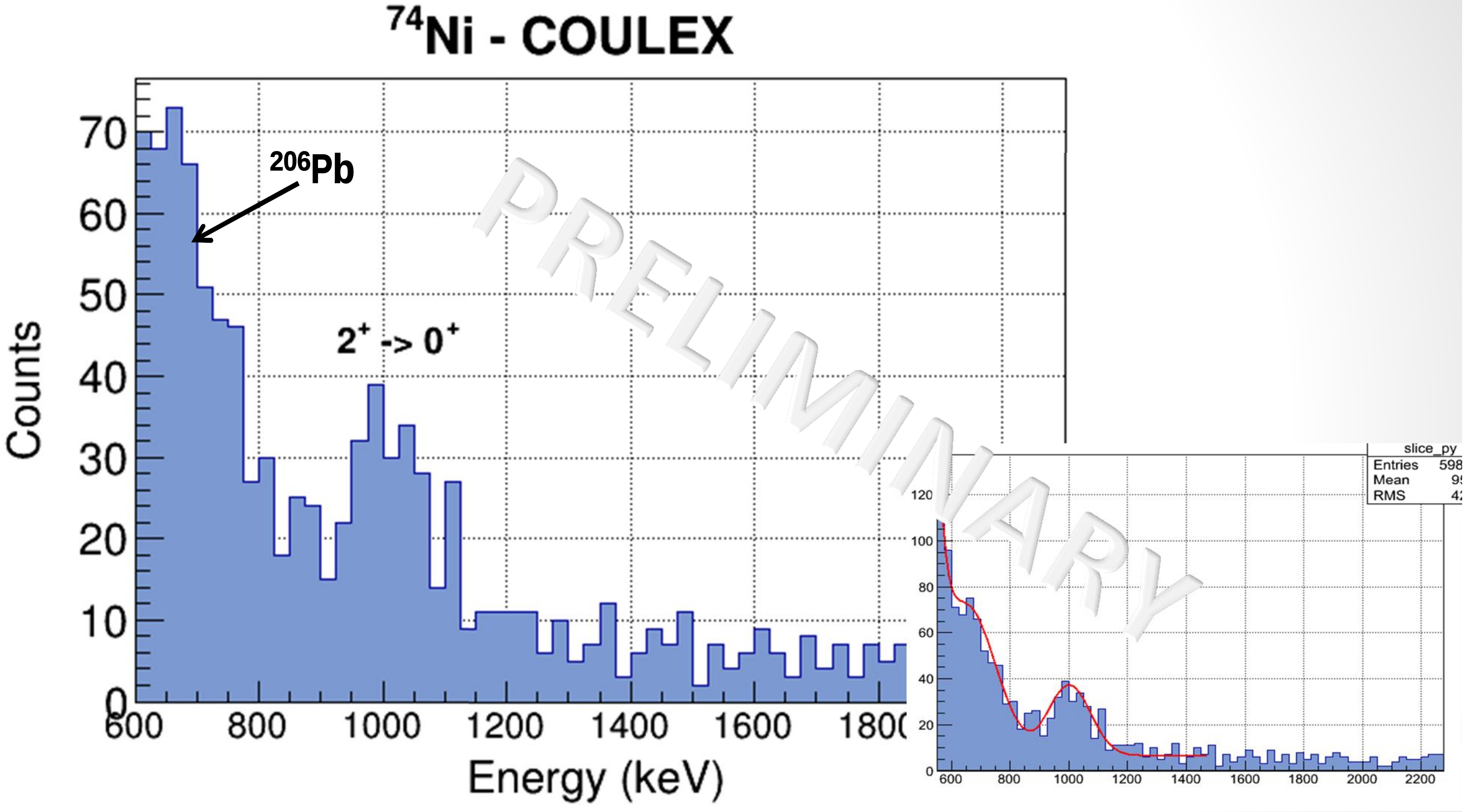
Pb target ~1 g/cm²

ID plot after coulex Pb target



$^{73-74-75}$Ni coulex @ RIKEN

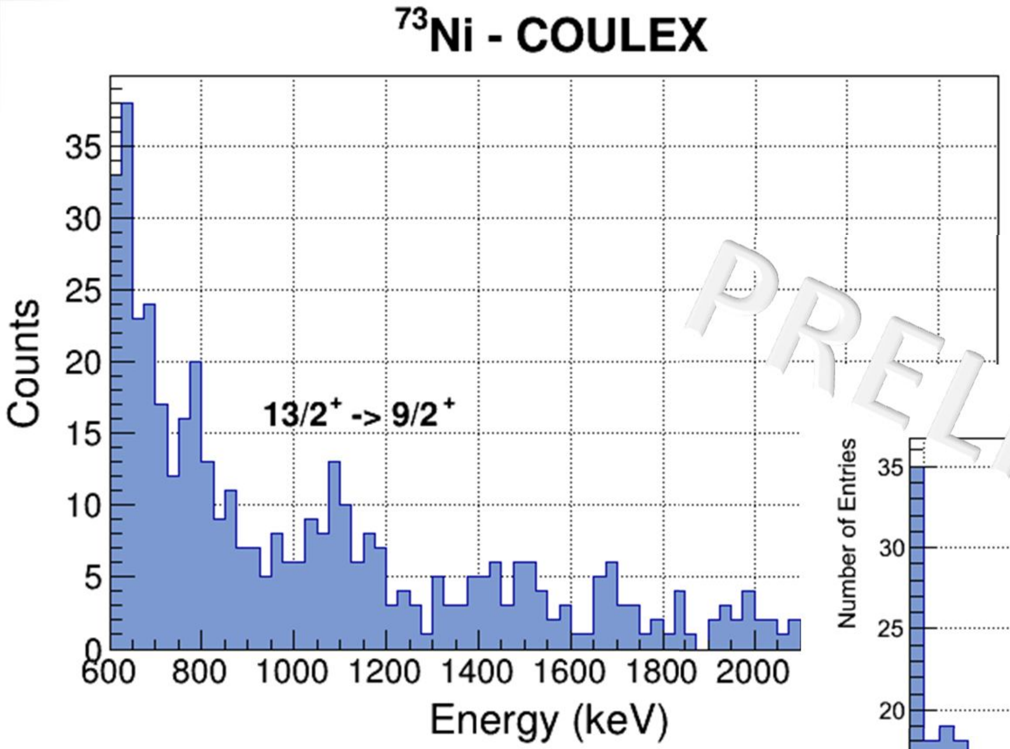
Courtesy of A. Gottardo

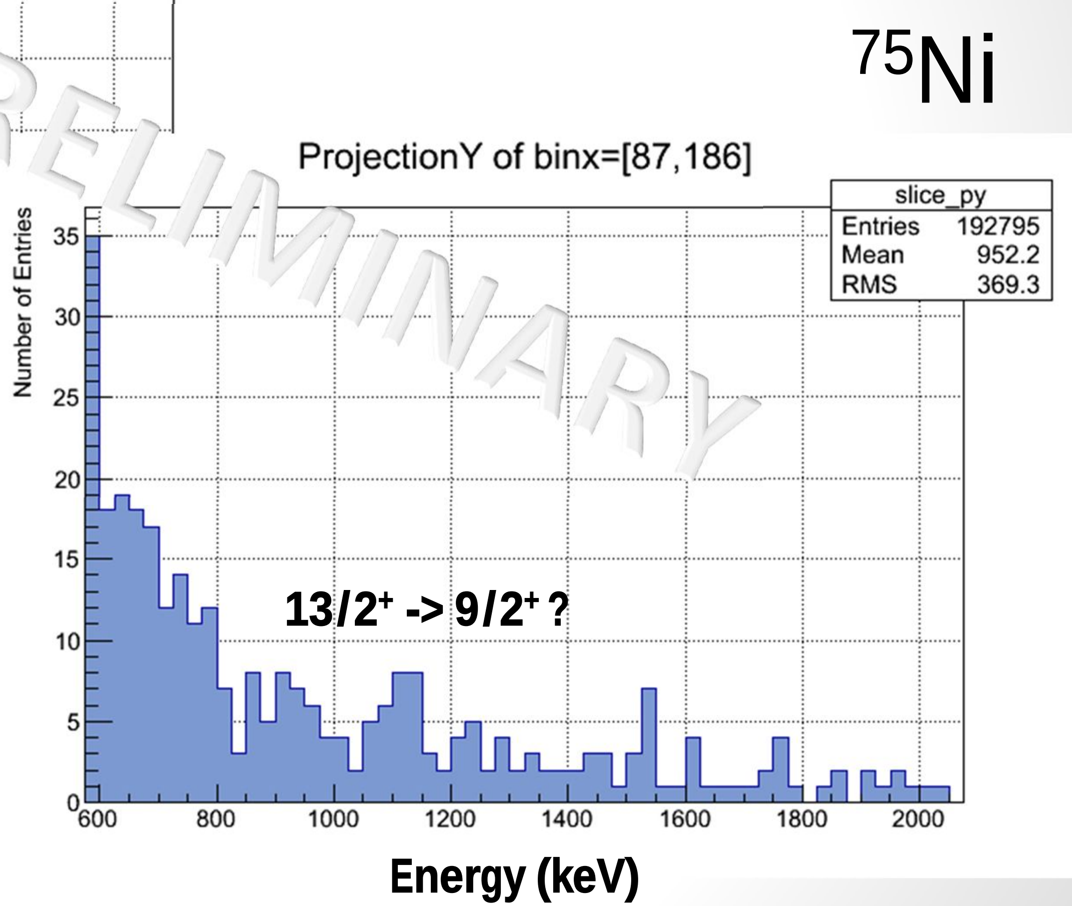


~ 170 events on the peak

$^{73\text{-}74\text{-}75}$Ni coulex @ RIKEN

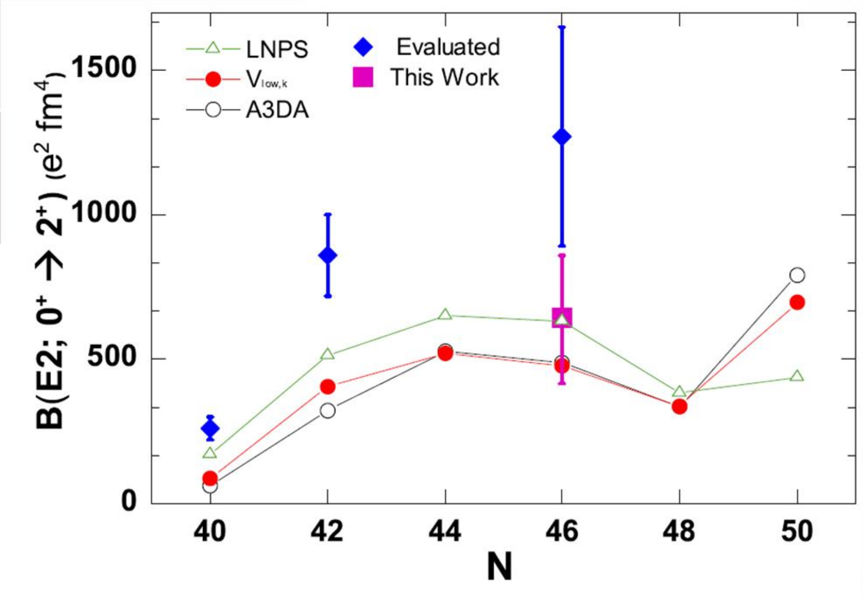
Courtesy of A. Gottardo





Summary and partial conclusion

^{70}Ni	GANIL NSCL Gretina	Coulex (p,p’)	Perru et al, PRL 96, 232501 (2006) L. Cartegni Ph.D. Under analysis
^{72}Ni	NSCL Gretina Gretina	 Plunger (p,p’)	 K. Kolos DNP13, Under analysis
^{74}Ni	NSCL NSCL RIKEN	(p,p’) Coulex Coulex	N. Aoi et al, PLB 692 (2010) 302 T. Marchi et al, submitted RIKEN data under analysis
^{76}Ni			
^{78}Ni			



stay tuned!

Near future in Europe. Beams …

68, 56, 65, 70, 59, 67, 69, 57, 66 Ni

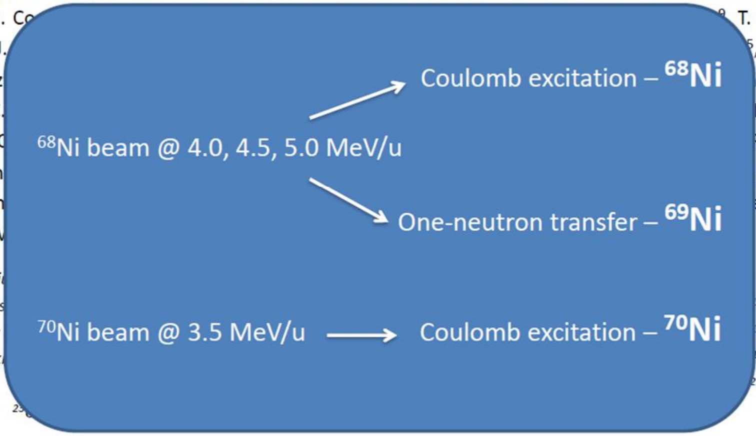
Element	A number	Half life	SC or PSB*	Yield at ISOLDE (ions/µC)	Target material
Ni	56	6.077 d 12	PSB	3.6E+03	ZrO_2
Ni	56	6.077 d 12	PSB	2.0E+03	UC_x
Ni	57	35.60 h 6	PSB	5	
Ni	59	7.6E+4 y 5	PSB	6	
Ni	65	2.5172 h 3	PSB	2	
Ni	65	2.5172 h 3	PSB	7	
Ni	66	54.6 h 3	PSB	1	
Ni	67	21 s 1	PSB	7	
Ni	68	19 s +3-6	PSB	1	
Ni	68	19 s +3-6	PSB	4	
Ni	69 - g	11.4 s 3	PSB	8	
Ni	69 - g	11.4 s 3	PSB	2	
Ni	70		PSB	1	
Ni	57 - g	35.60 h 6	SC	5	
Ni	65 - g	2.5172 h 3	SC	1	
Ni	65 - g	2.5172 h 3	SC	2	

In the ISOLDE Yield Database the beam inten… ISOLDE PSB (PS Booster with 1.0 or 1.4 GeV… yields are listed yet from the PSB, one can get an idea from looking at the available

Characterising excited states in and around the semi-magic nucleus ^{68}Ni using Coulomb excitation and one-neutron transfer

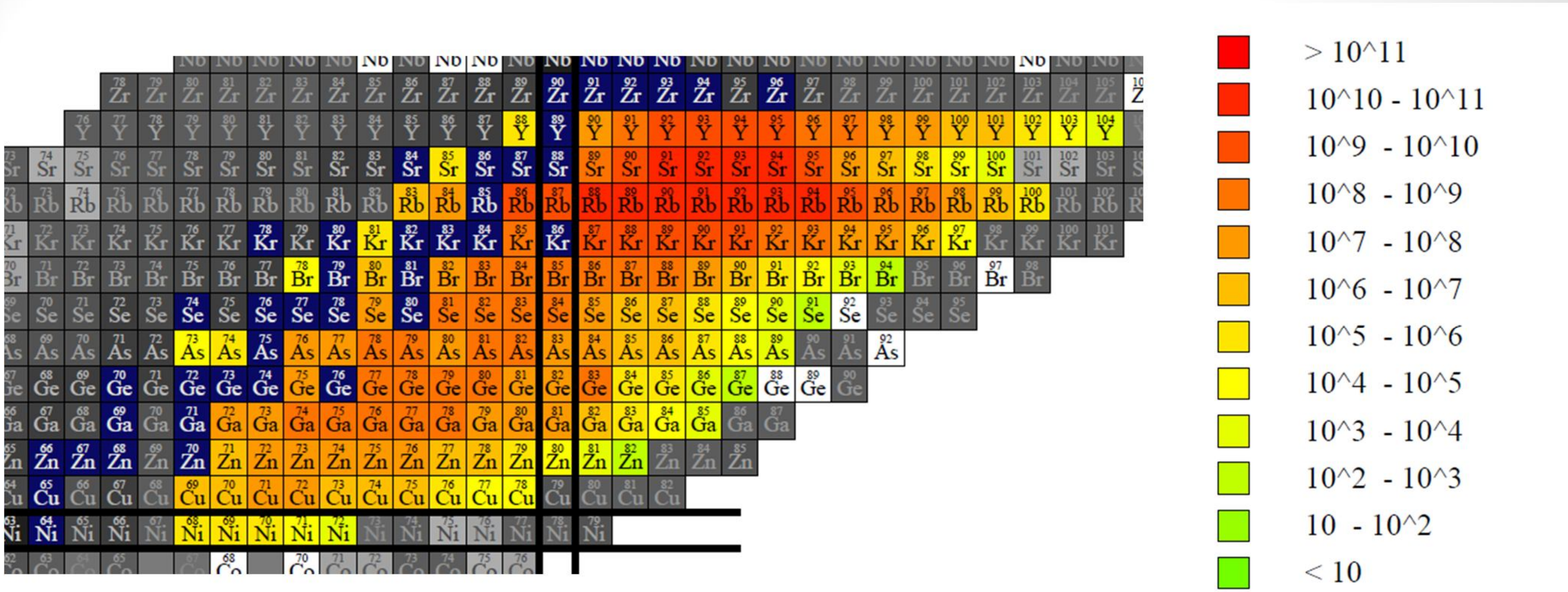
L. P. Gaffney[1], F. Flavigny[1], M. Zielińska[2], K. Kolos[4], A. N. Andreyev[5], M. Axiotis[6], D. L. Balabanski[7], A. Blazhev[8], J. Cederkäll[9], T. E. Co… T. Duguet[2], C. Fahlander[9], S. J. … L. Grente[2], R. K. Grzywacz… Kröll[17], A. Lagoyannis[6], C. … Nowak[14], F. Nowacki[21], A. … Rahkila[15], R. Raabe[1], G. Rain… Sharp[10], C. Sotty[1], O. Sorlin… enander[3], K. Wimmer[23], P. W…

[1]KU Leuven, Belgi… of York, U.K.; [6]NCSR-Demokritos… [10]Univeristy of Manchester, U.K.; … [15]University of Jyväskylä; Helsink… [18]Univeristy of Athens, Greece; … [22]University of Ioannina, Greece; …



KU LEUVEN · THE UNIVERSITY of TENNESSEE KNOXVILLE · Irfu · cea · ISOLDE

Near future in Europe: ALTO, ISOLDE, GANIL, SPES



Letter of intent: J. J. Valiente Dobón (INFN, LNL, Italy)

Spectroscopy studies around ^{78}Ni and beyond N=50 via transfer and Coulomb excitation reactions

… and detectors. Active Target Detector: ACTAR

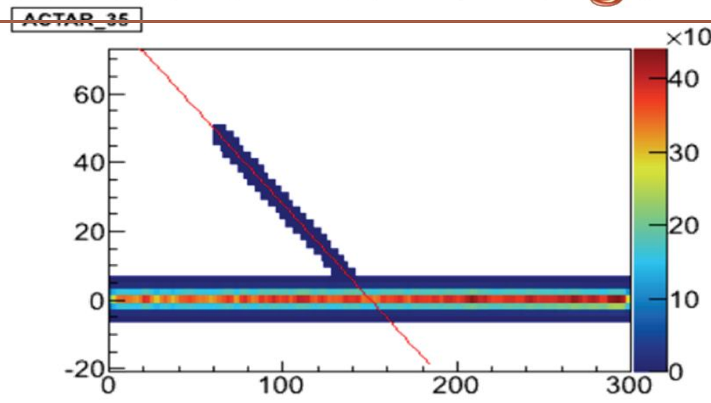
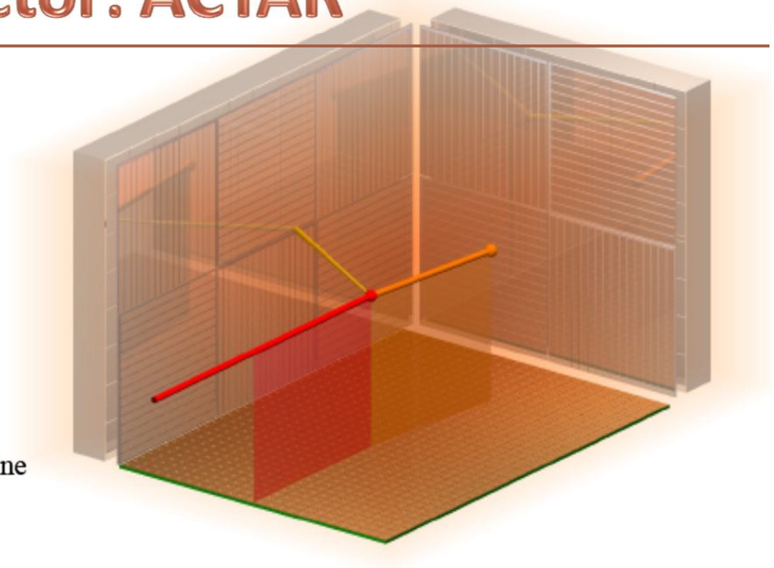
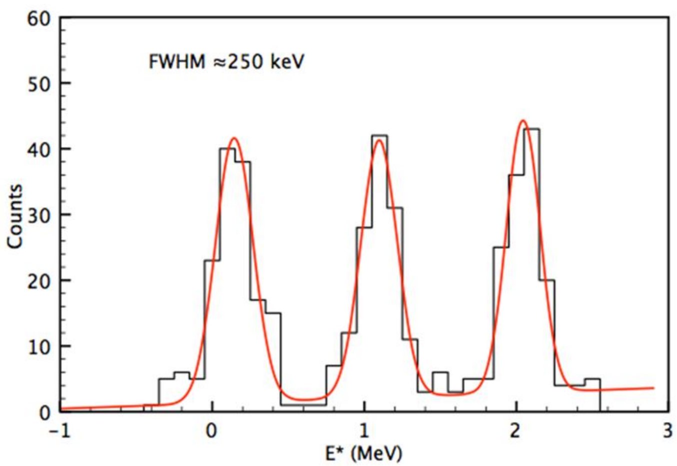
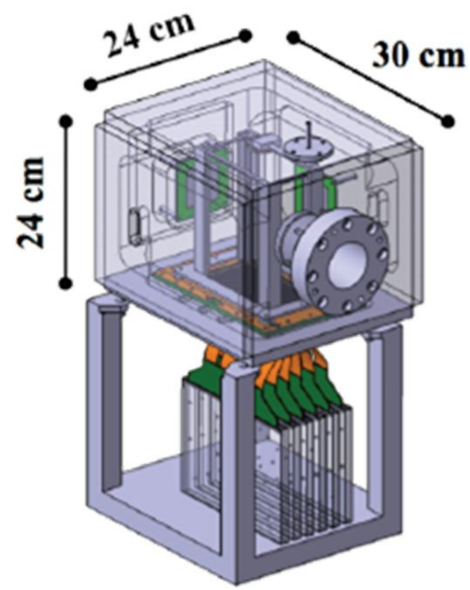


Fig. 4: Sample digitized trace for a ^{132}Sn(d,p) reaction with 2x2mm^2 sized pads. The red line corresponds to the fitted trajectory used for determining the range of the proton.

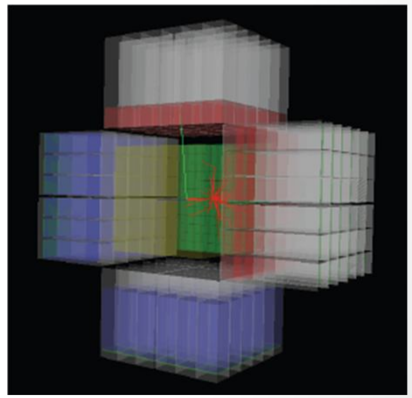




Proton energy resolution for the ^{78}Ni(d,p) reaction at 8 AMeV with 4x4 mm^2 pads



ACTAR + γ-ray array



ERC: ACTAR TPC - G. Grynier - GANIL
ERC: SpecMAT - R. Raabe - K.U. Leuven

ACTAR collaboration: http://pro.ganil-spiral2.eu/spiral2/instrumentation/actar-tpc]

Collaboration: e09031 - NSCL

T. Marchi,[1, 2] G. De Angelis,[1] J.J. Valiente-Dobón,[1] V. Bader[3], T. Baugher,[3] D. Bazin,[3] J. Berryman,[3] A. Bonaccorso,[4] R. Clark,[5] L. Coraggio,[6] E. L. Crawford,[5] M. Doncel,[7] E. Farnea,[8] A. Gade,[3] A. Gadea,[9] A. Gargano,[6] T. Glasmacher,[3] A. Gottardo,[1, 2] F. Gramegna,[1] N. Itaco,[10,6] P.R. John,[8,2] R. Kumar,[11] S. M. Lenzi,[8,2] S. Lunardi,[8,2] S. McDaniel,[3] C. Michelagnoli,[8,2] D. Mengoni,[8,2] V. Modamio,[1] D.R. Napoli,[1] B. Quintana,[12] A. Ratkiewicz,[3] F. Recchia,[8,2] E. Sahin,[1] R. Stroberg,[3] D. Weisshaar,[3] K. Wimmer,[3] and R. Winkler[3]

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[10]Dipartimento di Fisica, Università "Federico II", Napoli, Italy
[11]Deenbandhu Chhoturam University of Science and Technology, Haryana, 131039 India
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