

Influence of neutron enrichment on de-excitation properties

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- **GANIL**
- **Reaction mechanisms at intermediate energies**
- **Evaporation**
- **INDRA-VAMOS experiment**

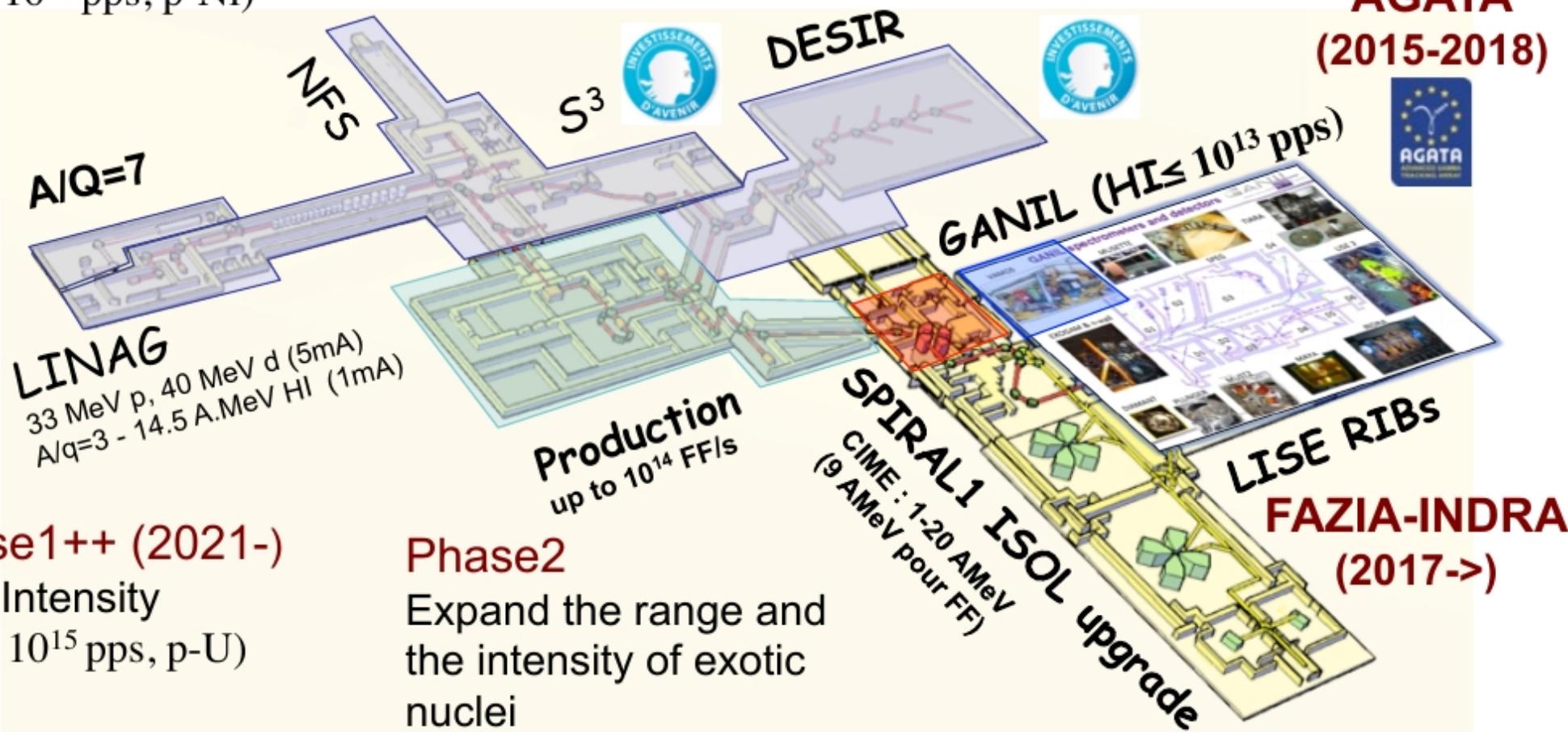
GANIL-SPIRAL2 Mid-term Roadmap

Phase1 (2016-)

Increase the intensity of stable beams
High intense neutron source
(HI $\leq 10^{15}$ pps, p-Ni)

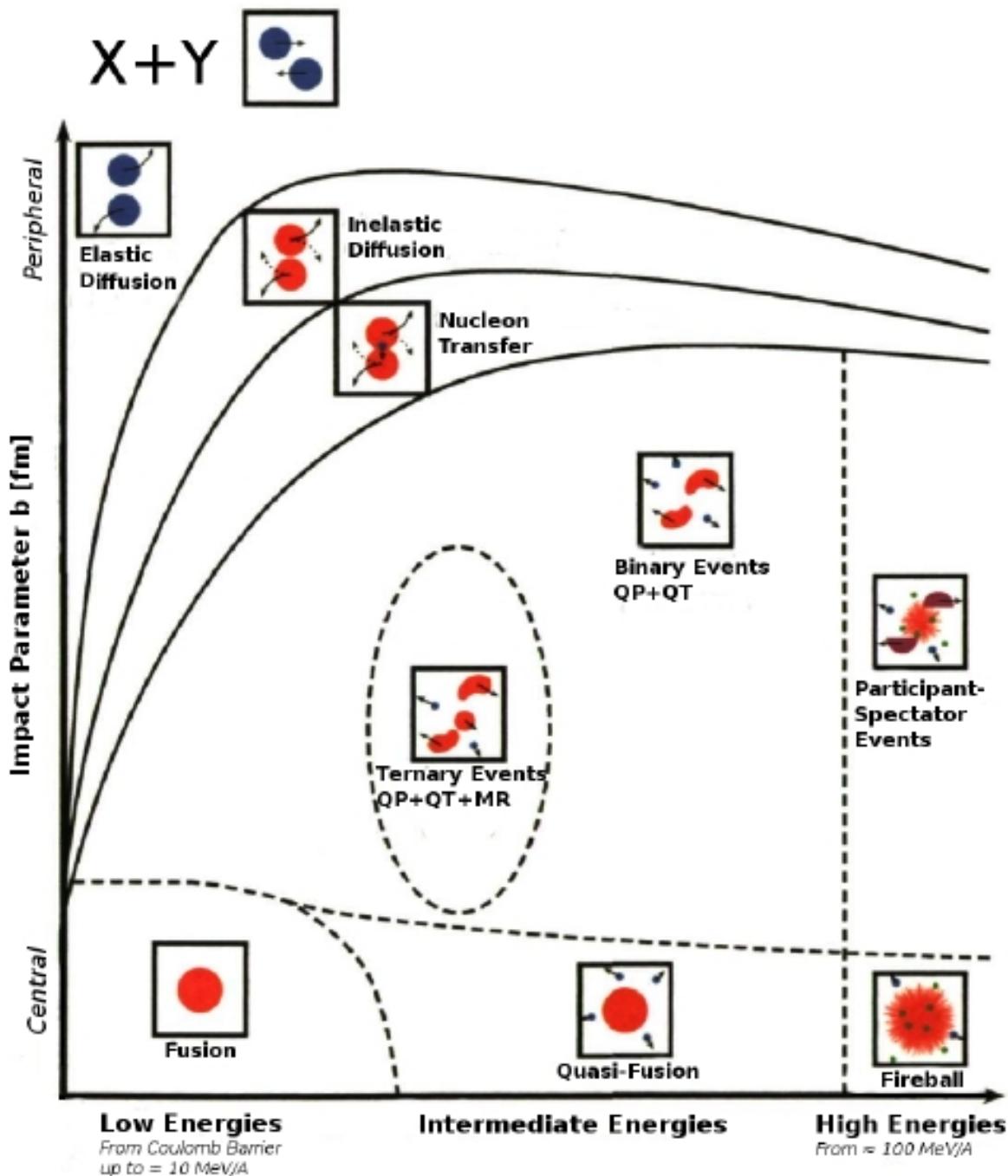
DESIR Phase1+ (2020-)

Low energy facility

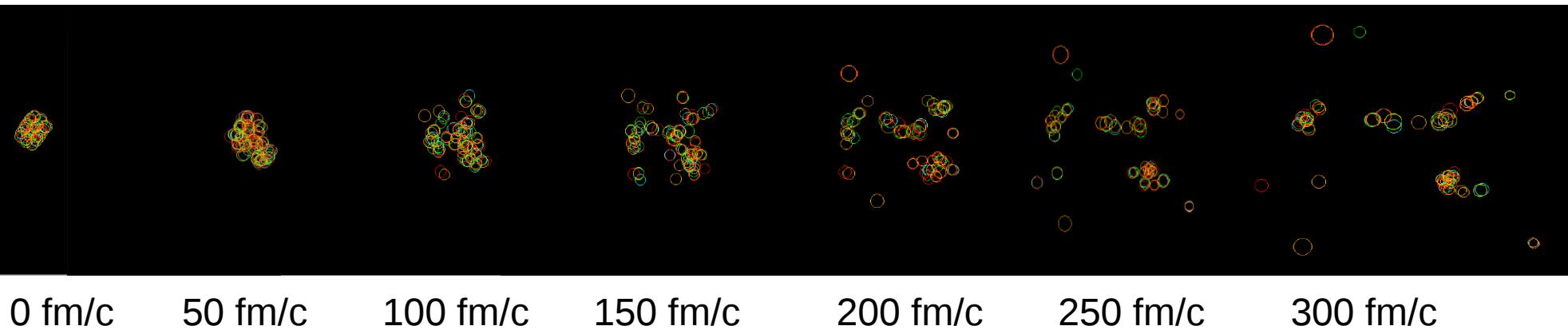


SPIRAL1 Upgrade (2017-)
New light RIBs from
beam/target fragmentation

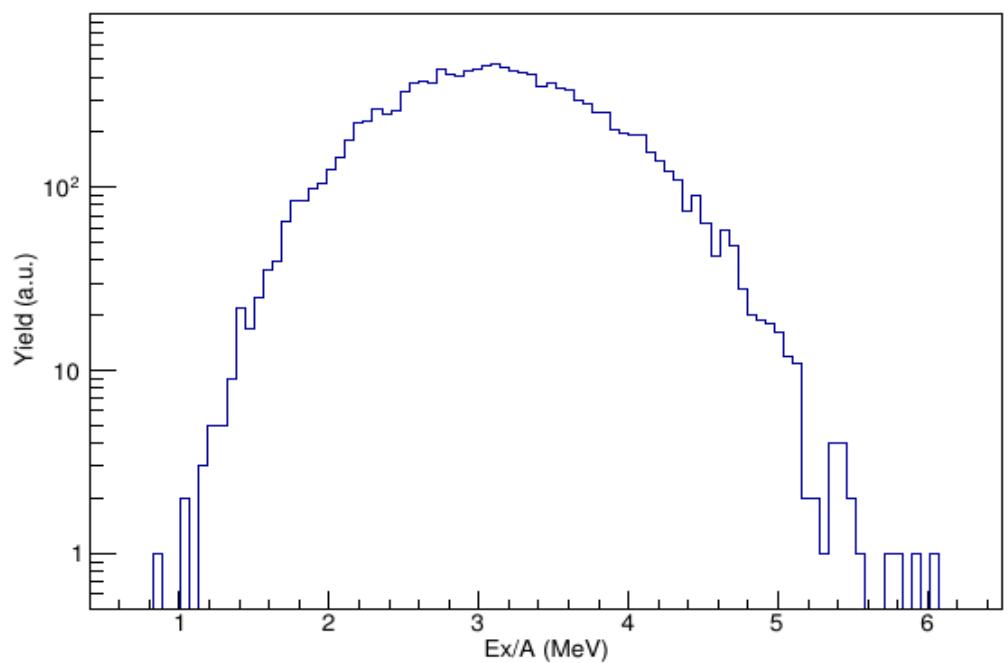
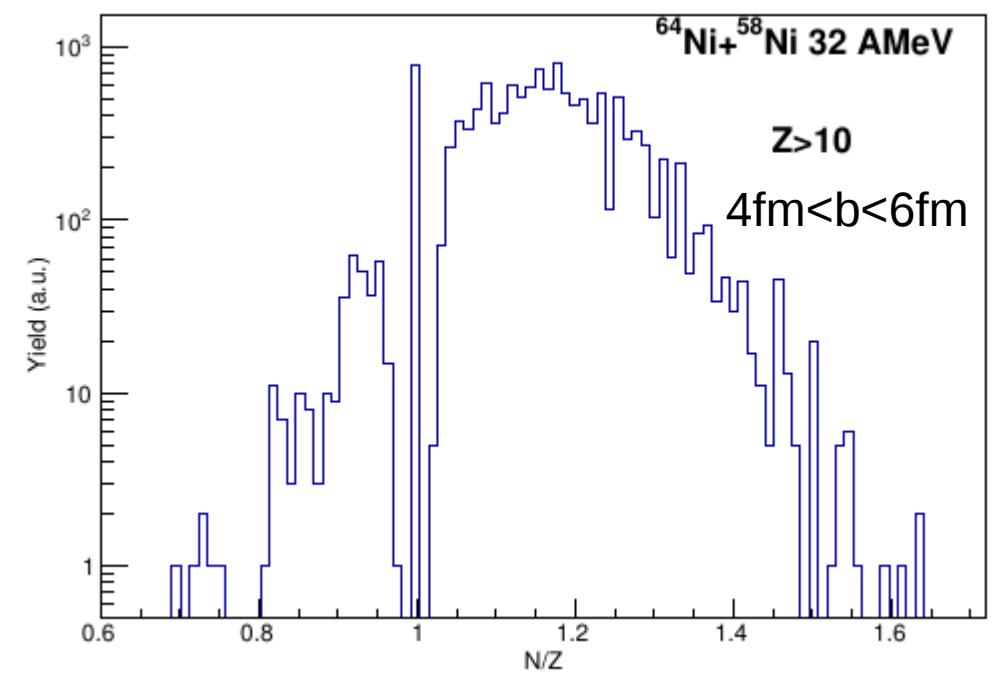
Reaction mechanisms at intermediate energies



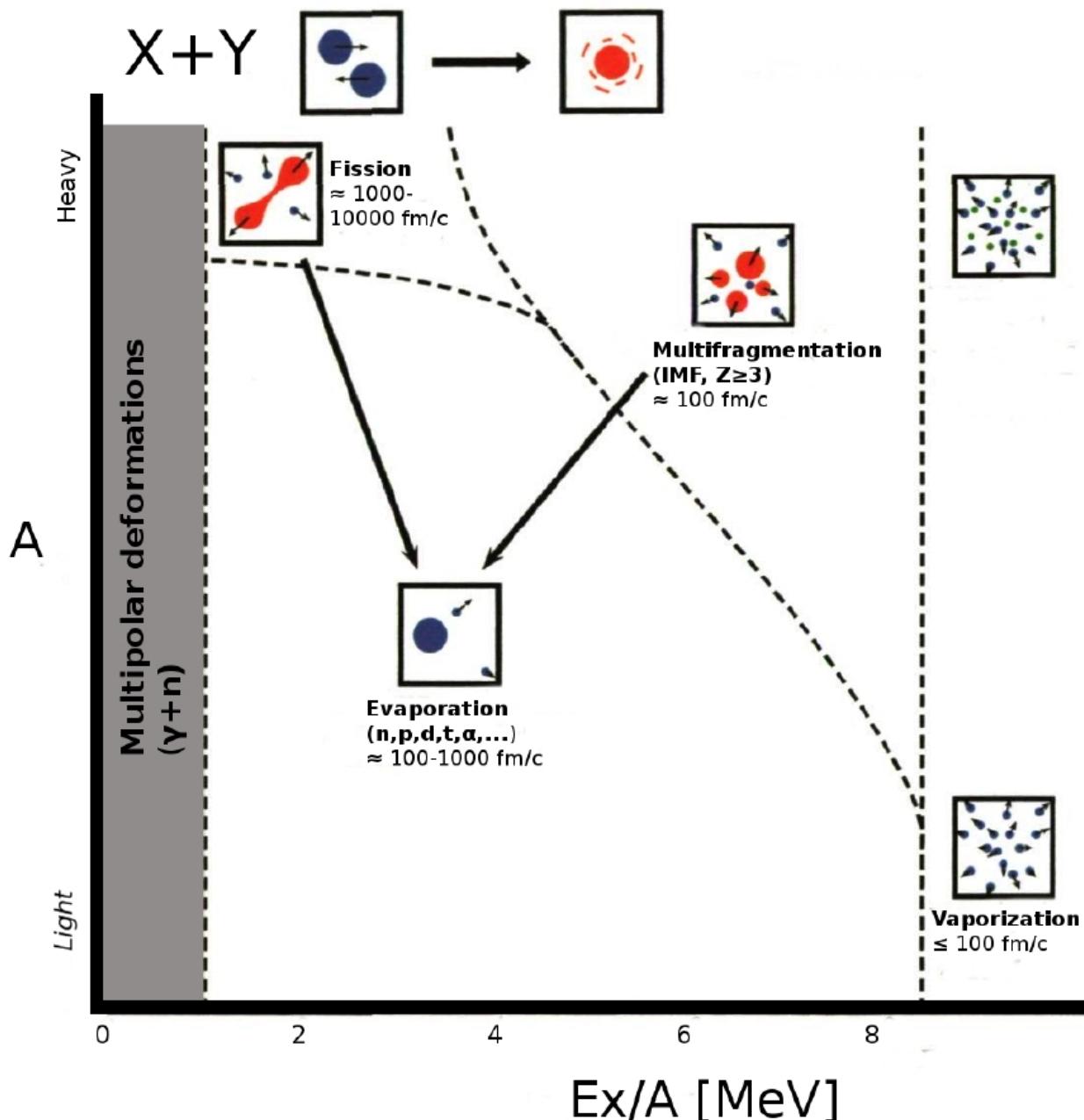
AMD simulation $^{64}\text{Ni} + ^{58}\text{Ni}$ 32 AMeV $b=4.7 \text{ fm}$



0 fm/c 50 fm/c 100 fm/c 150 fm/c 200 fm/c 250 fm/c 300 fm/c



De-Excitation mechanisms

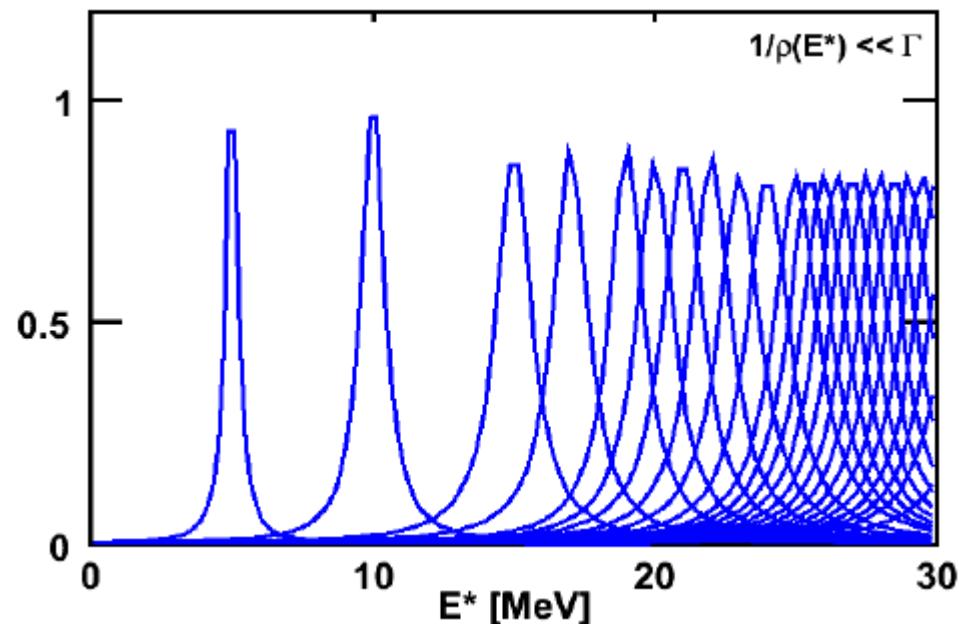


Compound nucleus hypothesis

- Nucleus decay independent of formation

Hauser-Feshbach formalism

$$\Gamma_i = \frac{1}{2\pi\rho_{CN}(E^*, S_0)} \int_0^\infty d\varepsilon \sum_{s_2=0}^\infty \sum_{J=|S_0-S_2|}^{S_0+S_2} \sum_{l=|J-S_1|}^{J+S_1} T_l(\varepsilon) \rho(E^* - B_i - \varepsilon, S_2)$$



Fermi-gas level density expression

$$\rho_{FG}(E_x, J) = (2J+1) \left(\frac{\hbar^2}{2I} \right)^{3/2} \frac{\sqrt{a}}{12} \frac{\exp(2\sqrt{aU})}{U^2}, \quad U = E_x - E_{rot}(J)$$

a = level-density parameter

- Level density parameter is extrapolated from low excitation energy experiments
- For heavy ion collisions at intermediate energies, excitation energy of primary fragments is around 3-5 MeV per nucleon
- Experimental results are necessary to evaluate the dependence with excitation energy and isospin

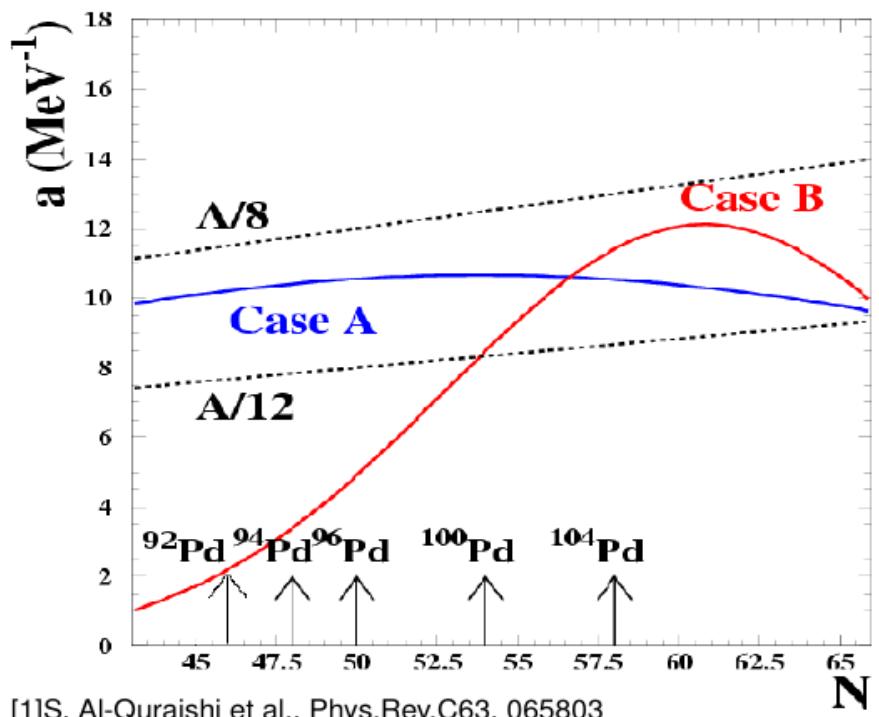
Variation with the isospin ?

$$FG \text{ model } a \approx mA \left[1 - \frac{1}{9} \left(\frac{N-Z}{A} \right)^2 \right]$$

Other theoretical predictions

$$a = \alpha A / \exp[\beta(N - Z)^2],$$

$$a = \alpha A / \exp[\gamma(Z - Z_0)^2].$$



Fusion-evaporation reactions

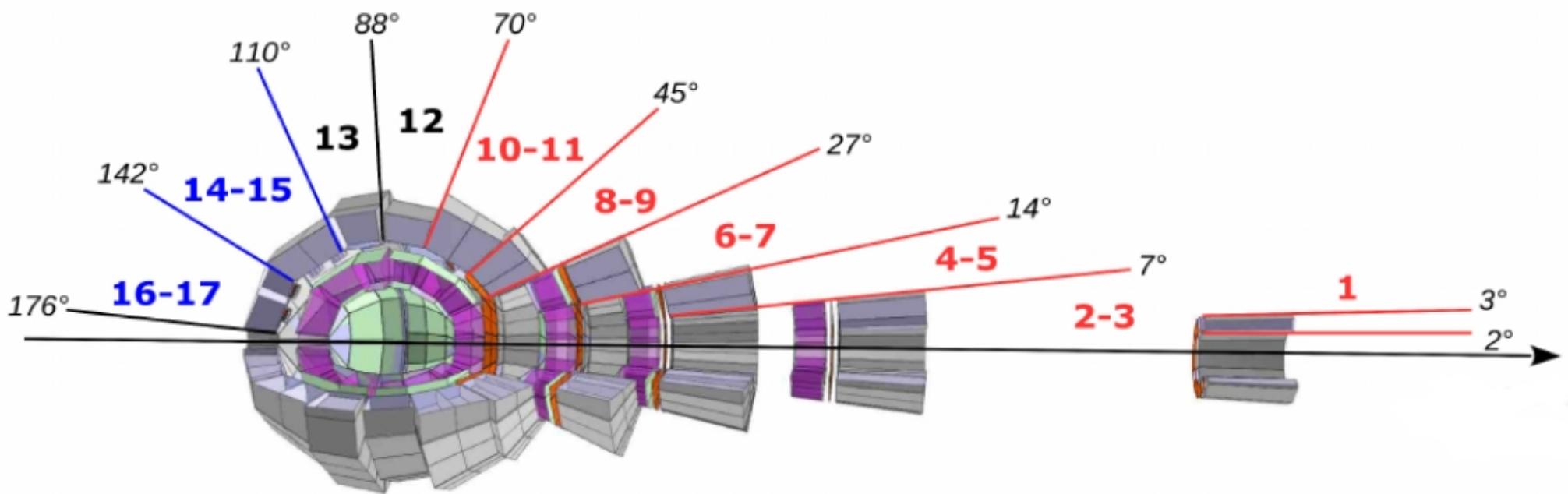
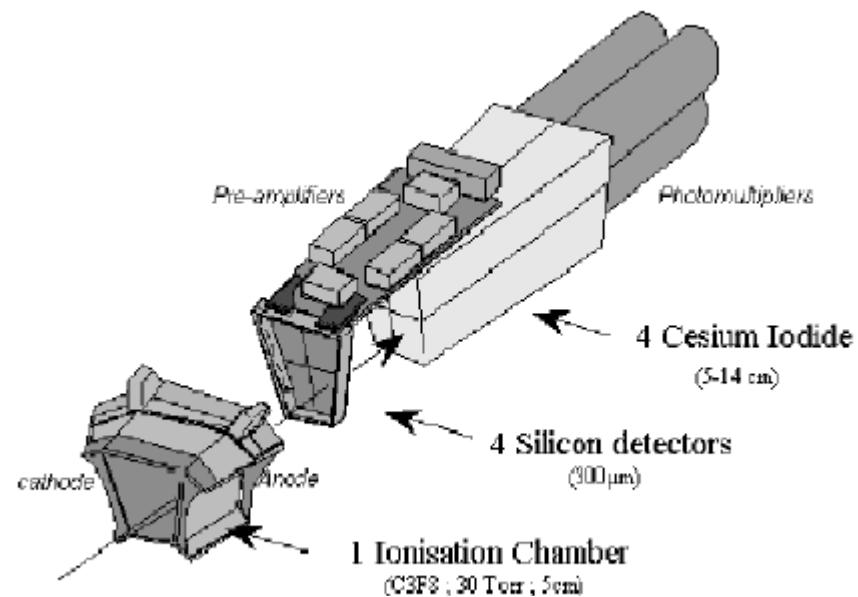
Constant excitation energy ≈ 2.9 AMeV

N/Z between 1 and 1.26

Beam	Target	E_{beam}	CN	E_{exc}	v_{rec}	N/Z
		(MeV/A)		(MeV/A)	(cm/ns)	
^{34}Ar	^{58}Ni	13.5	^{92}Pd	2.889	1.888	1
^{36}Ar	^{58}Ni	13.3	^{94}Pd	2.882	1.942	1.04
^{36}Ar	^{60}Ni	13.3	^{96}Pd	2.919	1.901	1.09
^{40}Ar	^{60}Ni	12.7	^{100}Pd	2.9	1.982	1.17
^{40}Ar	^{64}Ni	12.7	^{104}Pd	2.879	1.905	1.26

INDRA

- 17 rings, 336 modules
- Covers a solid angle of 90 % of 4π sr
- First 3 rings removed for VAMOS
- LCPs identification



INDRA

-17 rings, 336 modules

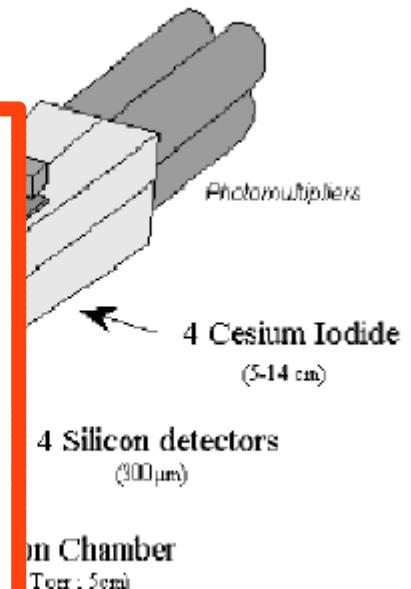
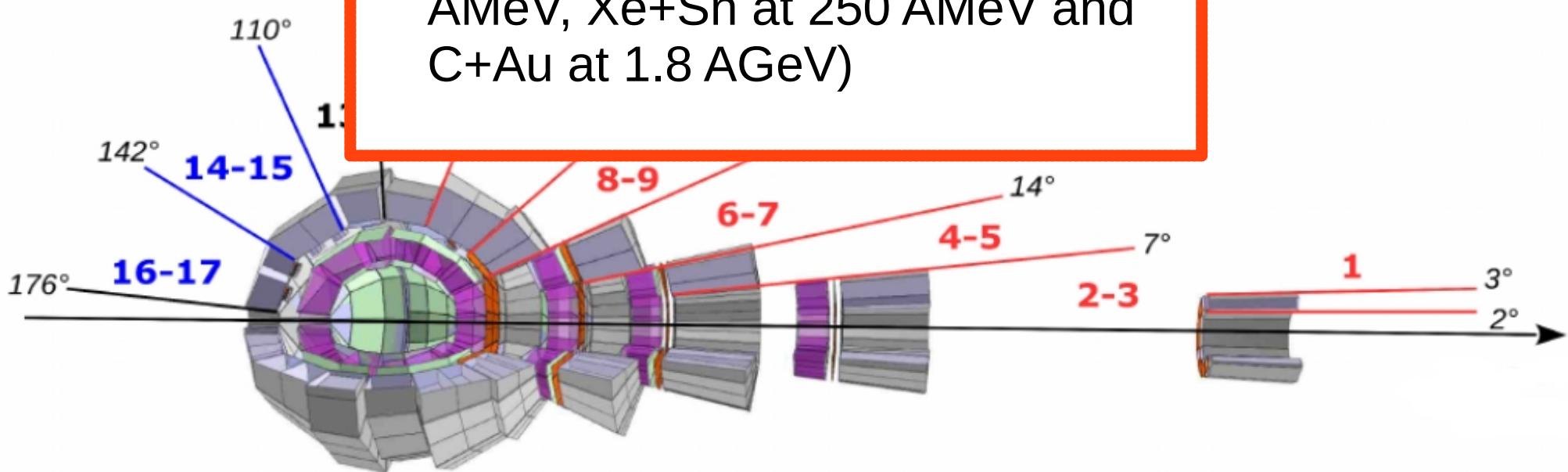
-Covers a solid angle
 $4\pi \text{ sr}$

-First 3 rings re

-LCPs identified

Large dynamic energy range

- Used primarily at intermediate energies 30-90 AMeV
- Was also used at low energy (Kr+Ca at 5.5 AMeV) and at high energy at GSI (Au+Au at 150 AMeV, Xe+Sn at 250 AMeV and C+Au at 1.8 AGeV)

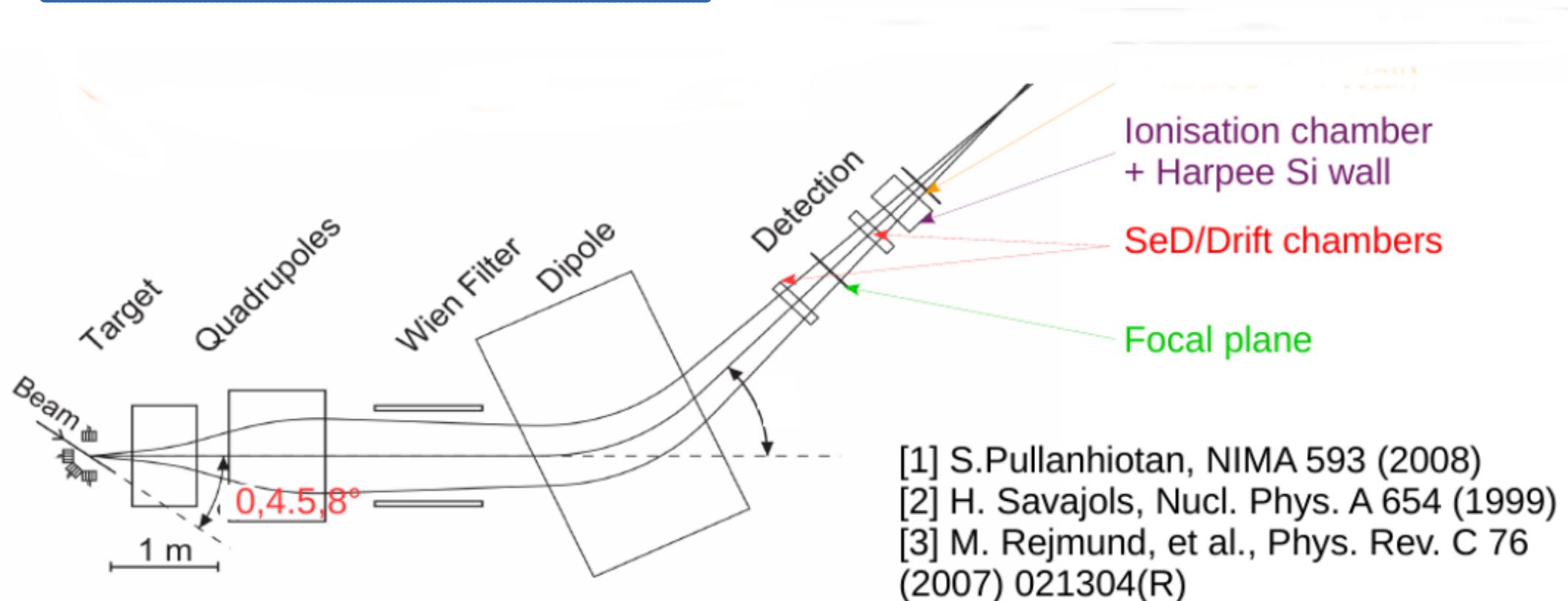


VAMOS

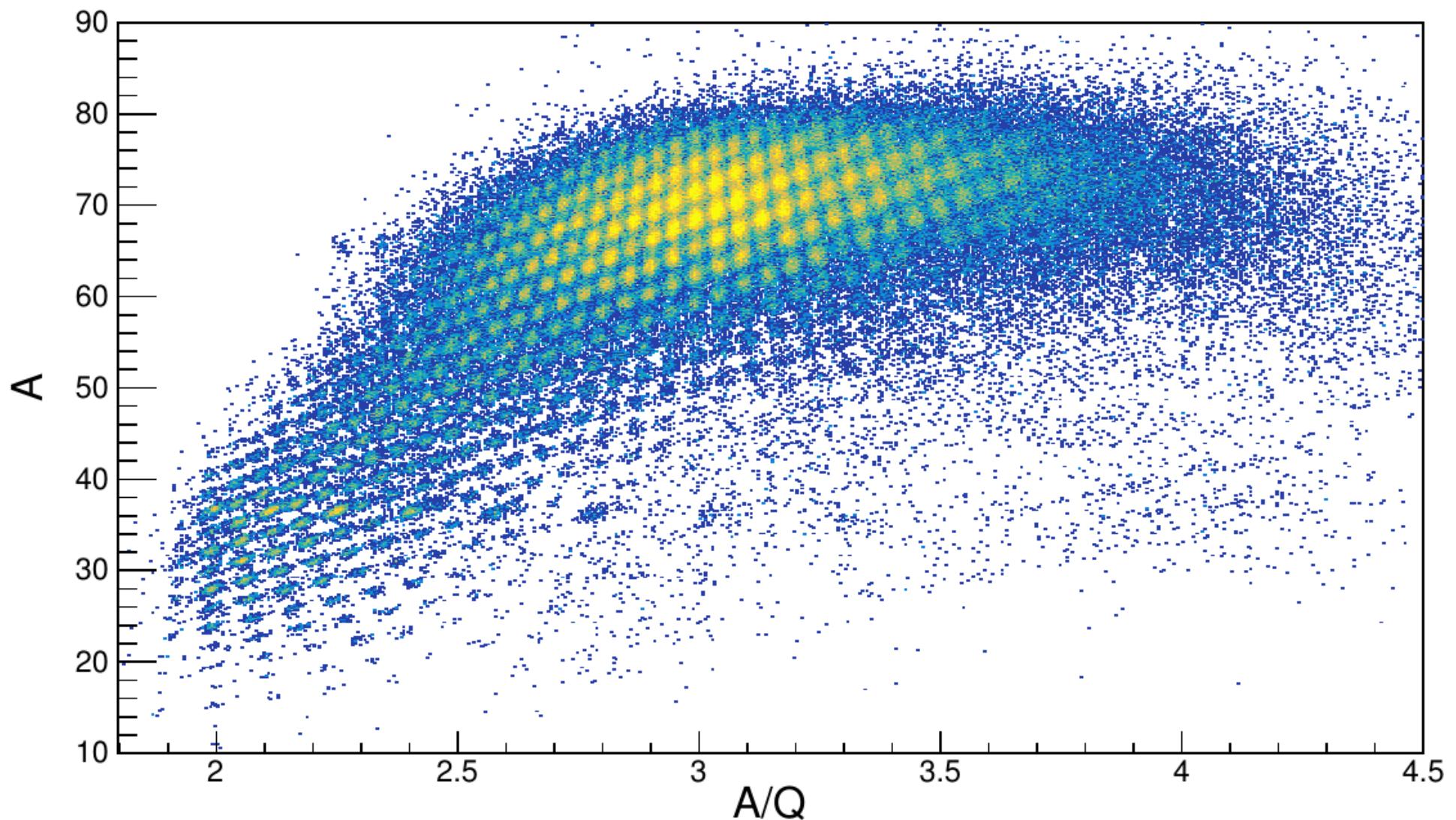
- CN residue identification
- $\beta\rho$ settings : 0.540-0.818 Tm
- θ settings : 0° , 1.5° , 2° , 4° and 8°

Operational features of VAMOS

Horizontal acceptance	-125 to +100 mrad
Vertical acceptance	± 160 mrad
Momentum acceptance	$\pm 5\%$ (at 25 msr)
M/q resolution	$\sim 0.6\%$
Maximum rigidity $B\rho$	1.6 T-m
Deflection angle θ_{dipole}	0 – 60° (variable)
Flight path length	~ 760 cm
Target—quadrupole distance	40–120 cm (variable)
Angular rotation	0 – 60°

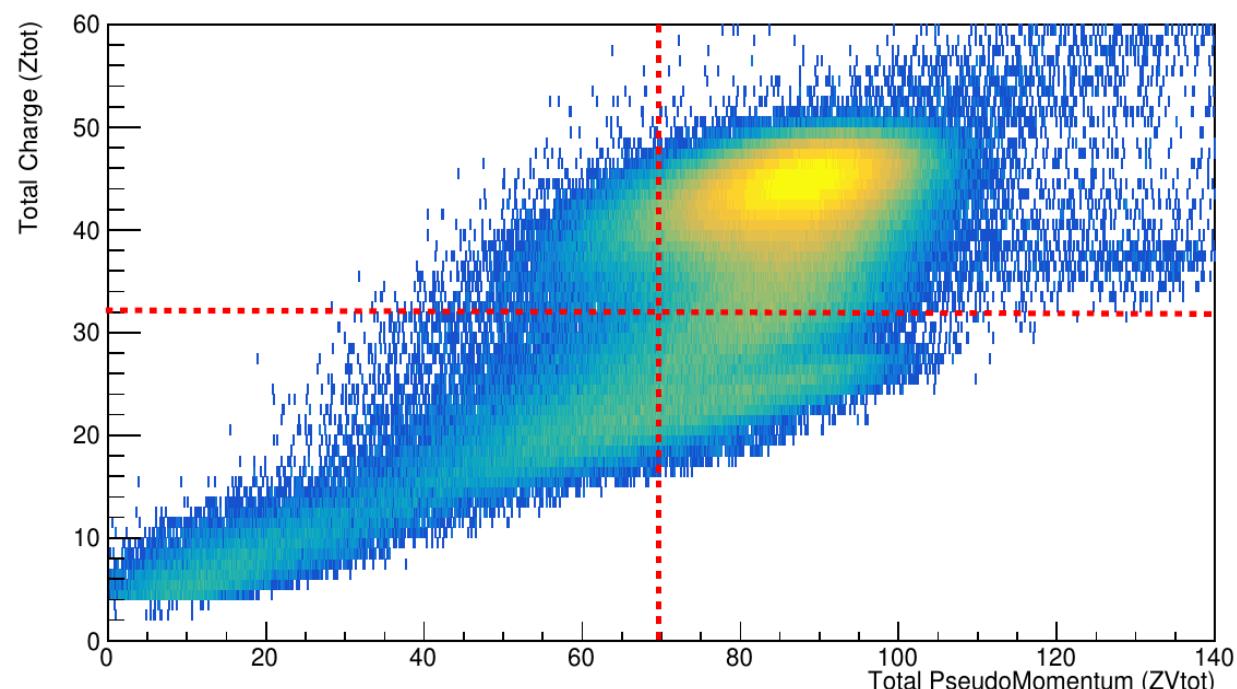


Mass identification with VAMOS

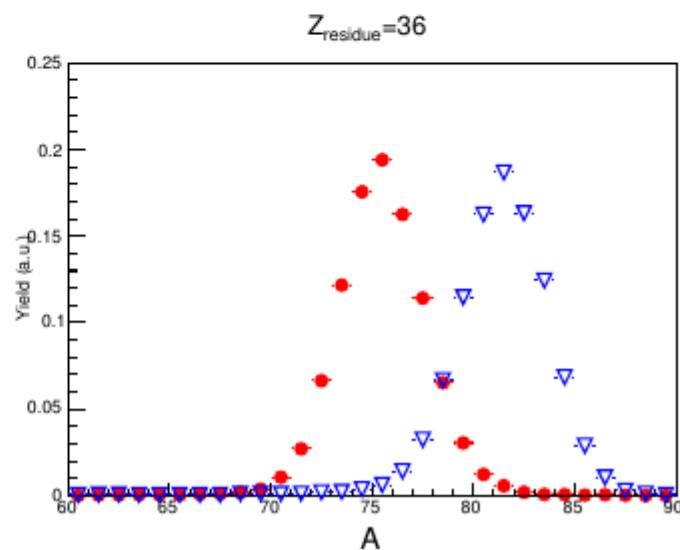
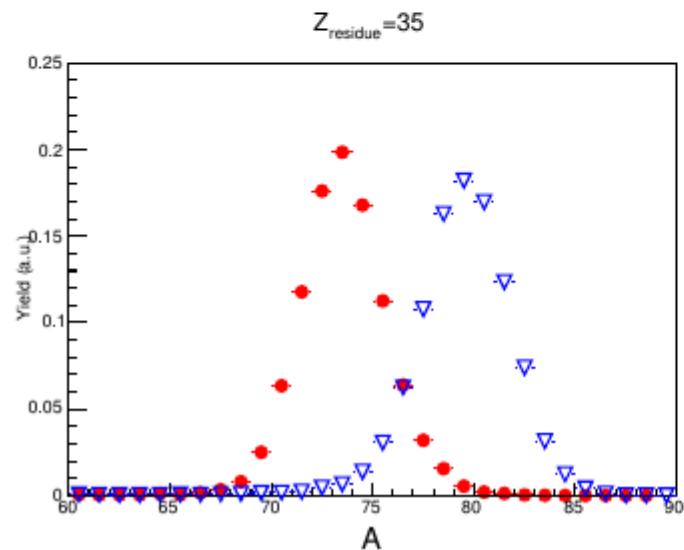
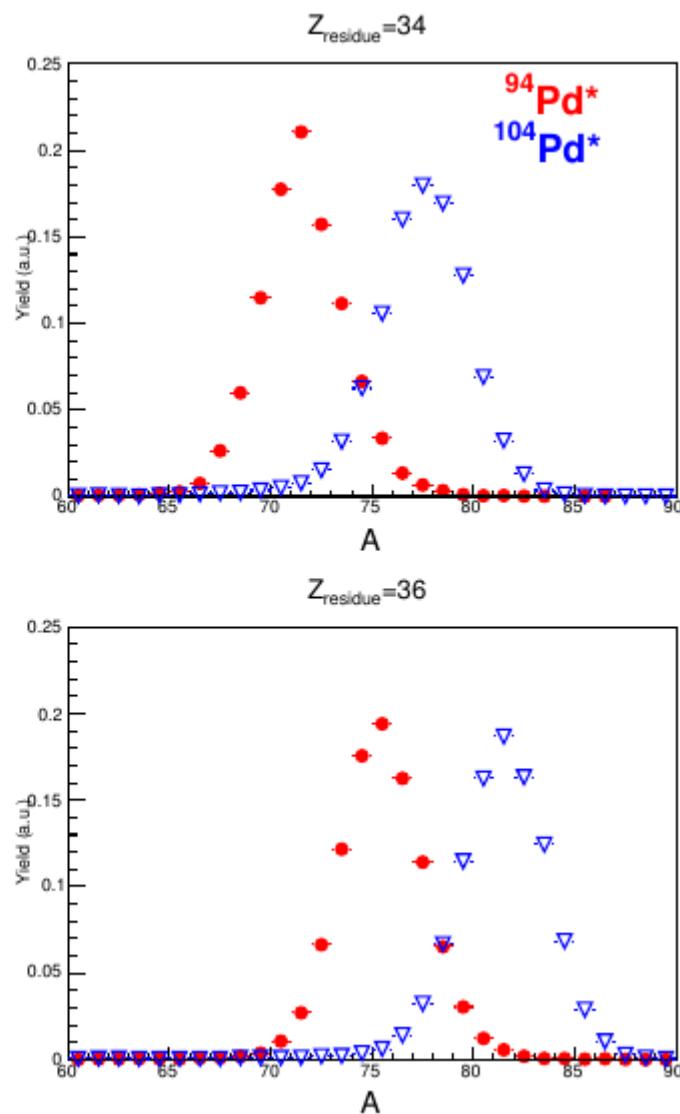
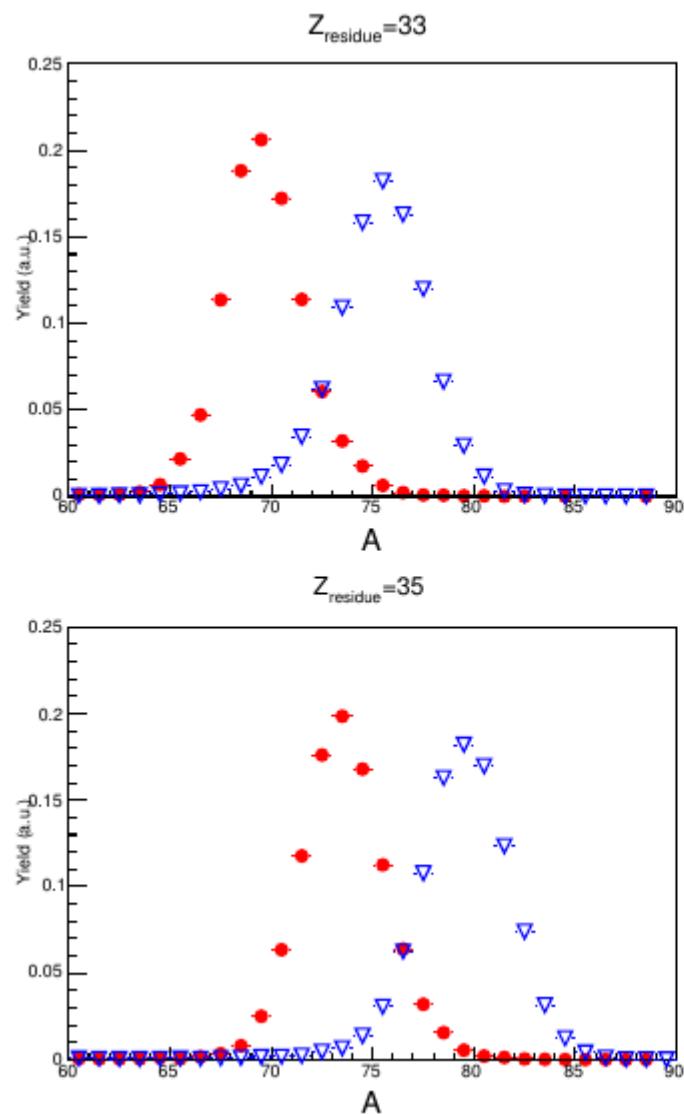
 $^{36}\text{Ar} + ^{58}\text{Ni}$ 13.3 AMeV

Coupling INDRA-VAMOS

- Residue isotopically identified in VAMOS
- Evaporated particles isotopically identified in INDRA
- Complete events if total charge detected
- Number of neutrons evaporated deduced from conservation of the mass

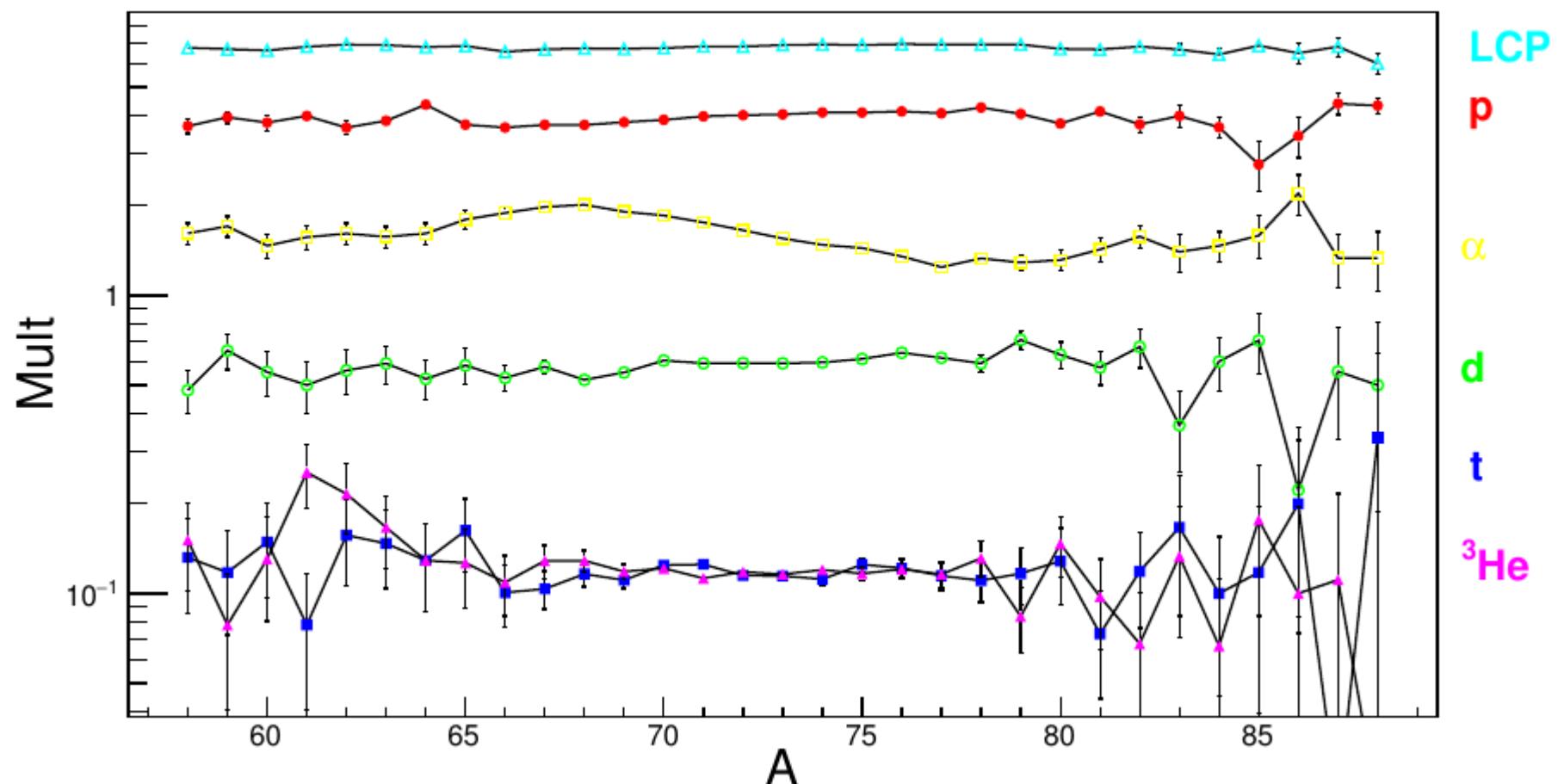


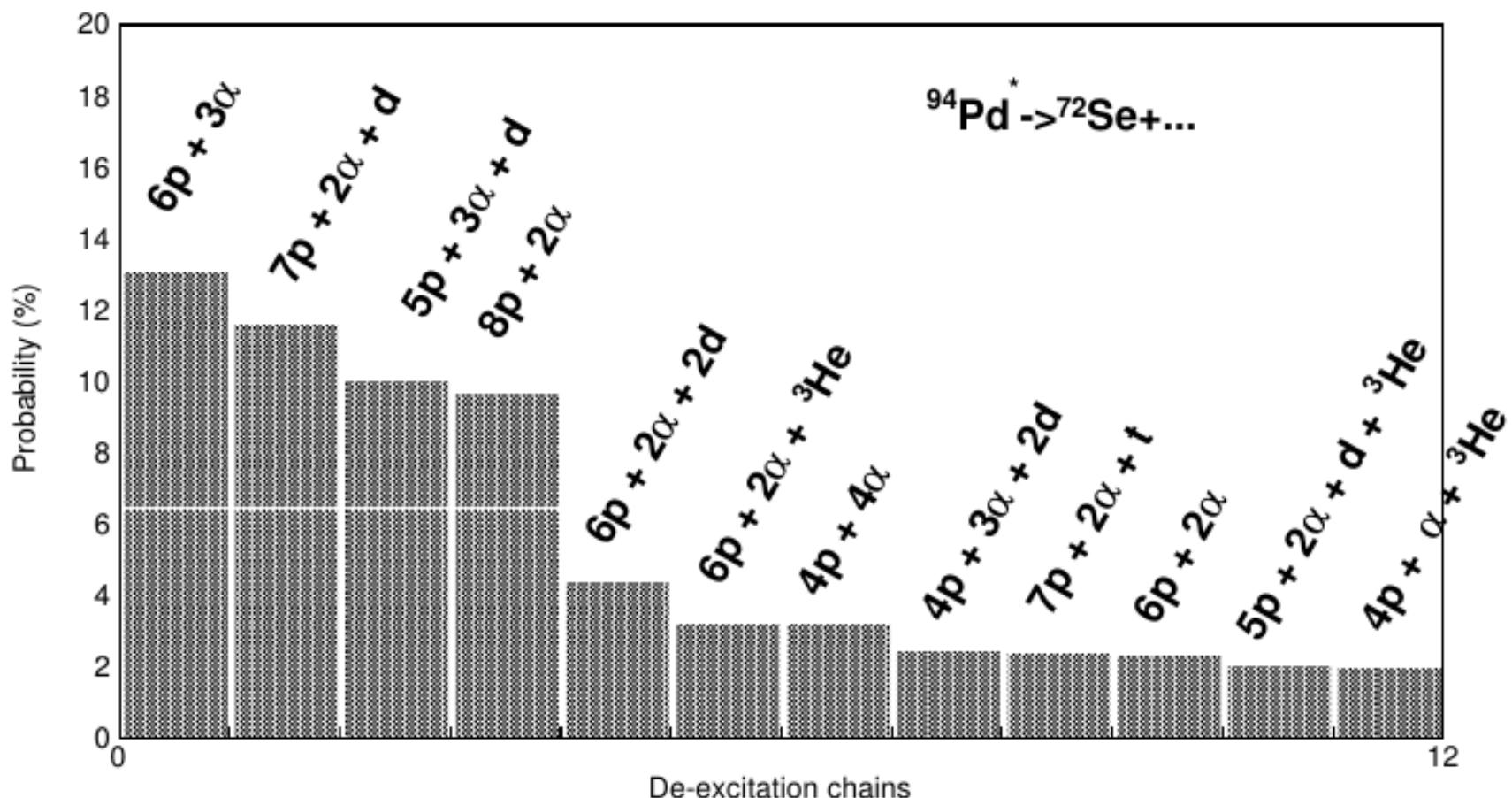
Residue detected in VAMOS



Multiplicity

Z=34 $^{36}\text{Ar} + ^{58}\text{Ni}$

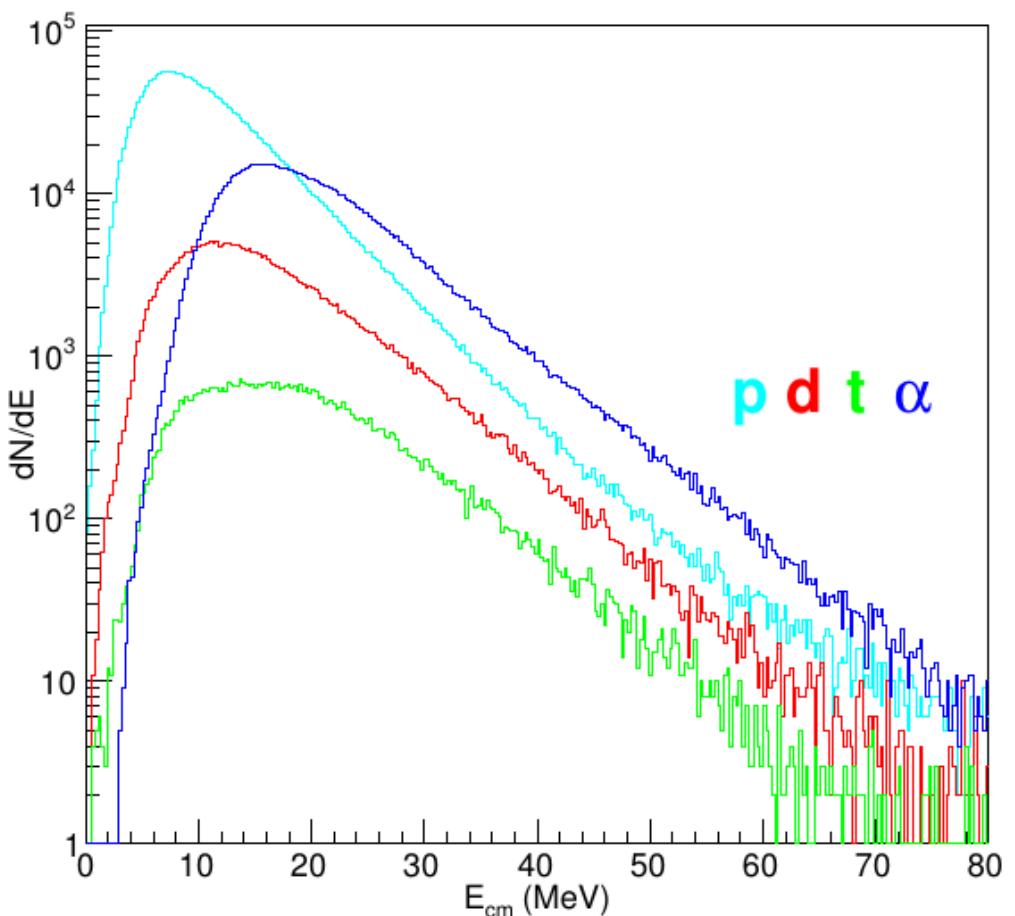


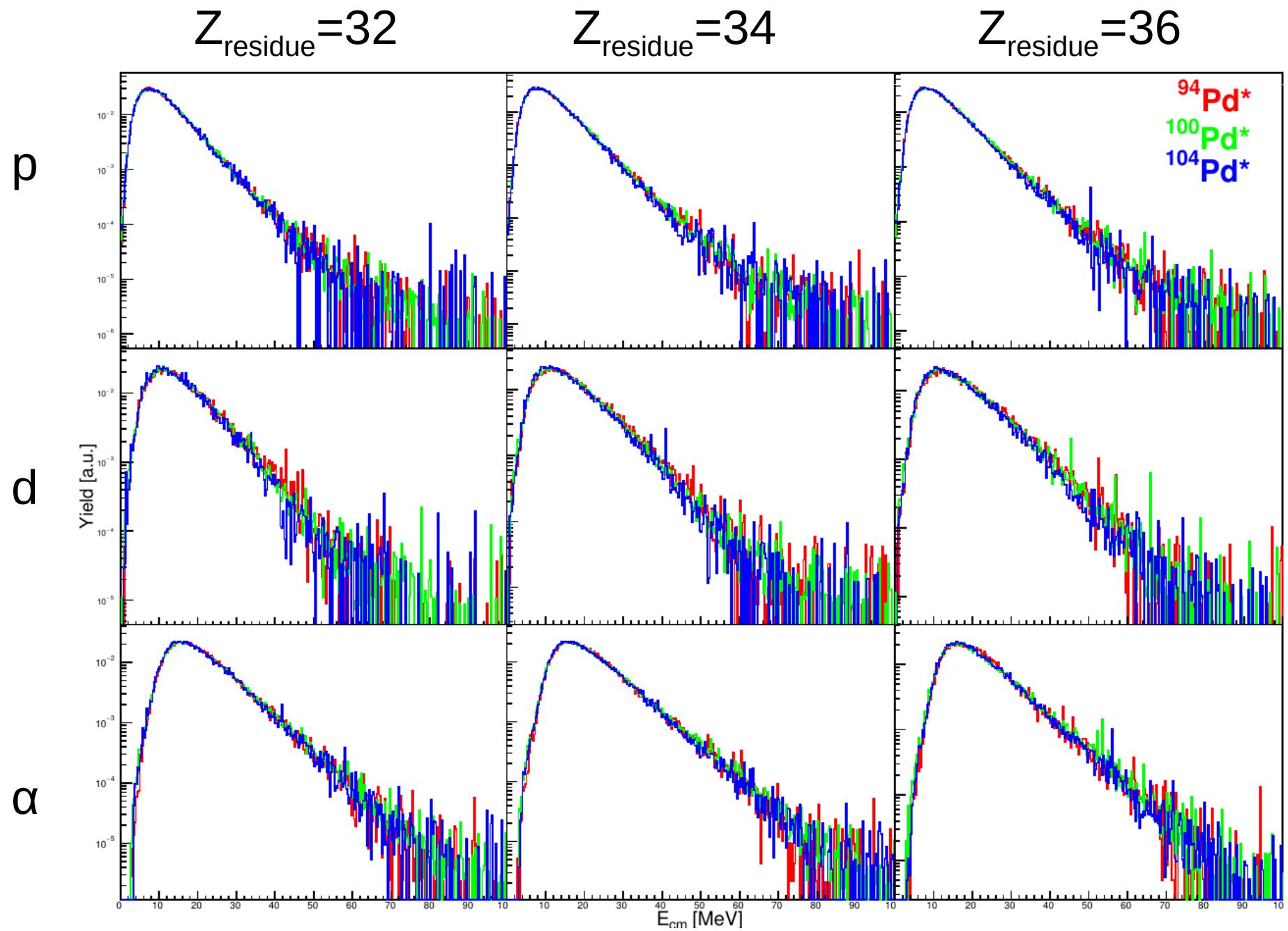


Level density parameter from evaporation spectrum

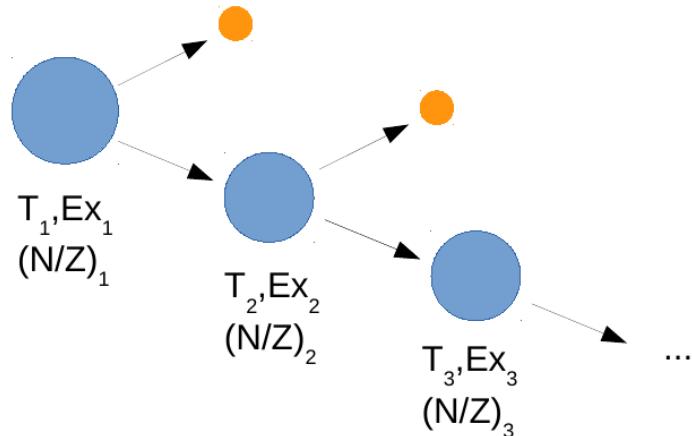
$$U = aT^2$$

$$\frac{d\sigma}{dE} \propto (E - Cb) \exp\left(\frac{-(E - Cb)}{T}\right)$$

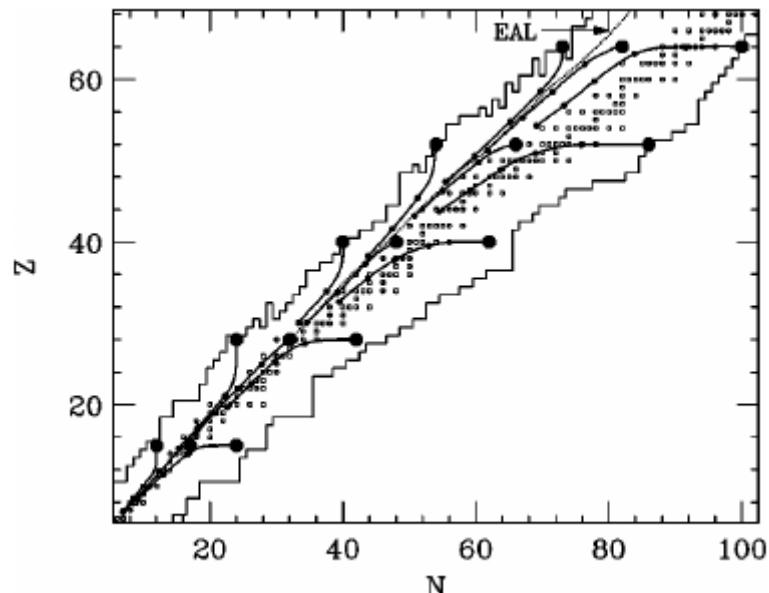




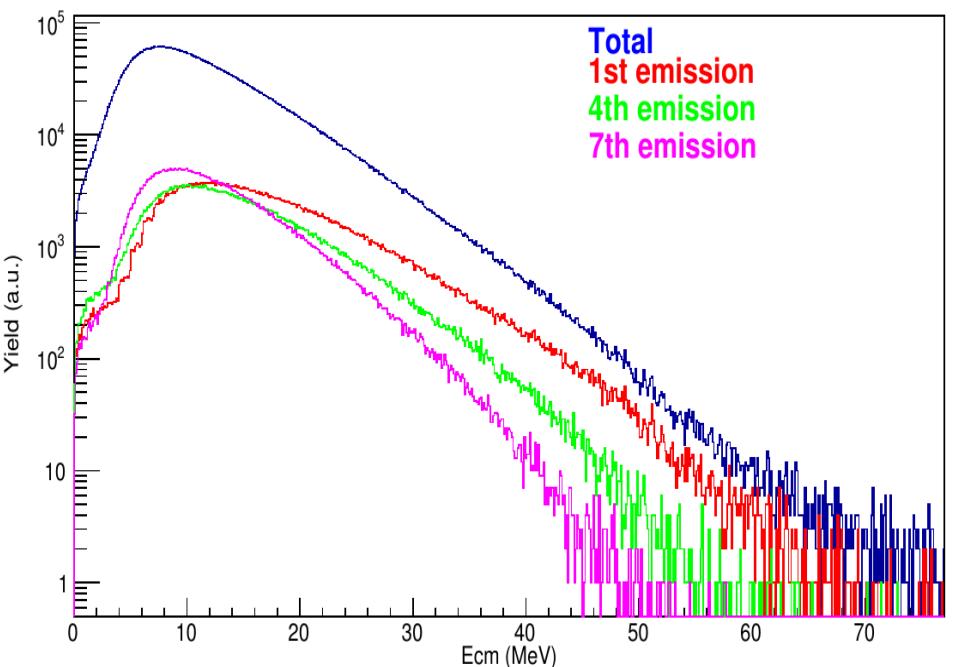
Sequential Decay



Evaporation attractor line



R. J. Charity Phys. Rev. C 58, 1073 (1998)



Conclusion

- Coupling of INDRA and VAMOS gives unique results
- Mass identification of the residue with VAMOS gives new ways to study de-excitation properties
- Thank you for your attention !