Population of Neutron-rich Nuclei around ^{48}Ca with Deep Inelastic Collisions

D. Montanari – Università degli Studi di Padova – INFN PD

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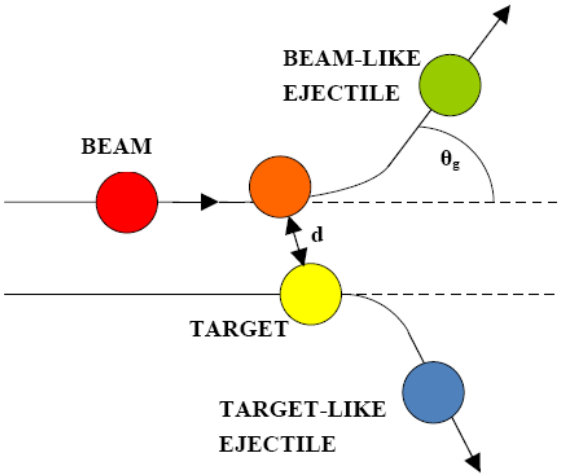
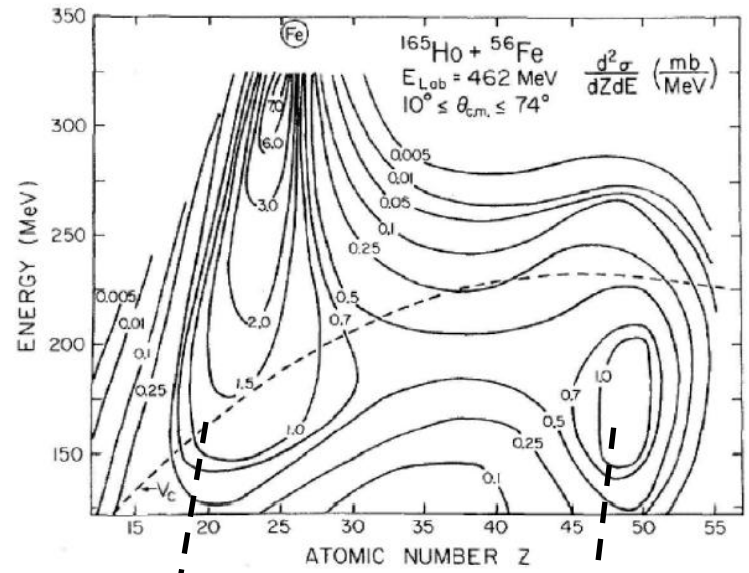
LEA-COLLIGA – LNL – 18/19 Februrary 2010

Multi-nucleon transfer reactions among heavy ions





Energy range ≥ Coulomb barrier

Degrees of freedom

- single particle states
- surface vibrations
- pair modes

Many transfer channels available
Importance of particle and pair transfer

Multi nucleons transfer channels

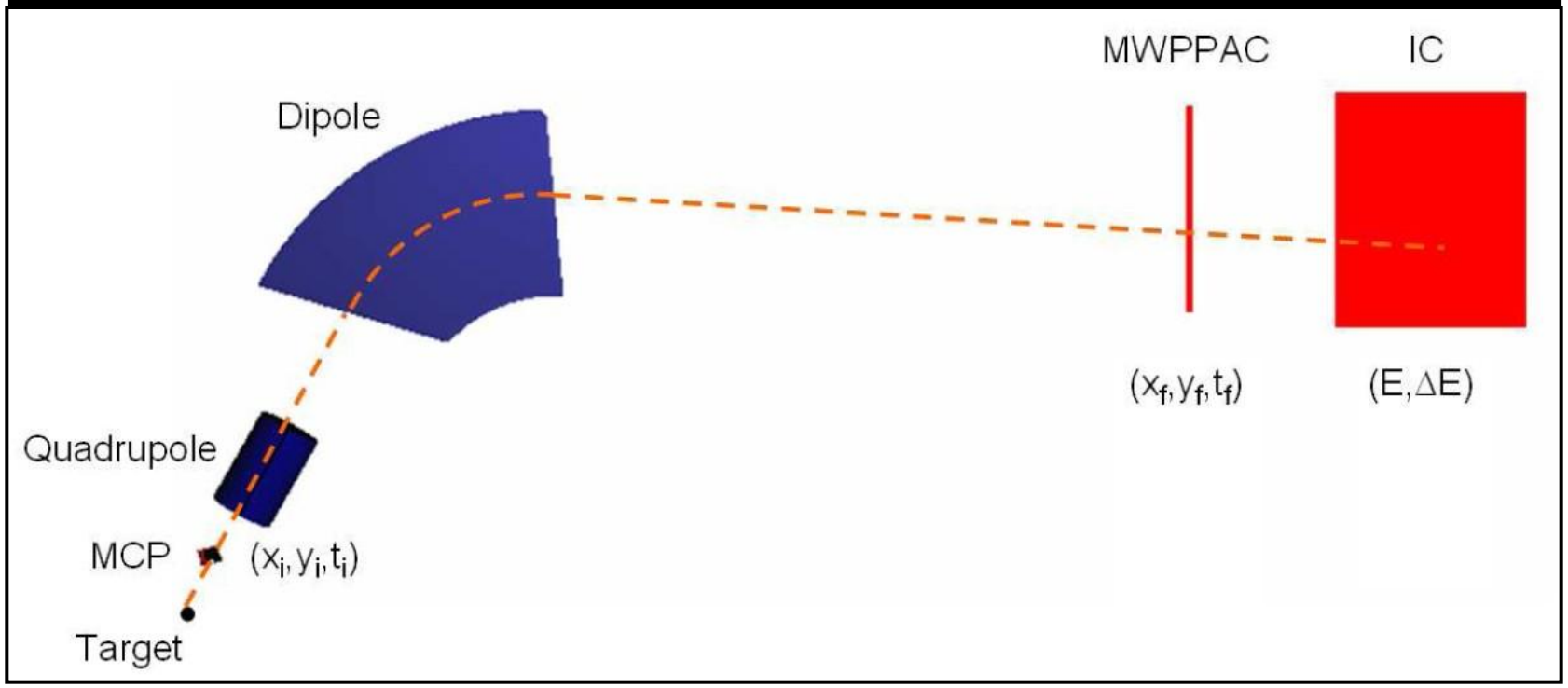
Fusion-fission

Inclusive interpretation of data:
semi-classical model GRAZING
- Sequential transfer
- Surface modes

The PRISMA-CLARA experimental setup

Laboratori Nazionali di Legnaro - INFN

The PRISMA magnetic spectrometer



Optics:

- **quadrupole magnet**
- **dipole magnet**

Detectors:

- **entrance detector (MCP)**
- **focal plane detector (MWPPAC)**
- **ionization chamber (IC)**

The multi-detector array CLARA

Efficiency ~ 3 %
Peak/Total ~ 50 %
Positions θ ~ 90°-180°
FWHM ~ 10 keV for E_γ= 1.3 MeV
with v/c = 10 %

25 Clover detectors

For each Clover:

4 HPGe crystals

1 anti-Compton BGO shield

1 criostate

4 signals :

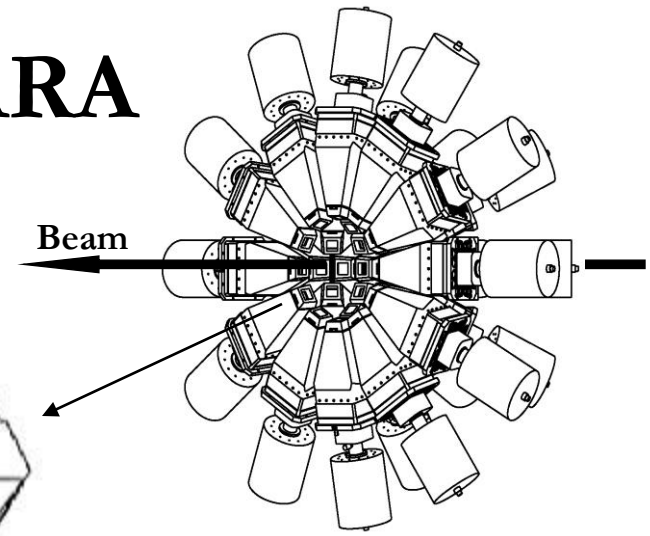
Ge energy (< 4 MeV)

Ge energy (< 20 MeV)

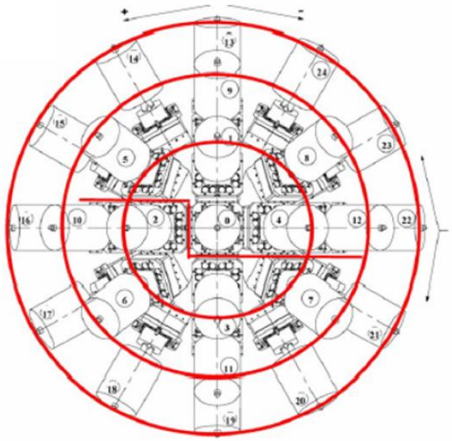
BGO energy

Time

CLARA



3 rings in ϑ

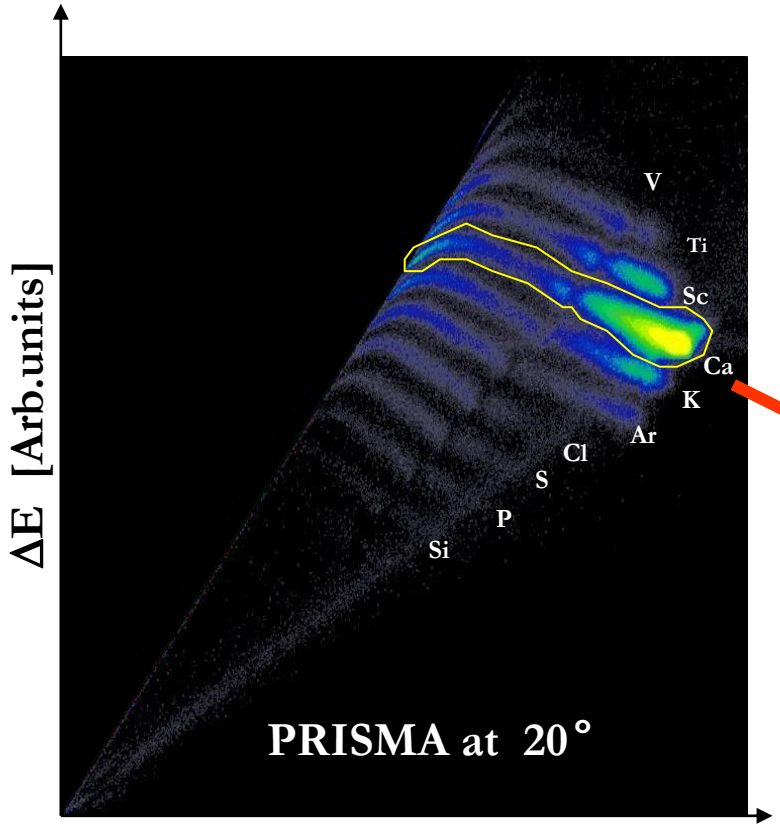


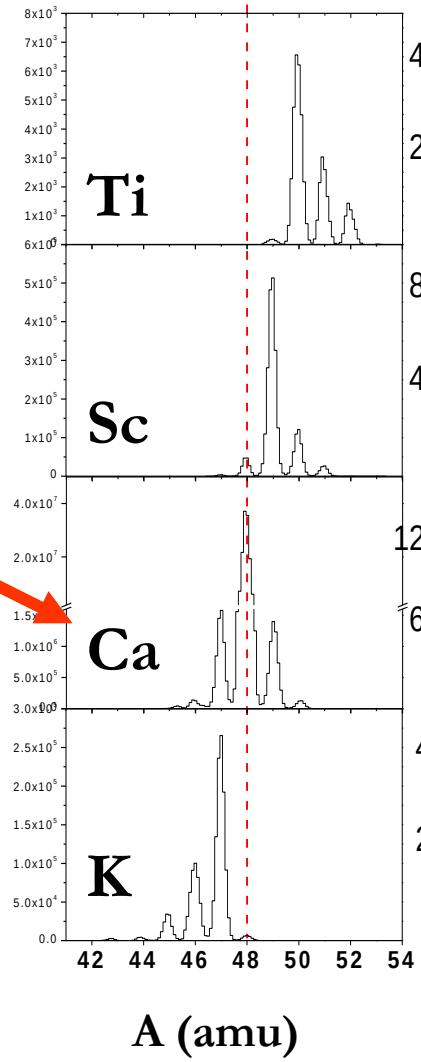
Isotope Selection

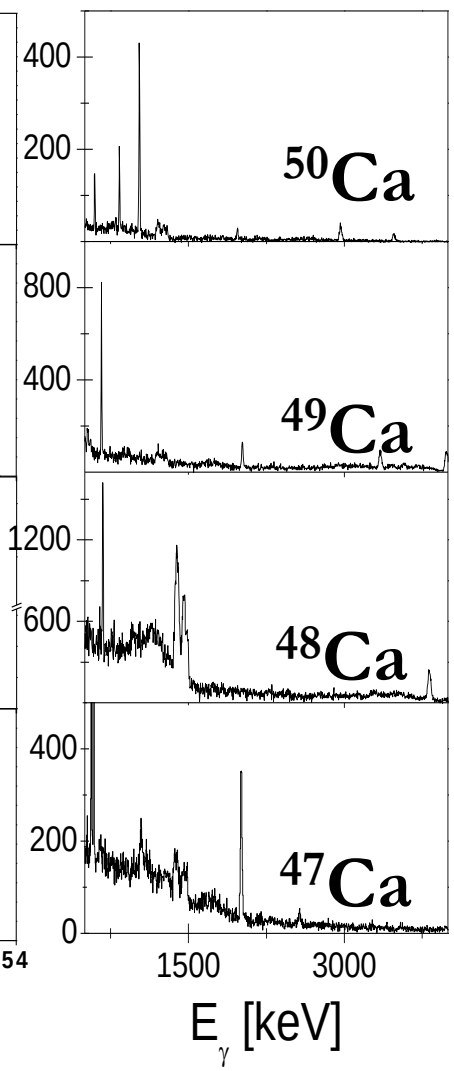
Mass distributions
Reaction studies

Gamma spectra
Nuclear structure

$^{48}Ca + ^{64}Ni$ at 282 MeV







Response Function → Correction of Data

↓

Measurement of Cross Sections

① Elastic scattering of ^{48}Ca (exp + theory)

② Inclusive angular distributions $d\sigma/d\Omega$ (exp + theory)

③ Angular distributions of specific states (exp + theory)

Transport of the magnetic spectrometer PRISMA

Monte Carlo simulation based on the ray tracing code originally developed by A. Latina and E. Farnea

Generation of Monte Carlo INPUT events distribution in $[E_{kin}, \theta, \phi]$

→

Transport event by event in PRISMA

↓

Sorting of transported events by PRISMA Analysis software package (GSORT)

←

Response of PRISMA

$$R(E,\theta,\phi) = \frac{\#\ \text{OUTPUT Events}}{\#\ \text{INPUT Events}}$$

Response of PRISMA

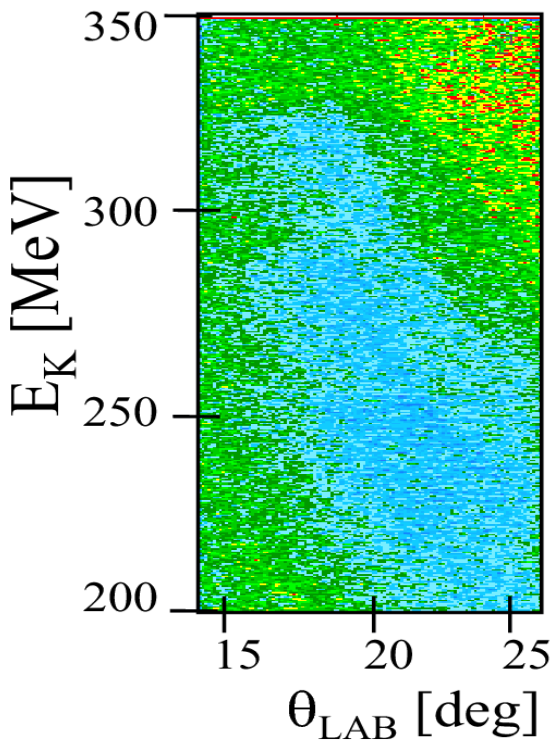
Correction Factor

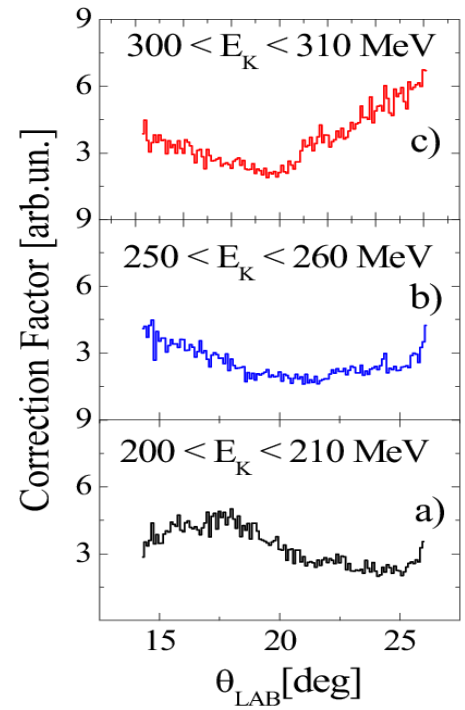
$$R\left(\vartheta_{lab}, \varphi_{lab}, K\right) = \frac{N_o}{N_i}$$

$$f\left(\vartheta_{lab}, K\right) = \frac{1}{R\left(\vartheta_{lab}, K\right)}$$

N_0 = output distribution

N_i = input distribution

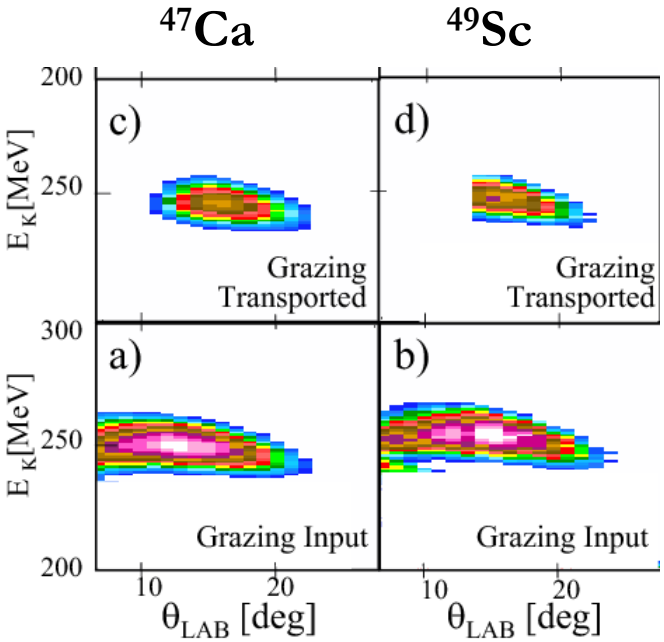




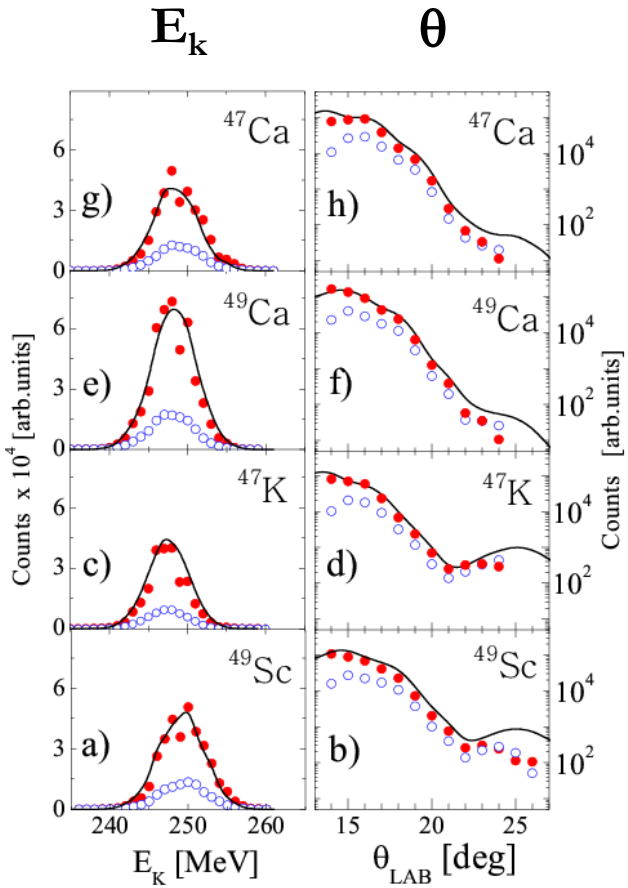
^{48}Ca

Test of the calculated response with INPUT theoretical distributions

$$(d\sigma/d\Omega dE)_{GRAZING} \leftrightarrow (d\sigma/d\Omega dE)_{GRAZING\text{-}Transp} * f(E,\theta)$$



GRAZING model: (A.Winther, Nucl.Phys.A594 (1995)203)



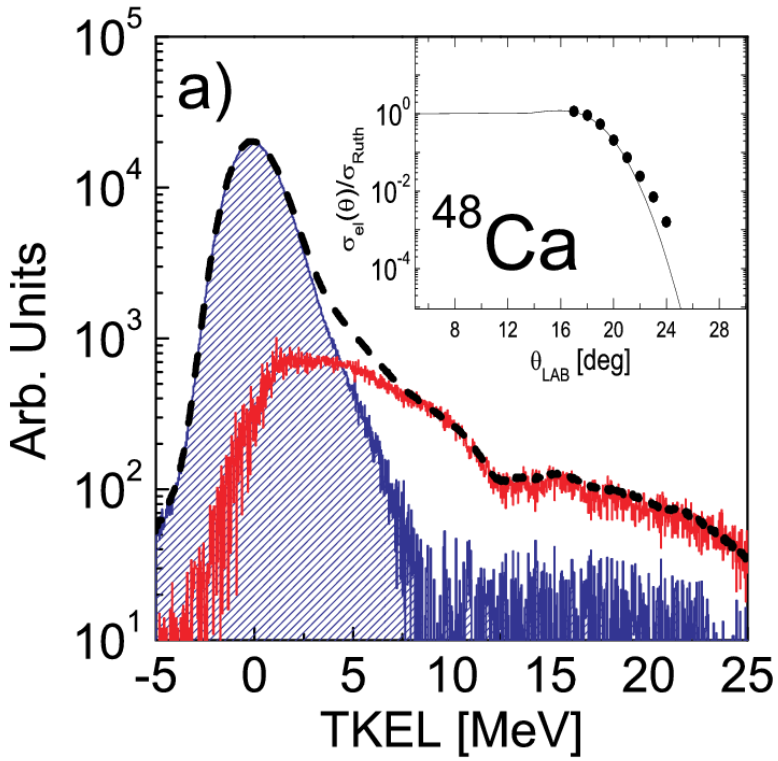
GRAZING input

GRAZING-Transp

GRAZING-Transp * f(E,θ)

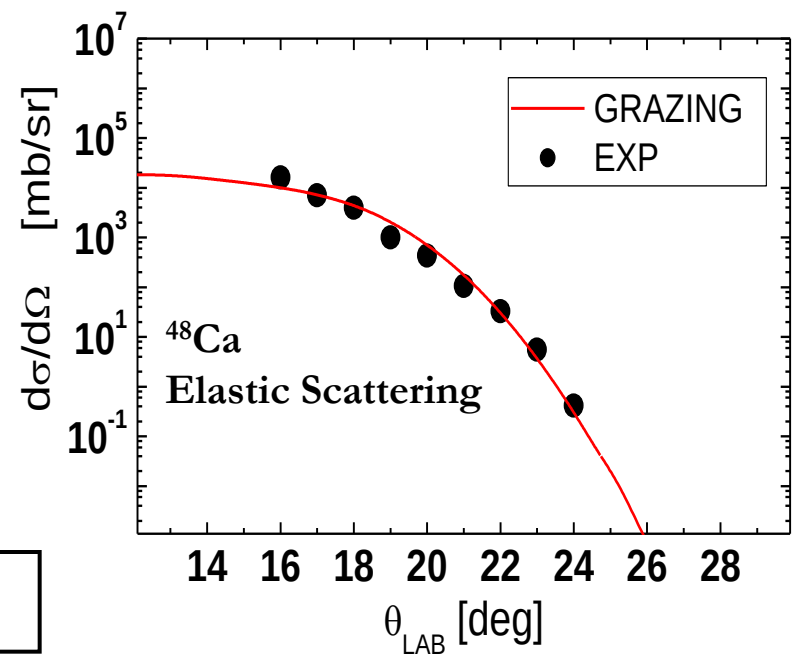
Starting point: measurement of σ_{el} for Elastic Scattering

S.Szilner et al., PRC 76 (2007)



RATIO between Elastic and Rutheford scattering cross sections

$$C = 1\ \frac{mb}{sr} = 2580\ counts$$



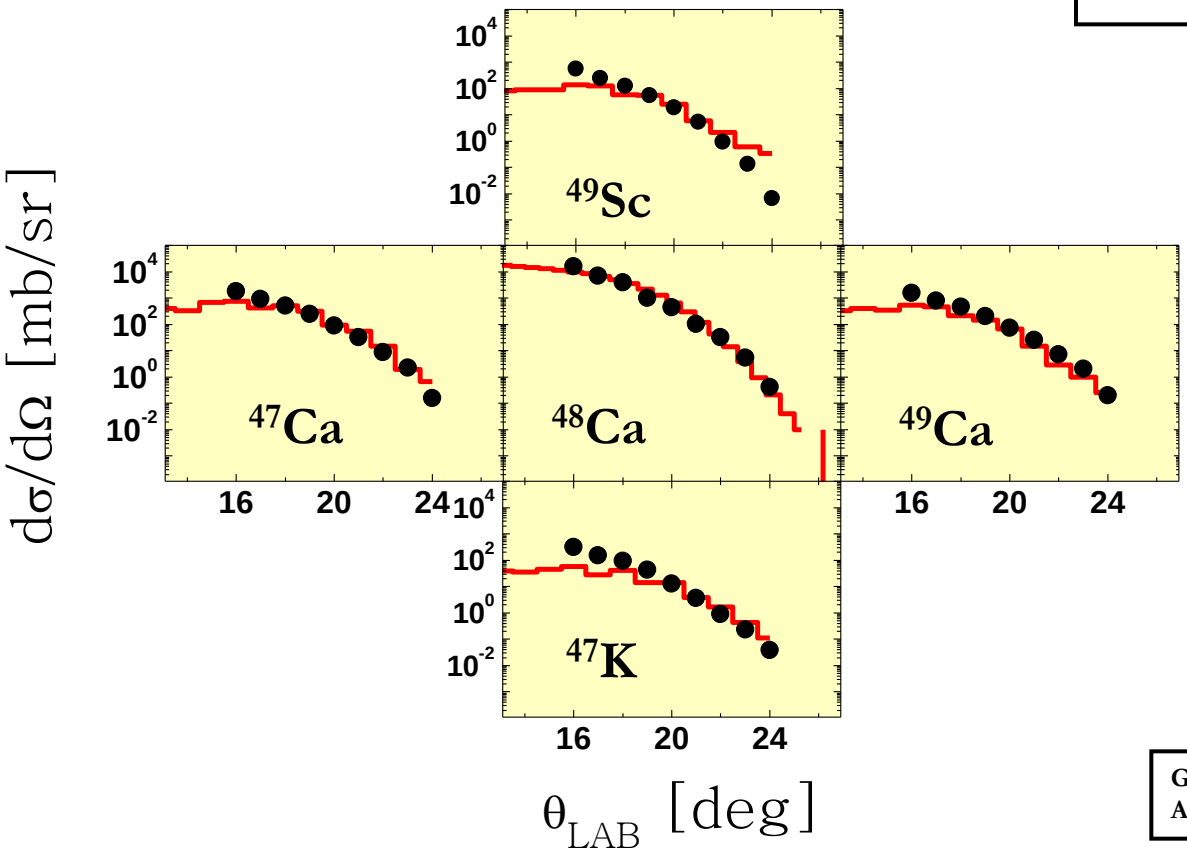
Absolute measurement of cross sections

Inclusive angular distribution: 1 nucleon transfer

Experiment vs GRAZING

Good agreement with semiclassical model for

1 nucleon transfer channels

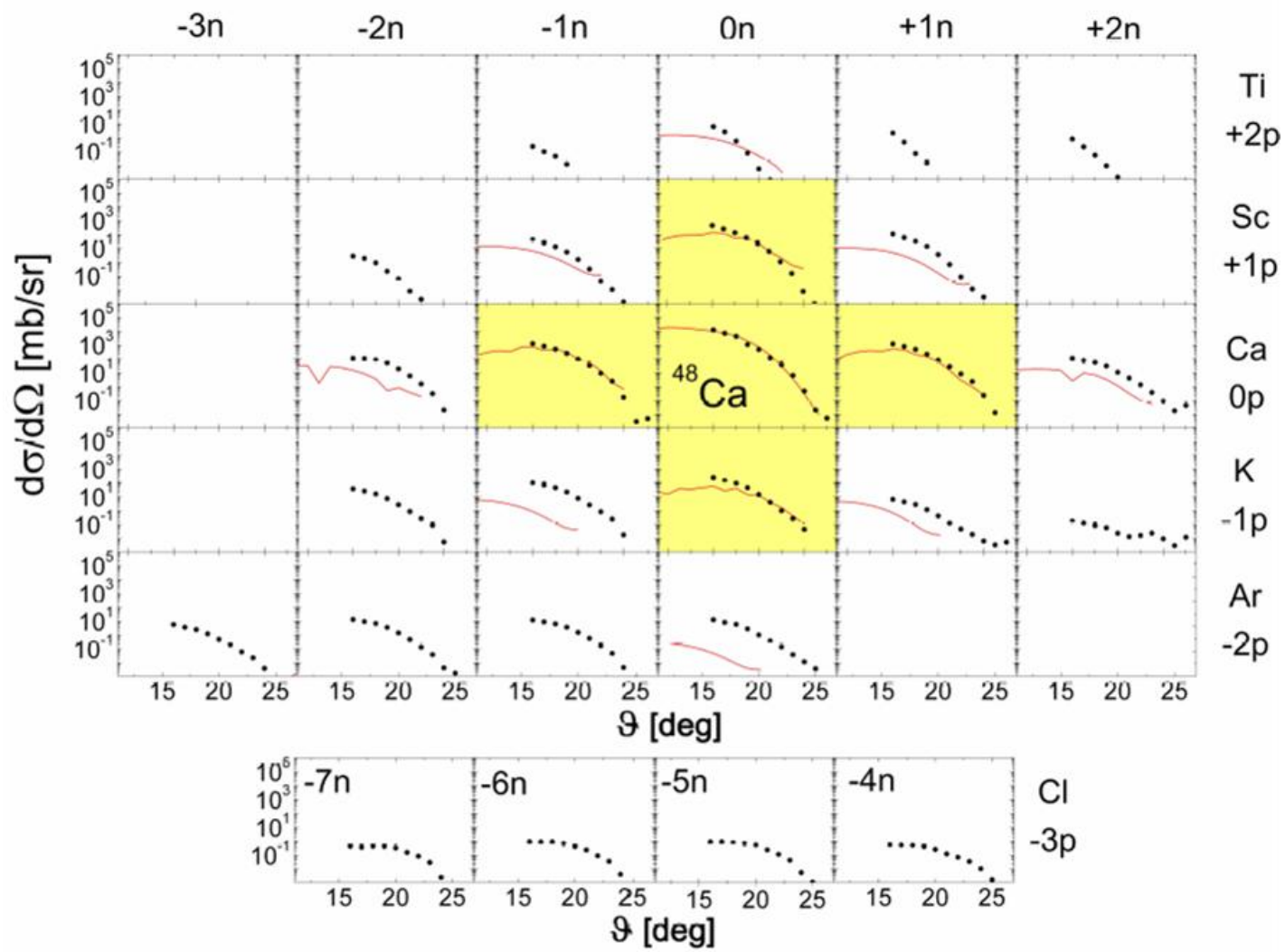


GRAZING model
A.Winther, Nucl.Phys.A594 (1995)203

Inclusive angular distribution: all reaction products

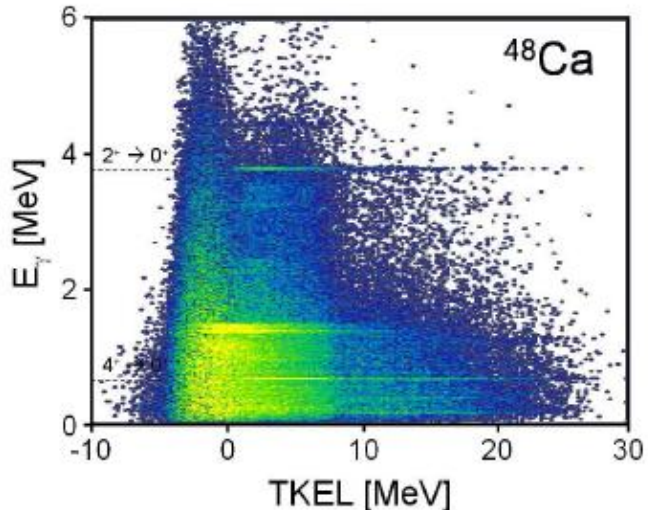
Experiment vs **GRAZING**

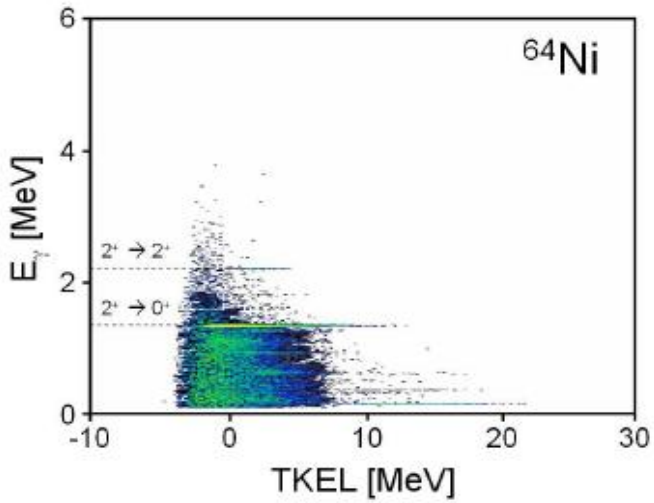
Comprehensive experimental analysis



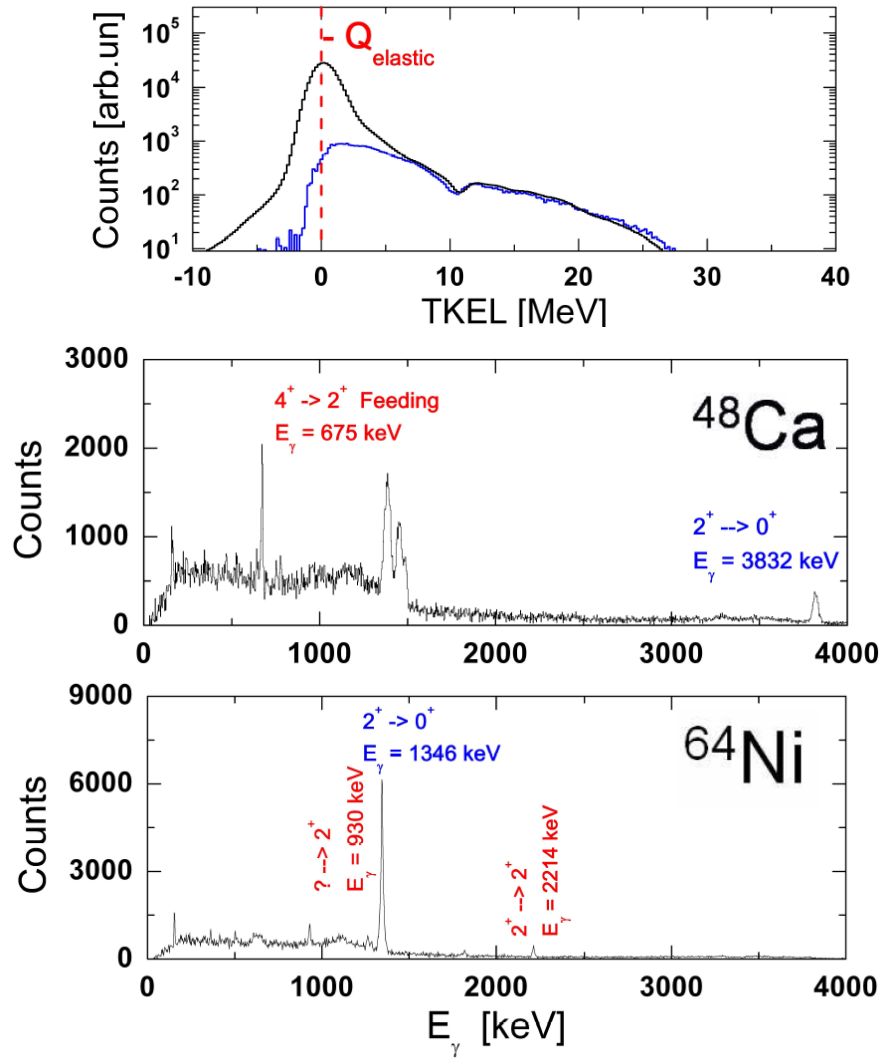
Angular distribution of inelastic scattering

$$TKEL = K^i - K^f = Q_{gg} + E_b^* + E_B^*$$



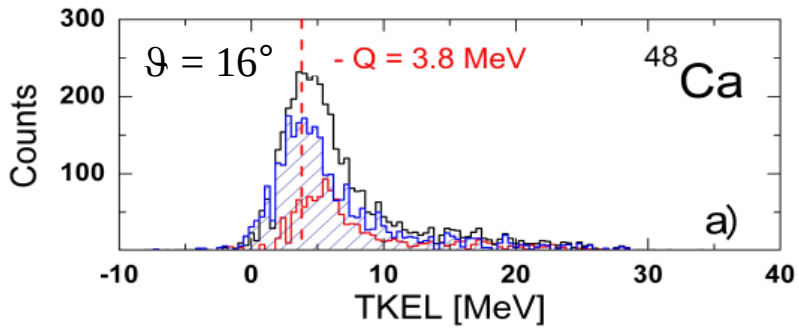


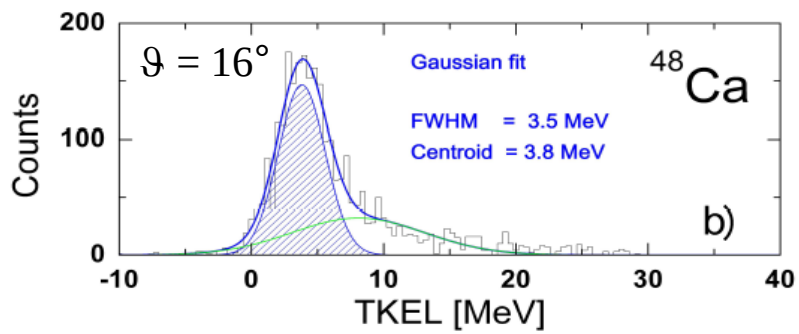
Total projections



Angular distribution of inelastic scattering: 2^+ state

TKEL spectra gated by gamma

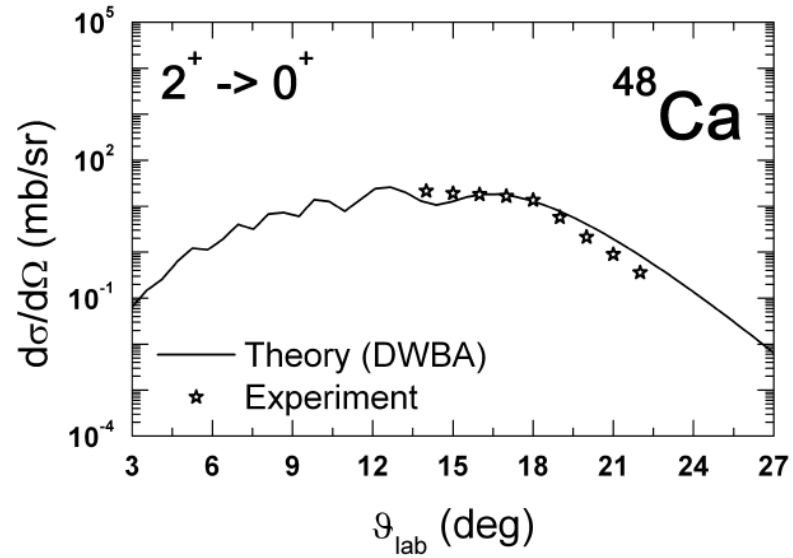


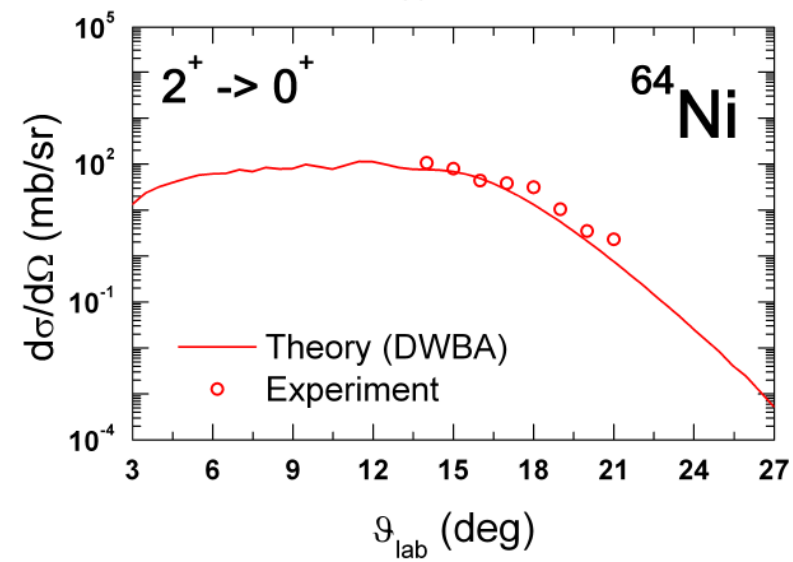


$2^+ \rightarrow 0^+$

$4^+ \rightarrow 2^+$

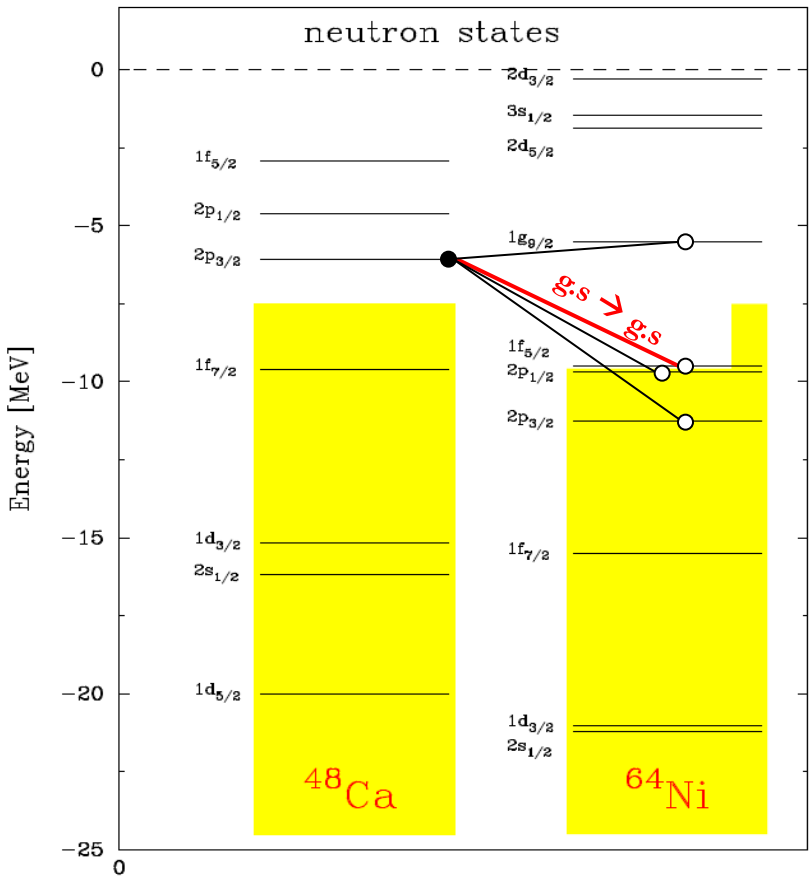
Difference





Angular distribution of TRANSFER to SPECIFIC STATES

Transfer to ground state



Feasibility of studies of transfer reactions to nuclear states with HI

$$\frac{d\sigma}{d\Omega} = S_{Ca} \times S_{Ni} \times \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$

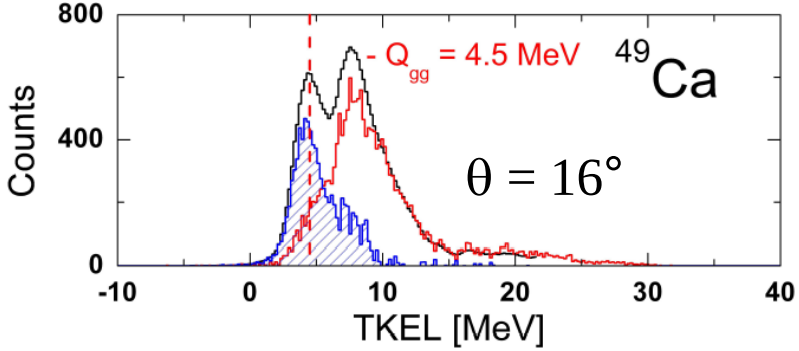
	Spin [ħ]	State	Energy [keV]	S
^{49}Ca	3/2 -	$p_{3/2}$	0	0.84
	1/2 -	$p_{1/2}$	2021	0.91
	5/2 -	$f_{5/2}$	3991	0.84
^{63}Ni	1/2 -	$p_{1/2}$	0	0.235
	5/2 -	$f_{5/2}$	87	0.572
	3/2 -	$p_{3/2}$	156	0.605
	3/2 -	$p_{3/2}$	518	0.205
	1/2 -	$p_{1/2}$	1002	0.260
	9/2 +	$g_{9/2}$	1294	0.082

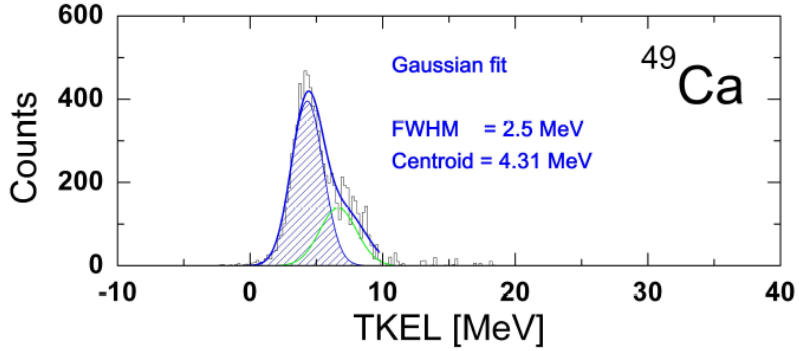
Limited by: Energy resolution (≈2.5 MeV)

gamma coincidences ($M_\gamma \approx 1$)

Angular distribution of TRANSFER to SPECIFIC STATES

Transfer to ground state





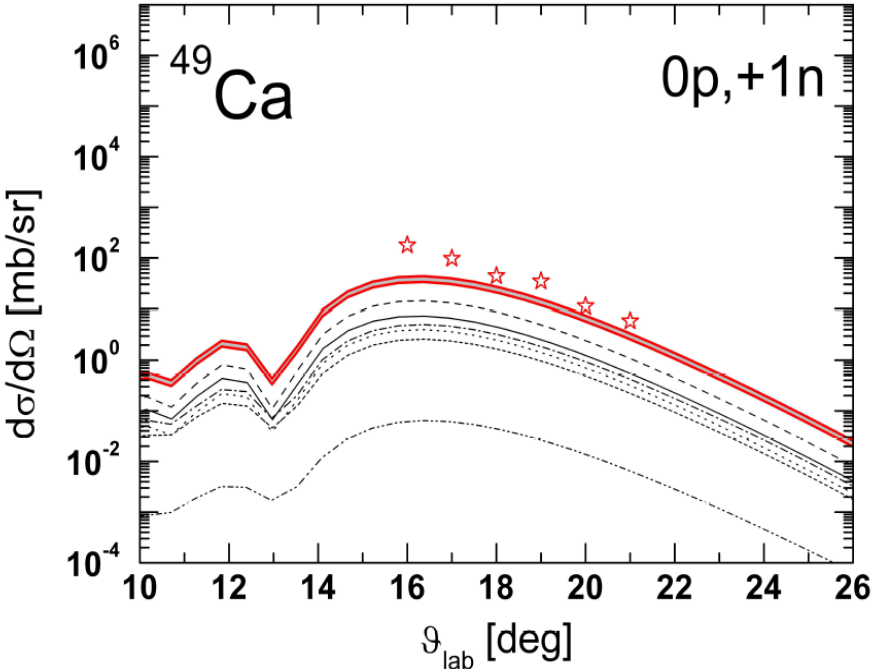
PRISMA

PRISMA.and.CLARA

Difference

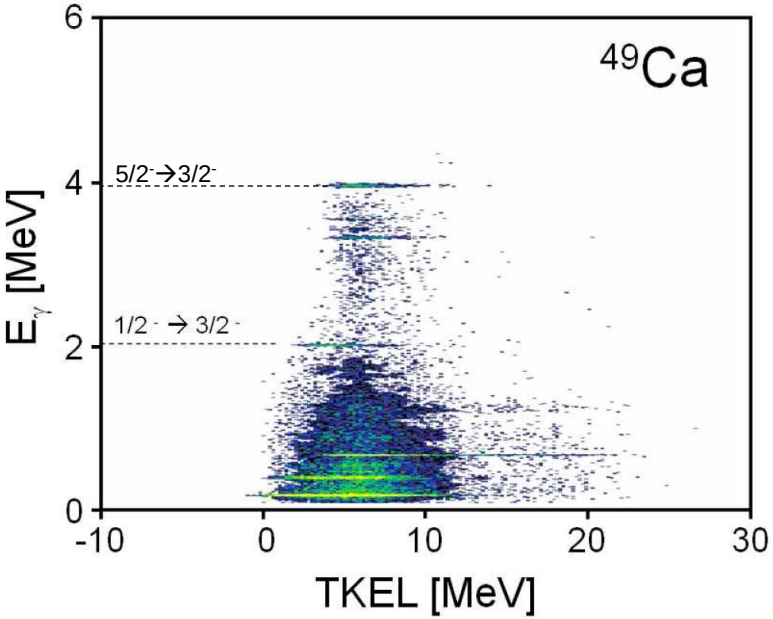
Experimental data (symbols)

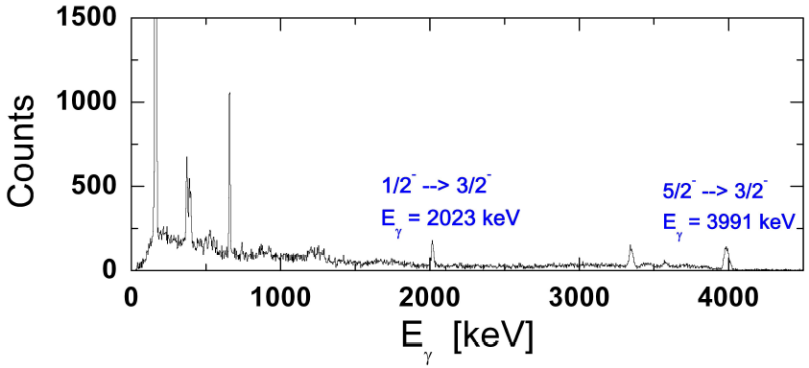
Theoretical DWBA calculations (lines)



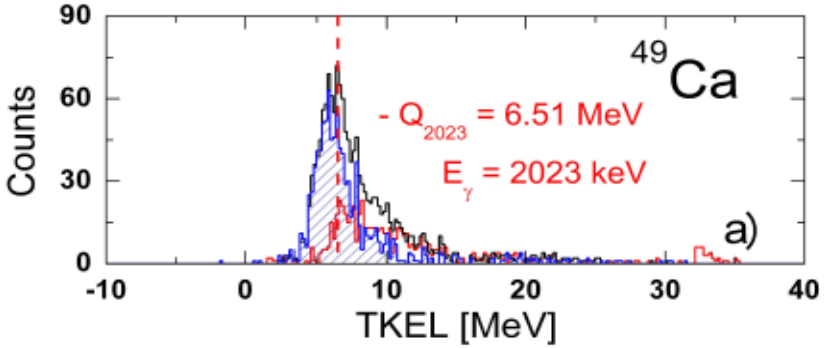
Angular distribution of TRANSFER to SPECIFIC STATES

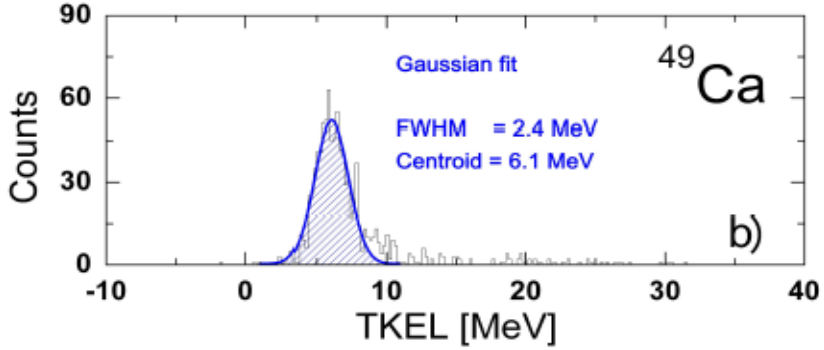
Transfer to excited states





TKEL spectra gated by gamma





Angular distribution of TRANSFER to SPECIFIC STATES

Transfer to excited states

$$\frac{d\sigma}{d\Omega} = S_{Ca} \times S_{Ni} \times \left(\frac{d\sigma}{d\Omega}\right)_{DWBA}$$

	Spin [ħ]	State	Energy [keV]	S
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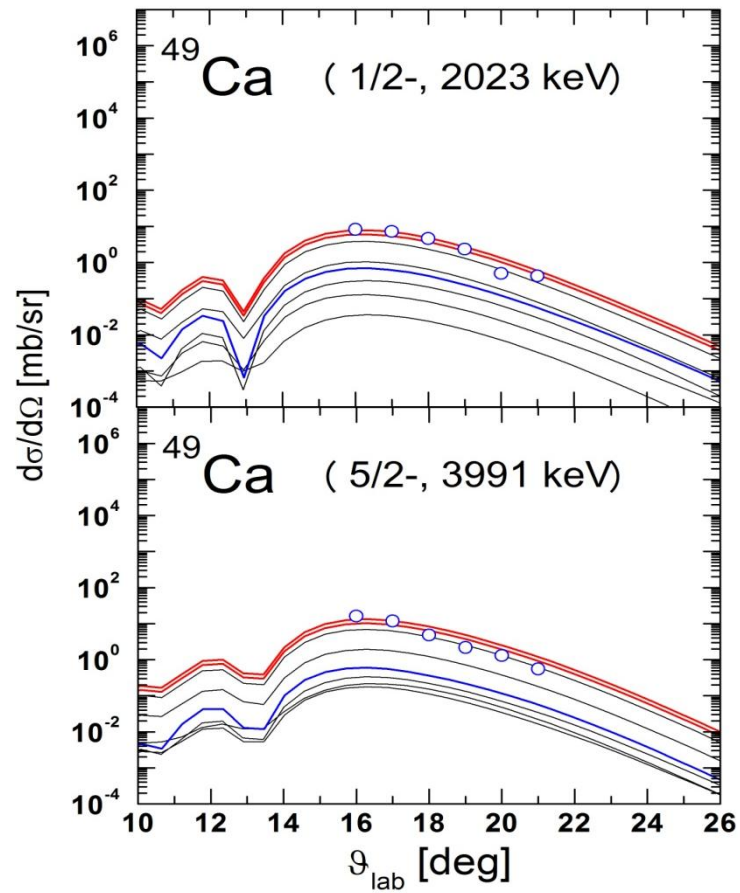
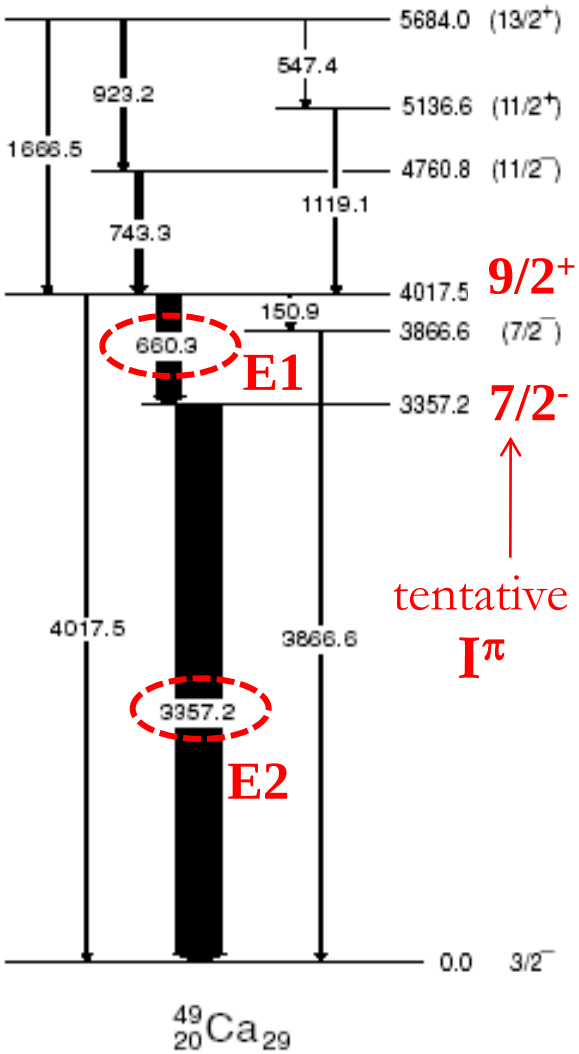
	9/2 +	$g_{9/2}$	1294	0.082

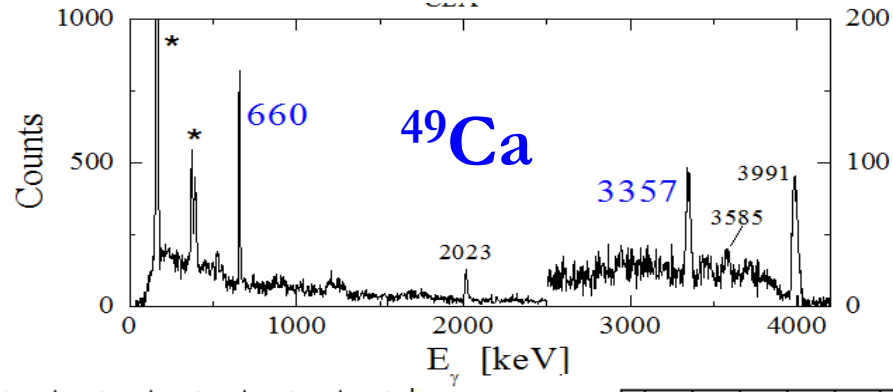
Feasibility of studies of transfer reactions to specific nuclear states with heavy-ions

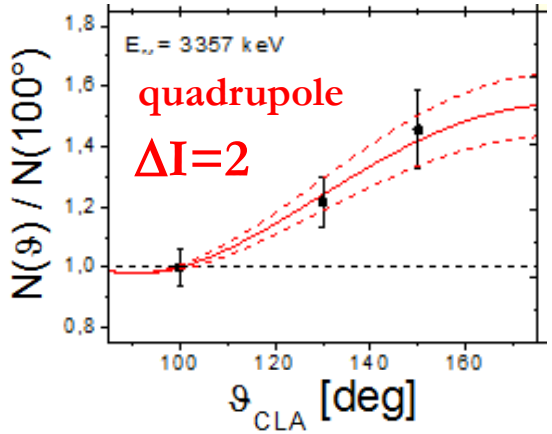
Possible evaluation of spectroscopic factors with better experimental conditions

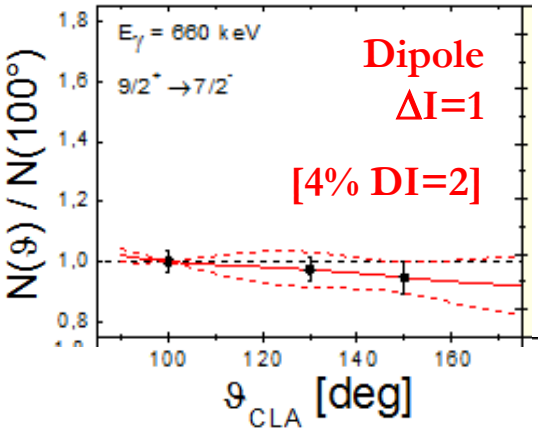


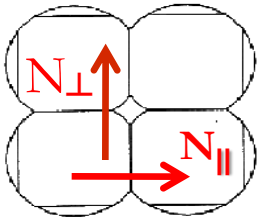
Spectroscopic studies – gamma angular distributions





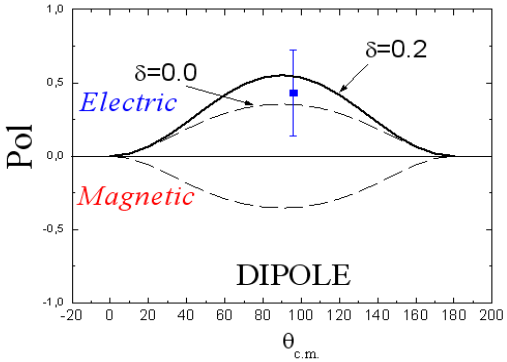






$$A = \frac{N_{\perp} - N_{\parallel}}{N_{\perp} + N_{\parallel}} = 0.08^{\pm 0.05}$$

Electric > 0



R. Broda, J.Phys.G32(2006)R151

MNT & Thick target data

CONCLUSION

1. Extensive Experimental Analysis of Inclusive Angular Distribution of

   ^{48}Ca (@ 6 MeV/A) on ^{64}Ni

2. Evaluation of response function of PRISMA (basic information of the spectrometer)

3. Interpretation of the data with GRAZING semiclassical model:
   good agreement for 1 nucleon transfer channels

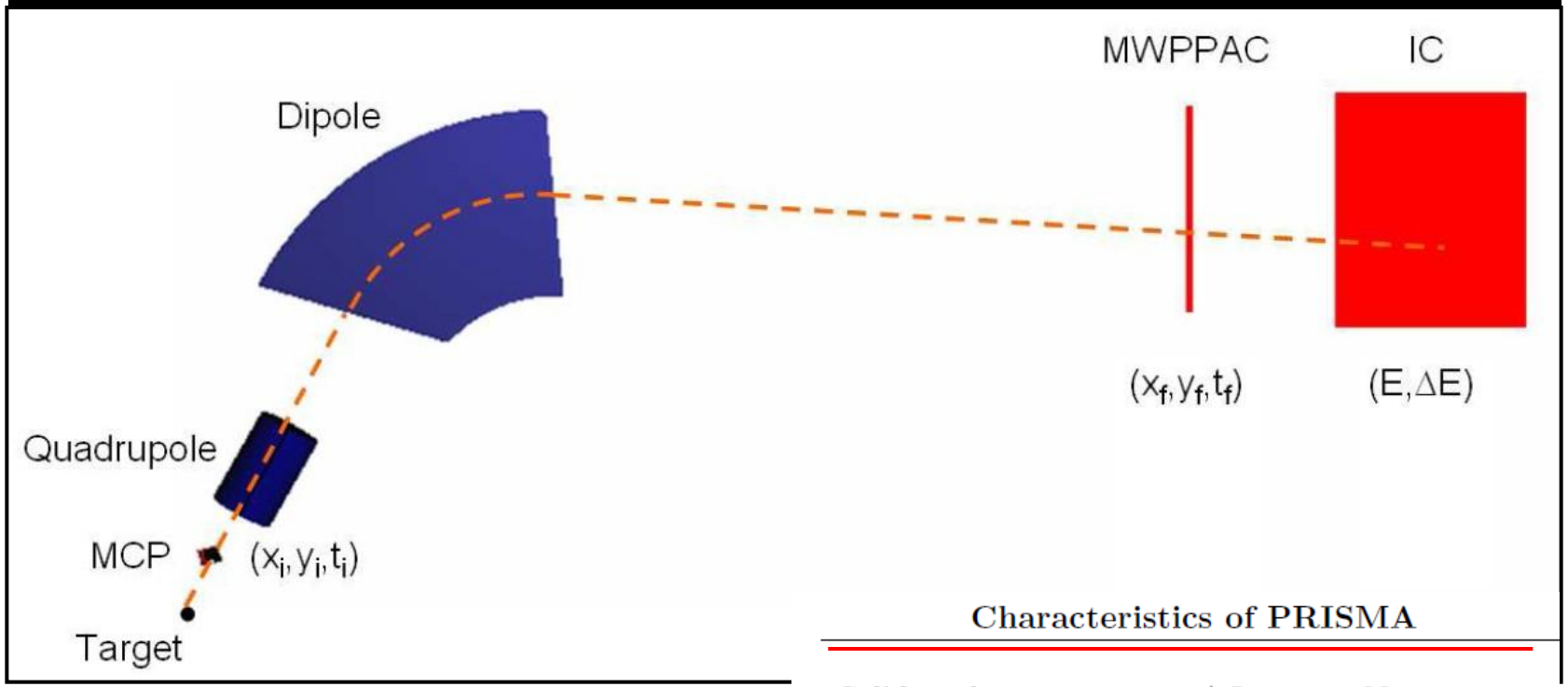
4. Comparison between theory (DWBA) and experiment for the inelastic scattering and for the transfers to the ground state and to excited states of the +1n channel

5. Possibility offered by heavy ion reactions to obtain information on nuclear structure (spectroscopic factors)

5. Perspectives: heavy-ions reactions with exotic nuclei and new generation gamma array

The End

The PRISMA magnetic spectrometer



Components	Distance
Target - MCP	250 mm
Target - Quadrupole	250 mm
Target - Dipole	1600 mm
Dipole - MWPPAC	3285 mm
MWPPAC - IC	720 mm
Angular position	-30° – 130°

Total path of the ions ≈ 6 m

Characteristics of PRISMA

Solid angle	$\Delta\Omega$	≈ 80	msr
Azimuthal acceptance	$\Delta\vartheta_{lab}$	$\approx \pm 6$	deg [1]
Polar acceptance	$\Delta\varphi_{lab}$	$\approx$ -	deg [2]
Energy acceptance	ΔK	$\approx \pm 20$	%
Momentum acceptance	Δp	$\approx \pm 10$	%
Z resolution	$\Delta Z/Z$	$\approx 1/60$	-
A resolution	$\Delta A/A$	$\approx 1/200$	-

1 on the horizontal axis passing by the centre of the MCP.

2 depending on the angular position of PRISMA.

The experiment – $^{48}Ca + ^{64}Ni$ at 282 MeV

May 2007, PRISMA-CLARA experiment

PRISMA at 20°

Reaction	$^{48}Ca + ^{64}Ni$	
Target thickness	0.98	mg/cm^2
Target angle	45	deg
E_{lab}	282.0	MeV
E_{lab}/A	5.9	MeV/A
E_{cm}	162.3	MeV
V_{coul}	70.1	MeV
$(E_{loss})_{lab}$	7.9	MeV
v/c_{Ca}	≈ 10	%
v/c_{Ni}	≈ 2	%

Statistics in 6 days of beam time

Raw data (PRISMA)	$4.24 \cdot 10^8$
Raw data (CLARA)	$3.21 \cdot 10^8$

Population of many isotopic chains from -3p (Cl) to +2p (Ti)

Trigger condition	Rate [kHz]
	(I_{beam} = 1pnA)
MCP.and.MWPPAC	-
MCP.and.γ–γ	150
MWPPAC.and.γ	1500
DANTE.and.γ–γ	1600

Presorting of the data

PRISMA data – Trajectory reconstruction

Measured

- the spacial entrance coordinates on the MCP: (x_i, y_i);
- the spacial coordinates on the focal plane (MWPPAC): (x_f, y_f);
- the time of flight of the ions between the MCP and the MWPPAC: TOF;
- the partial and total energy released in the IC: (ΔE, E).

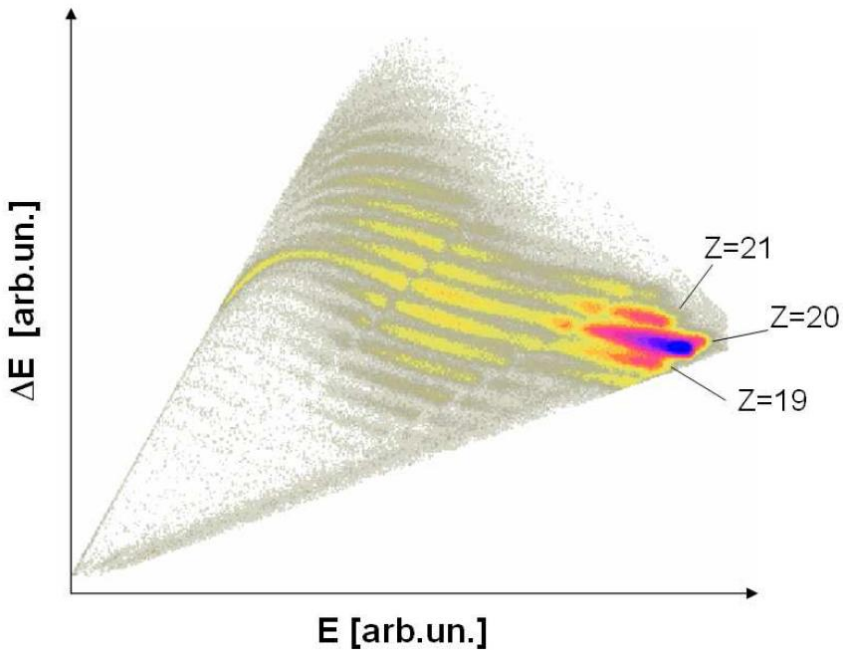
Reconstructed

- the length of the trajectories of the ions: L;
- the curvature radius inside the dipole magnet: R;
- the total energy released in the ionisation chamber: E;
- the range of the ions in the IC: r.

PRISMA data – Ions identification

Selection of the atomic number Z

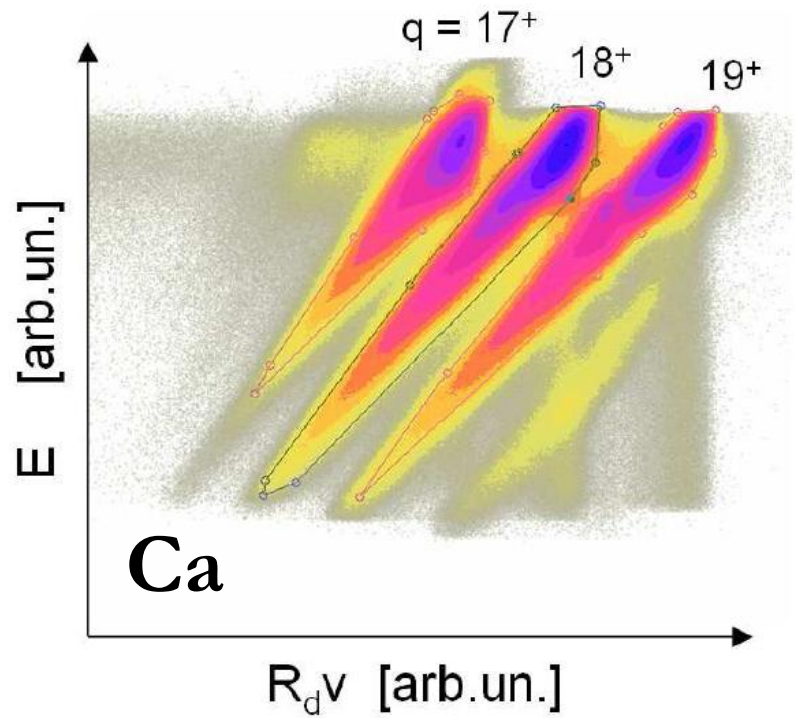
$$\frac{dE}{dx} \propto \frac{mZ^2}{E} ln \frac{E}{m}$$



Identification of the charge state q

$$\frac{m}{q} = B\frac{R_d}{v}$$

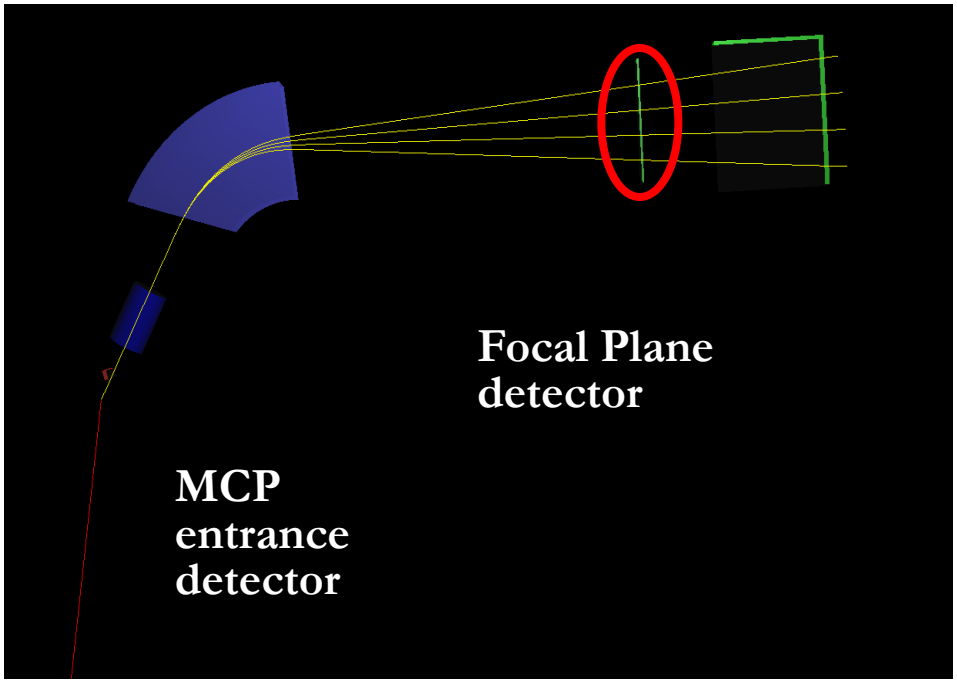
$$\frac{1}{2}mv^2 = qBR_dv$$

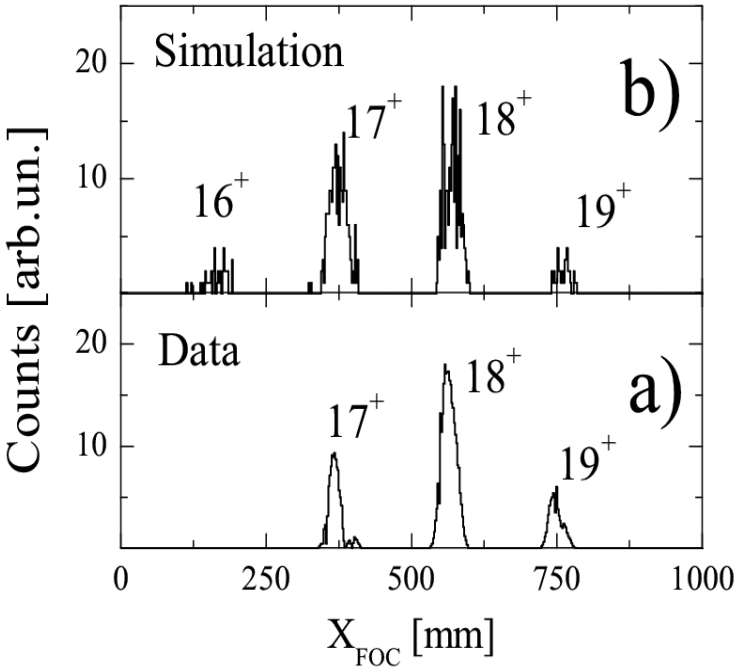


First Step

Check of Magnetic Fields

The charge states deflection in the simulation has to be the same as in the experiment





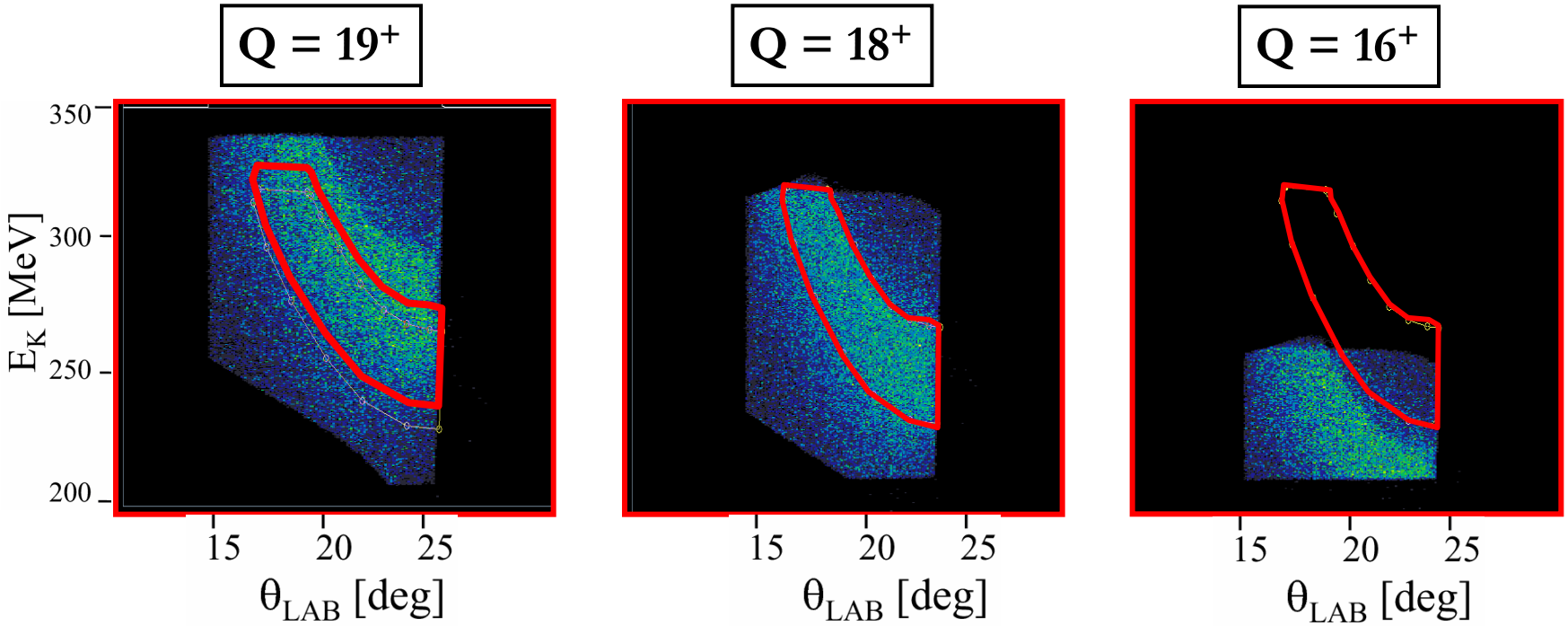
Second Step

Transport in PRISMA of a uniform distribution in (E_k,θ,ϕ)

E_K = [200, 400] MeV

ϑ = [10°, 40°]

φ = [-40°,40°]

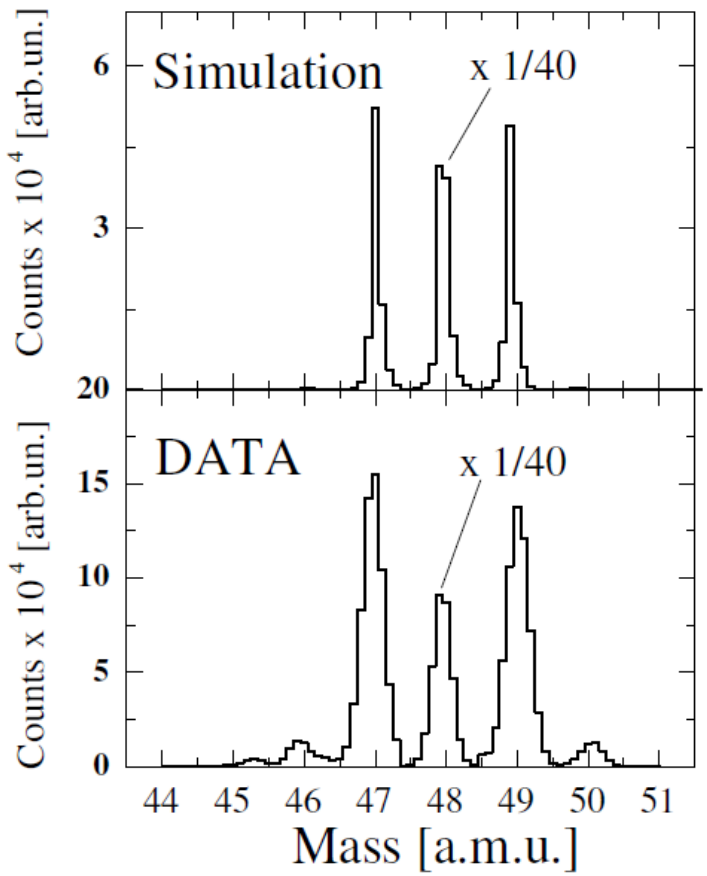


Mass distribution

Input theoretical distribution → Mixing of masses

Ca isotopes

Good mass resolution in both experiment and simulation



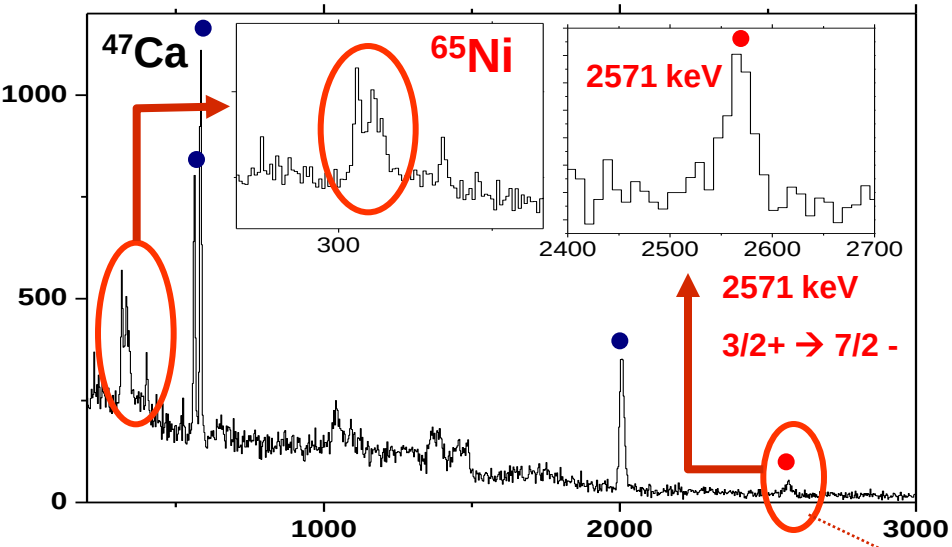
Presorting of the data – Trajectory reconstruction

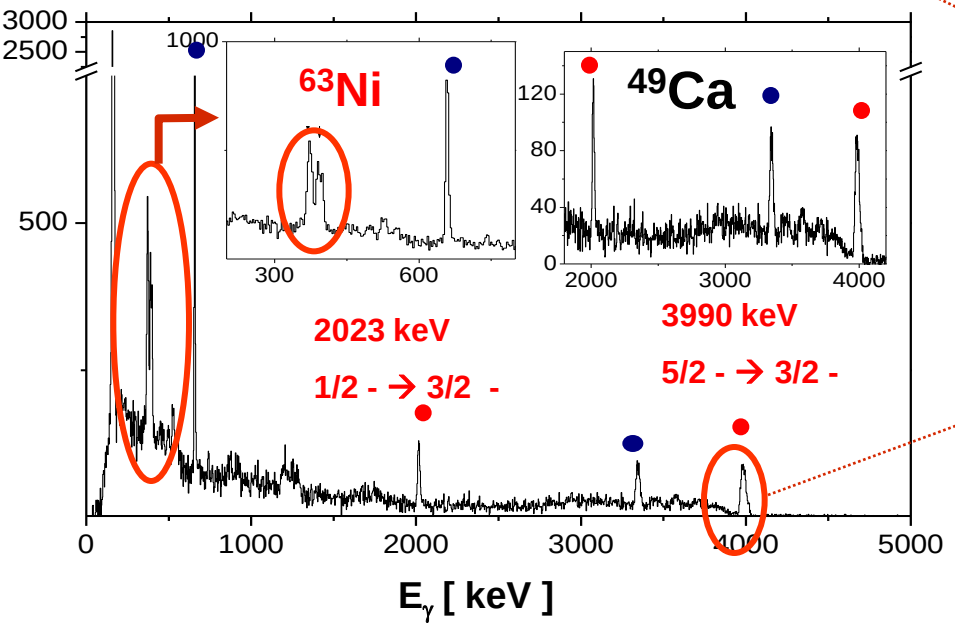
- a straight line from the target to the quadrupole entrance, L_{mcp};
- a hyperbolic path inside the quadrupole magnet up to its exit, L_{quad};
- a straight line to the dipole magnet entrance, L_{Q-D};
- a circular trajectory in the horizontal dispersion plane of the dipole magnet up to the dipole exit, L_{dip};
- a straight line in the dispersion plane from the exit of the dipole magnet up to the focal plane, L_{ppac}.

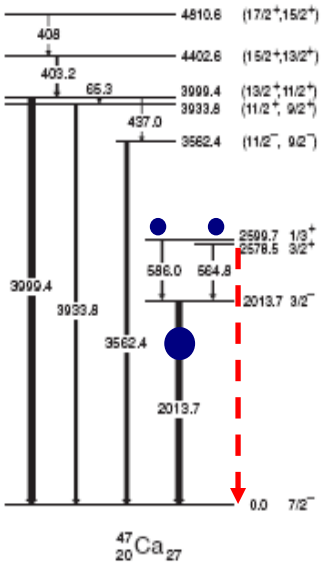
$$L = L_{mcp} + L_{quad} + L_{Q-D} + L_{dip} + L_{ppac}$$

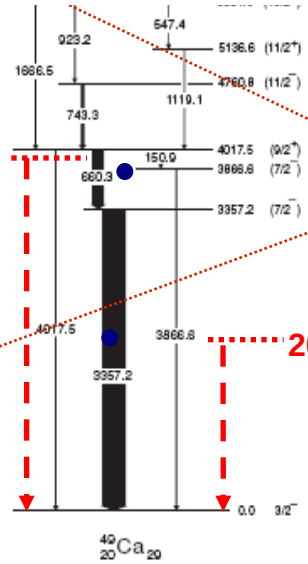
Gamma Spectra - Comparison With DIC at Lower Energy

R.Broda, J.Phys. G 32 (2006)









2023 keV

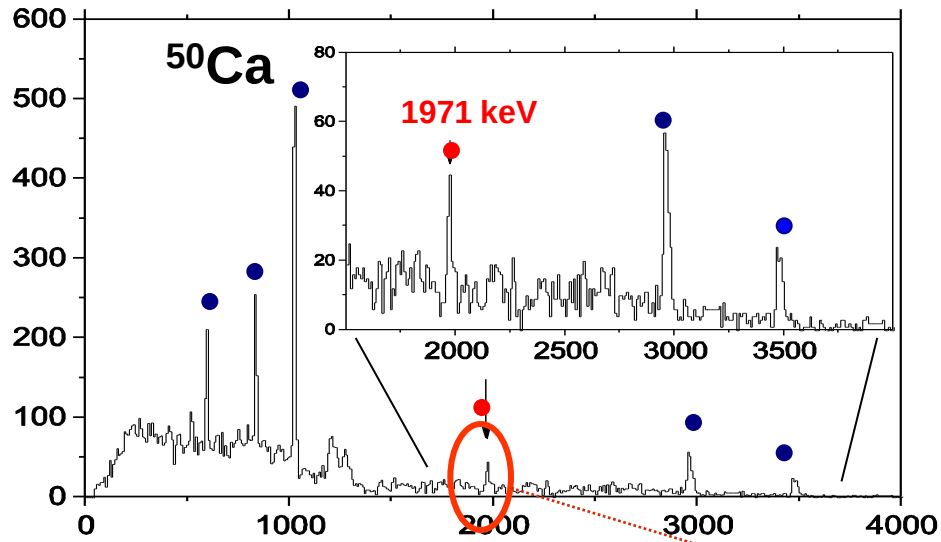
- Known transitions

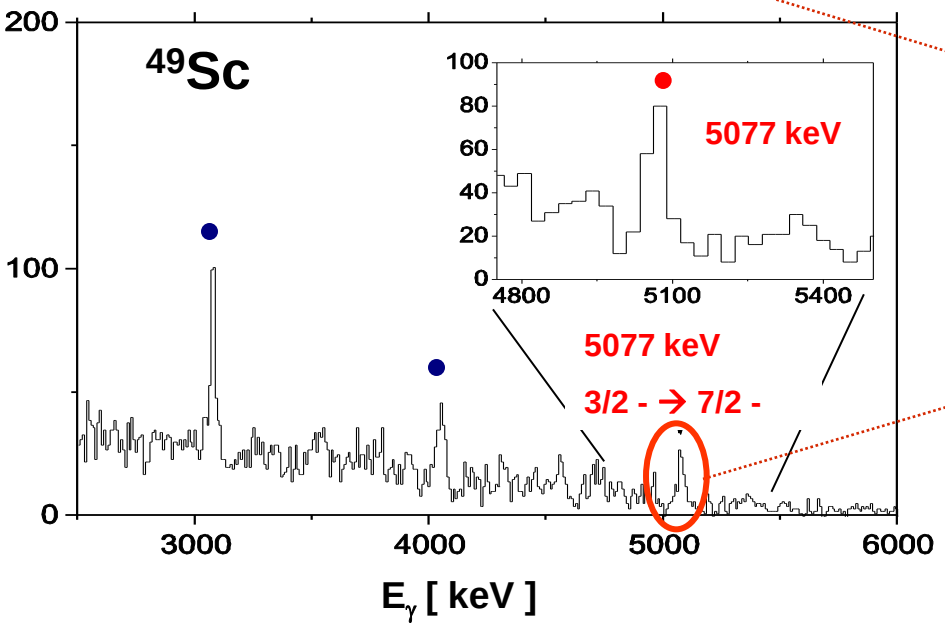
In RED: transitions not seen in deep inelastic reactions at lower E_{beam}

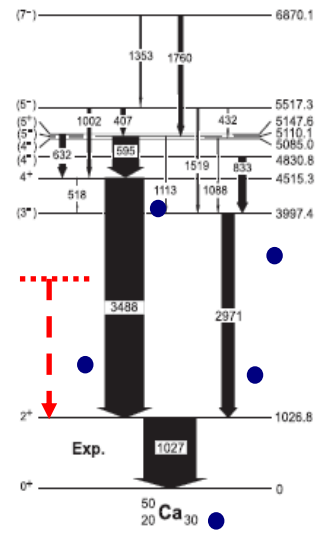
State populated in Light Transfer Reactions (d,p) – (d,n) - …

Gamma Spectra - Comparison With DIC at Lower Energy

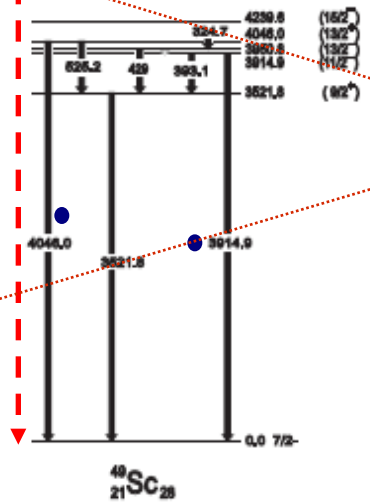
R.Broda, J.Phys. G 32 (2006)







5077 keV

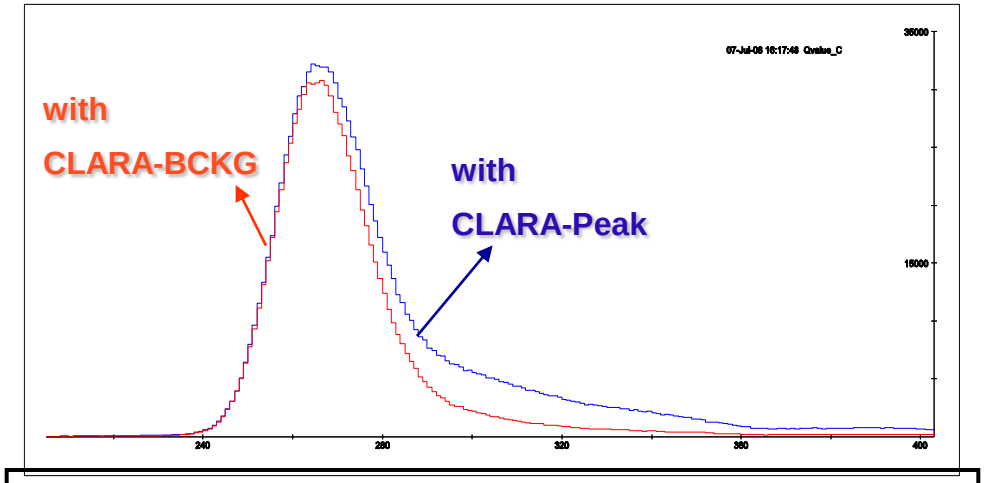


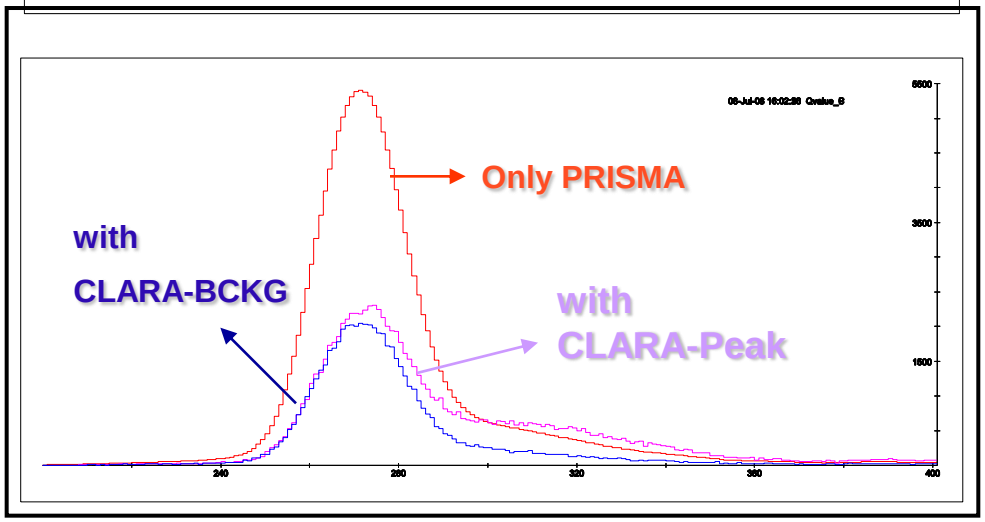
● Known transitions

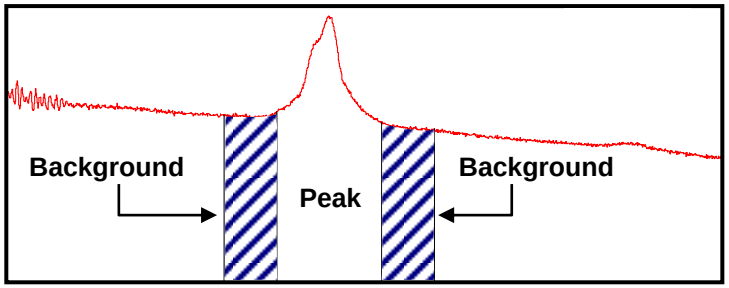
In RED: transitions not seen in deep inelastic reactions at lower E_{beam}

State populated in Light Transfer Reactions (d,p) – (d,n) - …

Background subtraction







TAC Ge-Prisma Time