Spectroscopic studies with the ray-tracing magnetic spectrometer MAGNEX

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The MAGNEX collaboration

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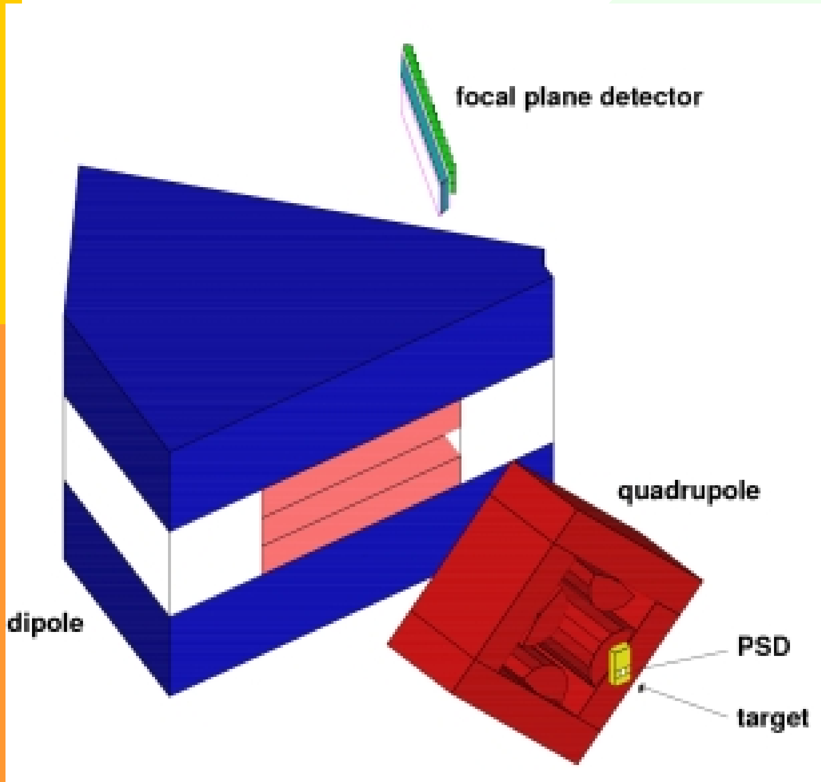
MAGNEX



Maximum magnetic rigidity	1.8 T• m
Solid angle	51 msr
E_{max}/E_{min}	1.5
Total energy resolution (target 1 mm^2) (90% of full acceptance)	~ 1000
Mass resolution	250

A.Cunsolo et al., NIMA 481 (2002) 4

A.Cunsolo et al., NIMA 484 (2002) 5

Topics

- Some experimental challenges associated with modern nucler spectroscopy
- The MAGNEX spectrometer
- Planned experiments
- Conclusions and outlook

Spectroscopy with EXCYT RIBs

- Low intensity (compared to normal) beams
- Excellent optical properties of the EXCYT RIBs.
- Tandem energies for light to intermediate mass nuclei

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New detection "philosophy"

Large acceptance and high resolution magnetic spectrometer

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Aberrations

Heavy nuclei spectroscopy

- **High density of states also at low excitation energy** → - **High energy resolution (beams from electrostatic accelertors, thin target thickness and good detectors)**

- **Spectroscopic information distributed over many transitions, many of which are weakly populated** → - **High beam intensity and efficient detection systems**

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- **Modern high resolution magnetic spectrometers are a good choice (e.g. Q3D with new focal plane detector was crucial to discover supersimmetry!)**

"Clever" spectrometers

- **Possible definition: spectrometer reconstructing a neet image by an optically aberrated one**

Practically one needs

- **Detailed knowledge of the magnetic field maps**
- **Algorithms for high order solution of equation of motion and inversion of transport matrices**
- **Detectors to measure positions and angles at the focus**

Inversion of transport matrices

$$x_i = F_1^{'}(x_f, \theta_f, y_f, \phi_f, l_f)$$
$$\theta_i = F_2^{'}(x_f, \theta_f, y_f, \phi_f, l_f)$$
$$y_i = F_3^{'}(x_f, \theta_f, y_f, \phi_f, l_f)$$
$$\phi_i = F_4^{'}(x_f, \theta_f, y_f, \phi_f, l_f)$$
$$\delta = F_5^{'}(x_f, \theta_f, y_f, \phi_f, l_f)$$

- **Large acceptance condition**

$$x_i(f) = \sum_j R_{ij} x_j(i) + \sum_{j,k} T_{ijk} x_j(i) x_k(i) + ...$$

- **For MAGNEX up to 11th order !**

- **Differential algebra (Ex:COSY INFINITY)** M. Berz *et al.*, PRC 47 (1993) 537

$$M_n =_n (A_1^{-1} \circ (I - A_n^{*} \circ M_{n-1}))$$

Iterative formula

Limits of the software techniques

Practical limit for software compensation of aberrations

$$x'_f = x_f - (x|\theta^3)\theta^3 = x_f - C$$

$$\sigma_C = \frac{fC}{f\theta}\sigma_\theta = 3(x|\theta^3)\theta^2\sigma_\theta$$

$\sigma_C / C = 3\sigma_\theta / \theta$, if $\sigma_\theta \sim 10$ mr and $\theta \sim 100$ mr

$\sigma_C / C \sim 30\%$! ! ! (partial compensation)

The aberrations should be minimised by hardware

Hardware minimisation for MAGNEX

- Rotation of focal plane detector of 59°
- 8th order polinomyal shaping of dipole boundaries
- Introduction of surface coils in the dipole pole

Overview of the detection system

- **Quantities to measure:**

Trajectory reconstruction

$x_f\ \theta_f\ y_f\ \phi_i$

Ion identification

$M \leftarrow T_{OF}\ ,\ l_f\ (\delta, \theta)$

$Z \leftarrow dE/dx\ ,\ E$

$q \leftarrow E\ ,\ T_{OF}\ ,\ l_f\ (\delta, \theta)$

- **Resolution constraints:**

$\Delta x_f < 1$ mm $\quad \Delta y_f \sim 1$ mm

$\Delta \theta_f < 10$ mr $\quad \Delta \phi_i \sim 8$ mr

$\Delta T_{OF} \sim 1$ ns $\quad \Delta l_f \sim (1/200)\ l_f$

$\Delta(dE/dx) \sim 5\ \%$ $\quad \Delta(E) \sim 1\ \%$

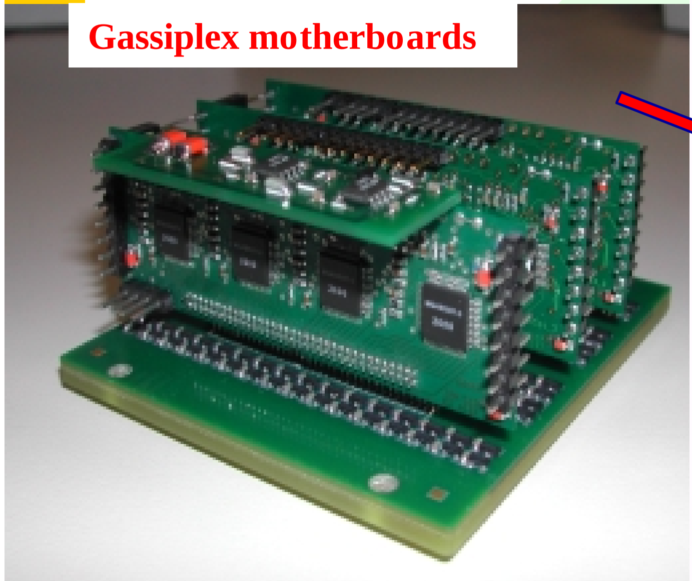
- **Geometrical constraints (space, magnetic fields, shapes, etc.)**
- **Energy threshold (foils, gas pressure)**
- **Cost and various complications (rate, electronics, number of channels, etc.)**

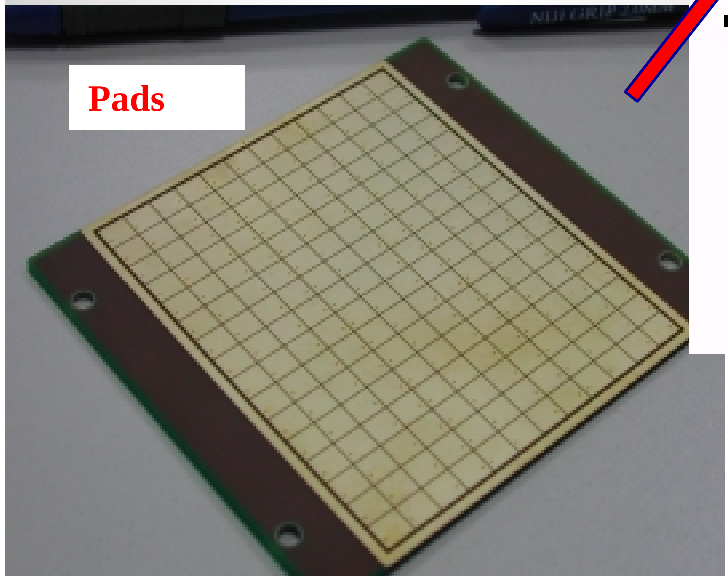
Definition of the detection system

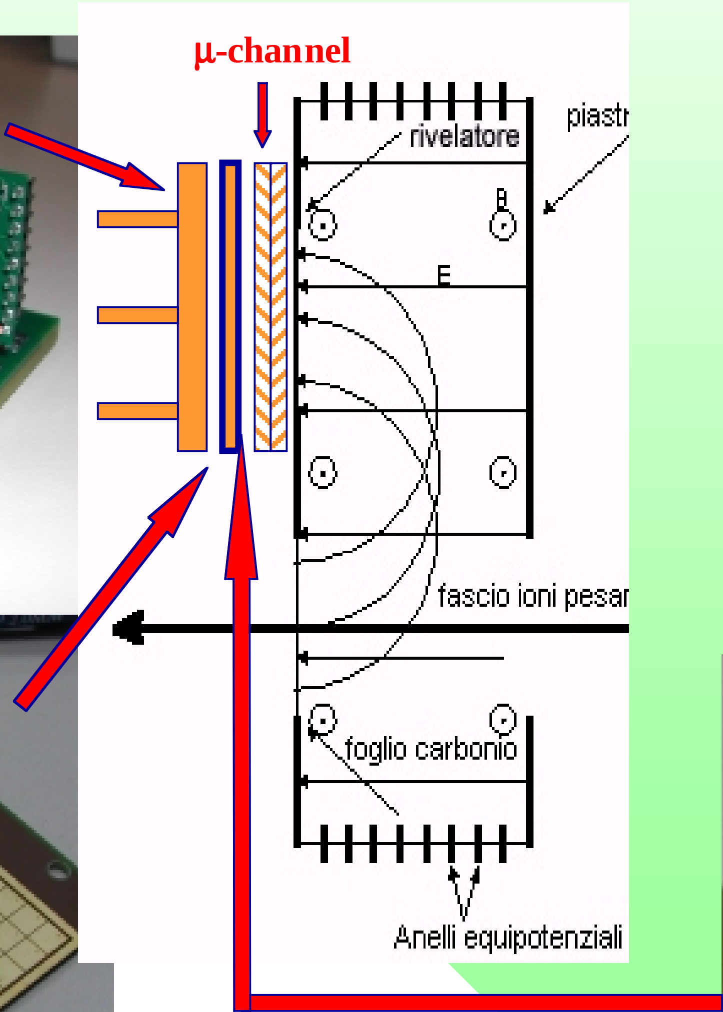
- **Position Sensitive start Detector (PSD), based on microchannel plate, for measurement of φ_i and θ_i and generation of T_{START}**

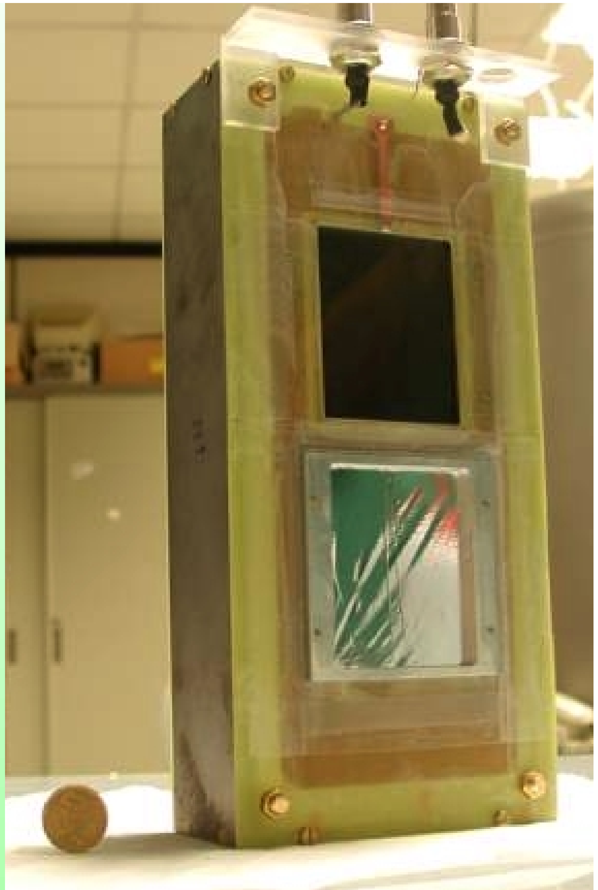
- **Focal Plane Detector (FPD) for measurement of x_f , y_f , θ_f , φ_f , dE/dx , E_{res} and T_{STOP} with low energy threshold**

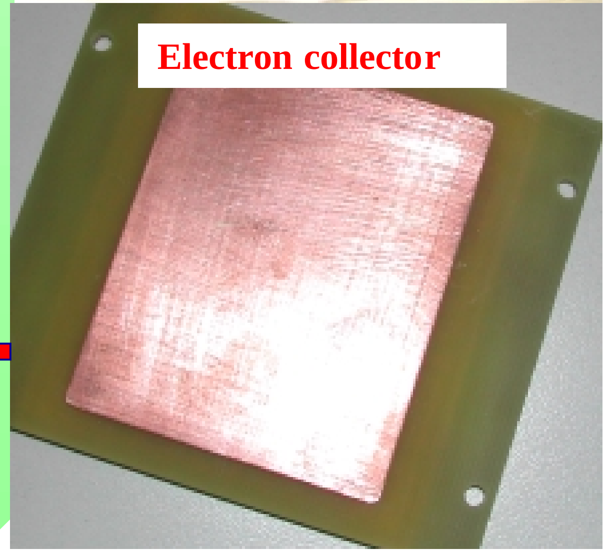
The PSD start detector



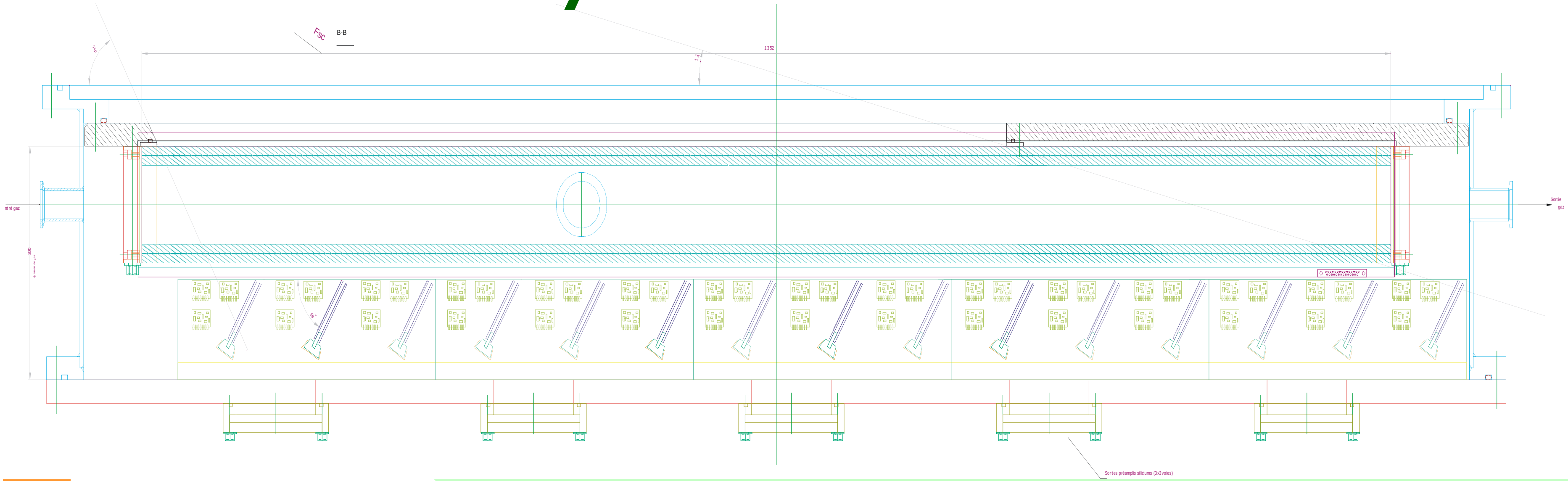








Layout of the FPD



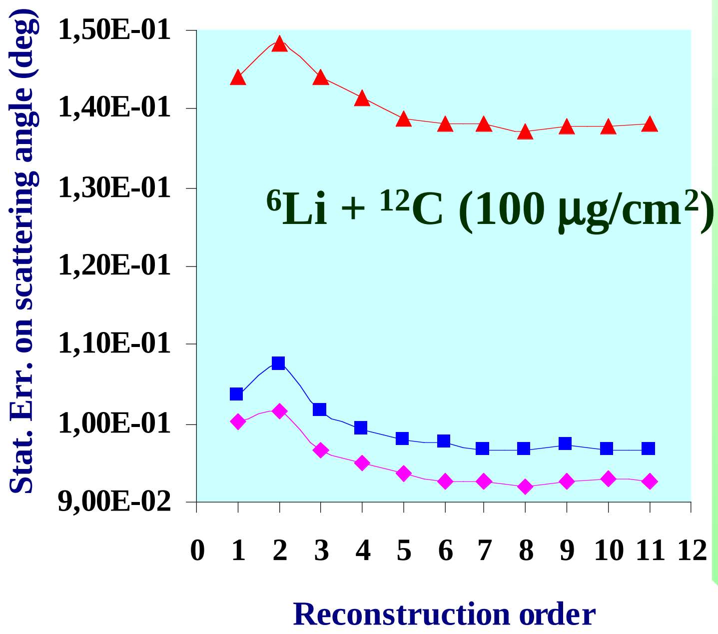
A.Cunsolo et al., NIMA 495 (2002) 216

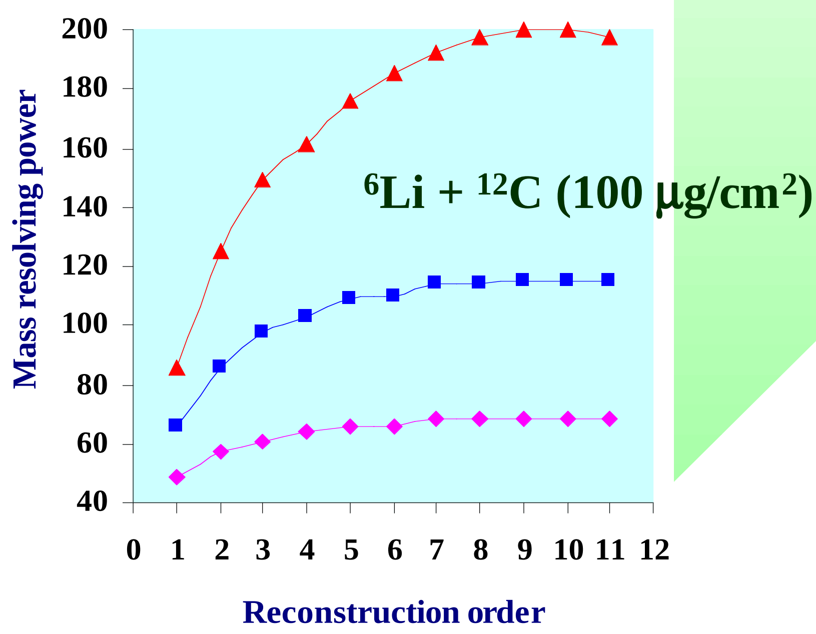
- Trapezoidal geometry
- Window length 92 cm. Height 20 cm. Depth 16 cm
- Isobutane pressure between 5 e 50 mbar
- Energy threshold down to 0.5 MeV/amu
- No intermediate foils
- Maximum counting rate 4 kHz

Reconstructing trajectories

ANGULAR AND MASS RESOLUTION

- Angular and mass resolution are ~ ion-independent



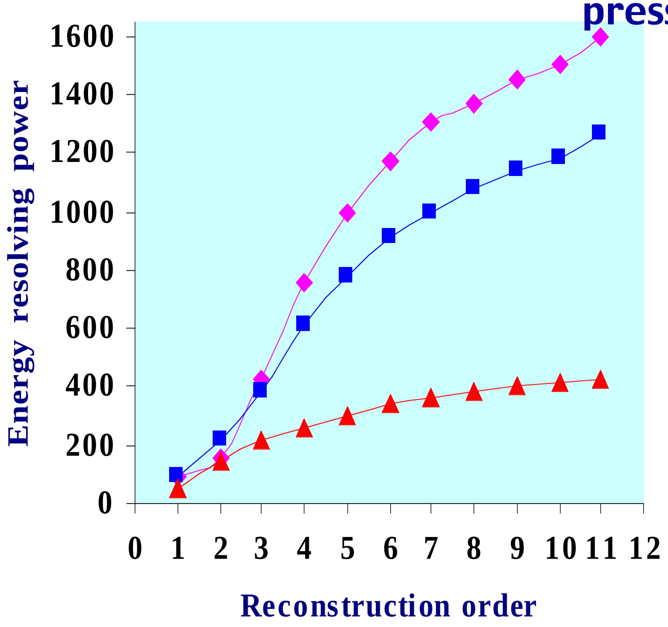


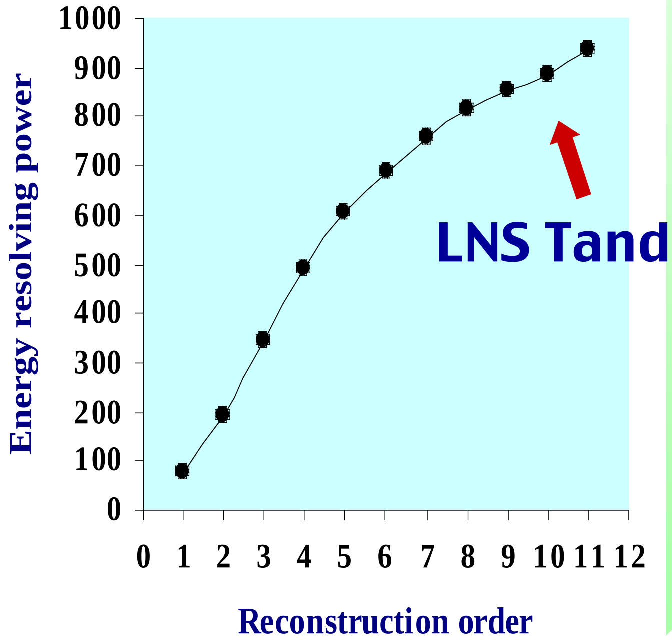
- Å 1.8 Tm ⇒ ~ 38 MeV/u
- Å 1.06 Tm ⇒ ~13 MeV/u
- Å 0.5 Tm ⇒ ~ 3 MeV/u

Reconstructing trajectories

Energy resolving power for $^{6}Li + ^{12}C$ (100 µg/cm^2)

A.Lazzaro et al. 7th ICAP, East Lansing, 2002, IOP publication, in press





- Å 1.8 Tm ⇒ ~ 38 MeV/u a)
- Å 1.06 Tm ⇒ ~13 MeV/u a)
- Å 0.5 Tm ⇒ ~ 3 MeV/u b)

- Å 0.815 Tm ⇒ 8 MeV/u b)

- LNS – Cyclotron energies
- LNS - Tandem energies

Experimental lines

- Commissioning of the spectrometer with known reactions like (^7Li,^7Be) with Tandem beams
- Experiments with EXCYT RIB's
- Spectroscopic studies of heavy ions with intense proton beams
- Experiments of nuclear astrophysics (Trojan Horse Method)
- Experiments with quasi-stable (e.g. ^{14}C and tritium) Tandem beams

Homologous states near shell closure

- Odd nuclei = even core + 1 nucleon
- Weak coupling between the unpaired nucleon and magic number core

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- Core excitations not washed out from spectator nucleon
- Core excited states are generators of multiplets on the odd nucleus with $|Jc - Jp| < J < Jc + Jp$
- Generator states and correspondent multiplets are said homologous

Properties of homologous states

- **Very similar response to direct reaction probes**

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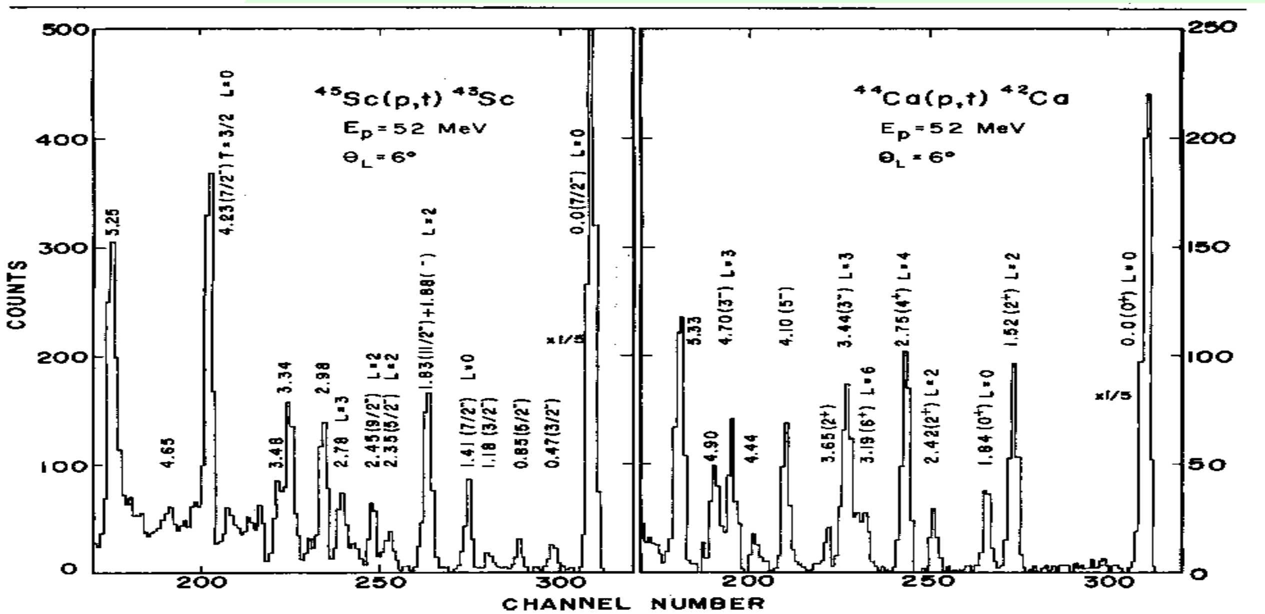
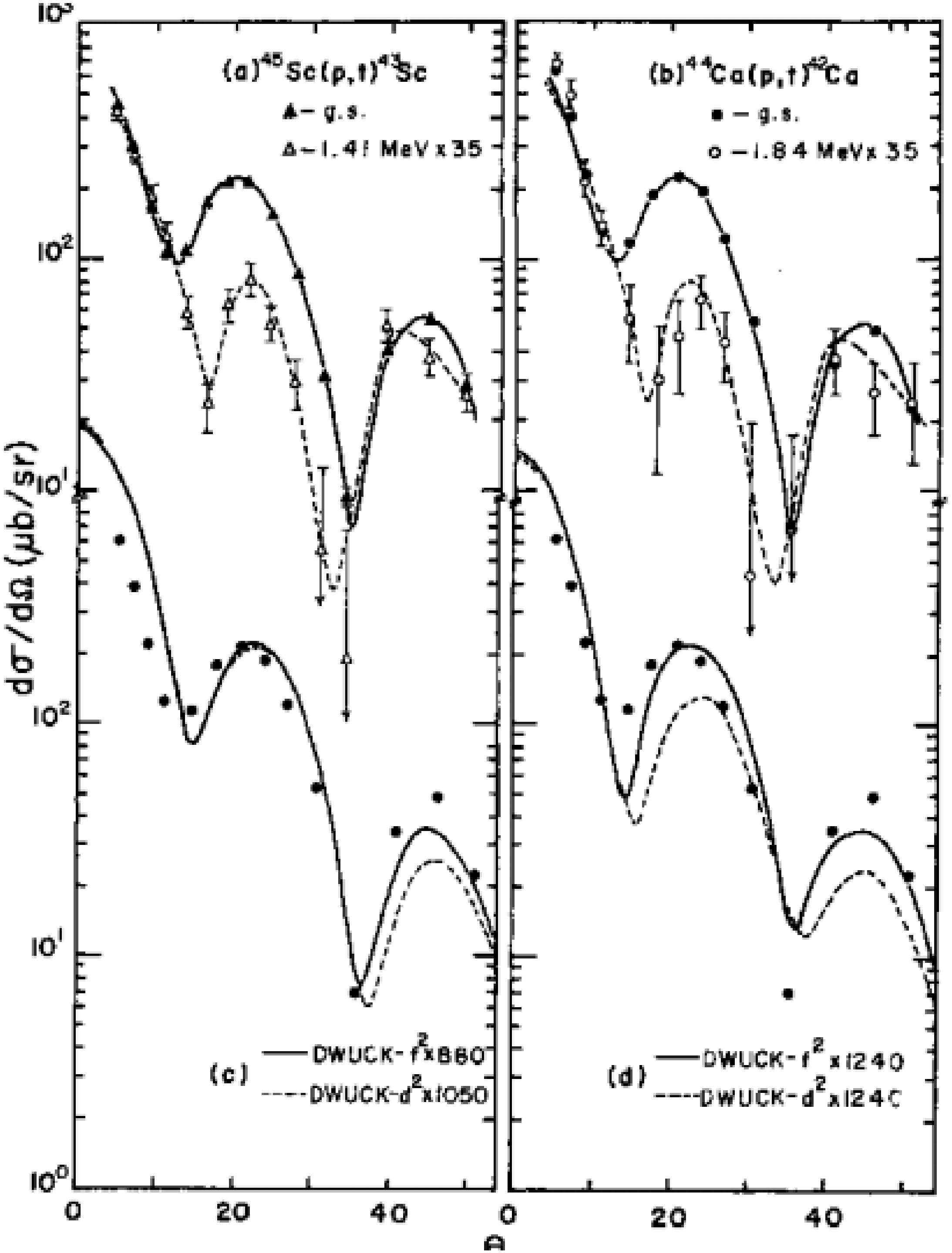
- **Same angular distriution shapes**
- **Same integrated cross section (of course distributed over all the multiplet states)**
- **Dependency of the integrated cross section on 2J+1 for the multiplet states**
- **Observed in (p,α) and (p,t) reactions** (J.N.Gu et al. PRC 55 (1997)2395 and P.Guazzoni et al., PRC 62 (2000) 054312)

(p,t) reaction on ^{45}Sc and ^{44}Ca targets

K.A.Erb and T.S.Bhatia PRC 7 (1973) 2500



- **Overall experimental energy resolution (only) 70 keV**
- **Consequently homologous states observed only for 0^+ core**



Astonishingly identical cross sections

(p,t) reaction on ^{45}Sc and ^{44}Ca targets

- What we expect to get with MAGNEX?

Some numbers

- **Proton beam expected intensity of 5×10^{12} pps and energy of 28 MeV**

- **MAGNEX acceptance 51 msr**

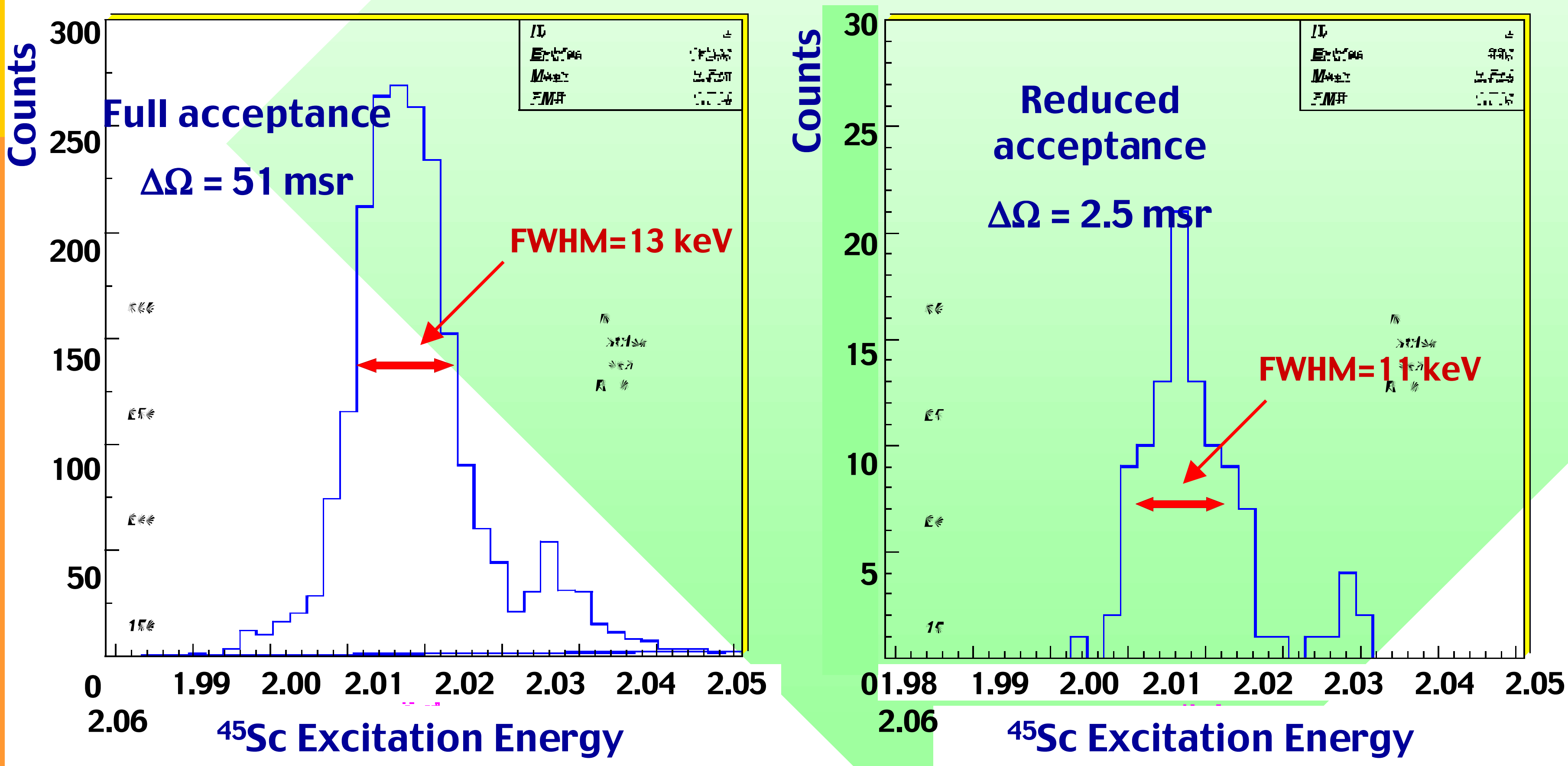
- **Scattering angles accepted with a unique setting θ_{lab} = 1°÷15° (5 angular settings to measure all the relvant angular distributions)**

- **Expected average cross section ~ 0.1 ÷ 100 μb/sr**

- **Explored energy spectrum up to 5 MeV for each magnetic setting**

11th order reconstructed ^{43}Sc doublet

$^{45}Sc(p,t)^{43}Sc$ at 28 MeV and $\theta_l = 1° \div 15°$



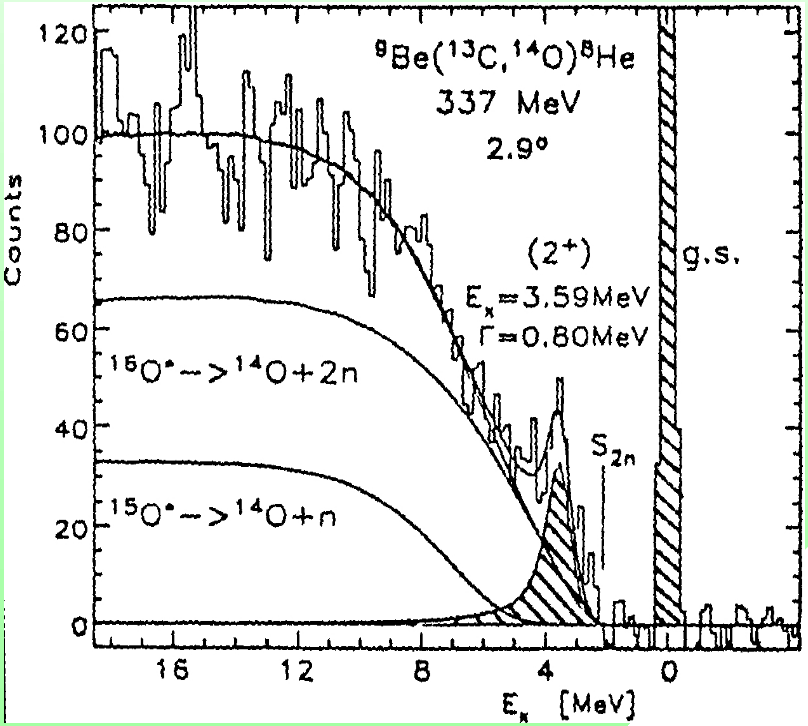
Exploration of ^{8}He

- **Excited states observed up to 7 MeV** T.Stolla et al. Z.Phys A 356 (1996) 233

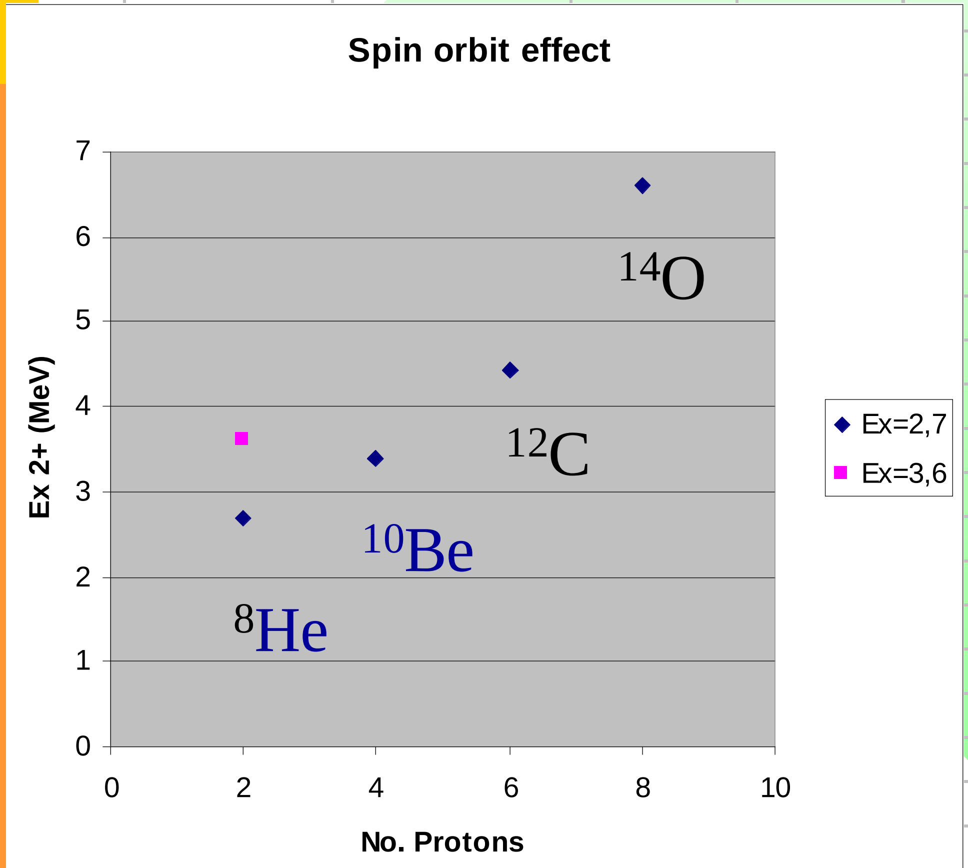
- **The 2^+ excited state was observed at 2.7 MeV in some experiments and at 3.6 MeV in other**

- **In the last compilation of A=8 nuclei (J.H.Kelley et al.) such state is given at 3.1 MeV ± 0.5 MeV**

W. Von Oertzen et al. Nucl.Phys.A588 (1995) 129



Importance of E_x of 2^+ in ^{8}He



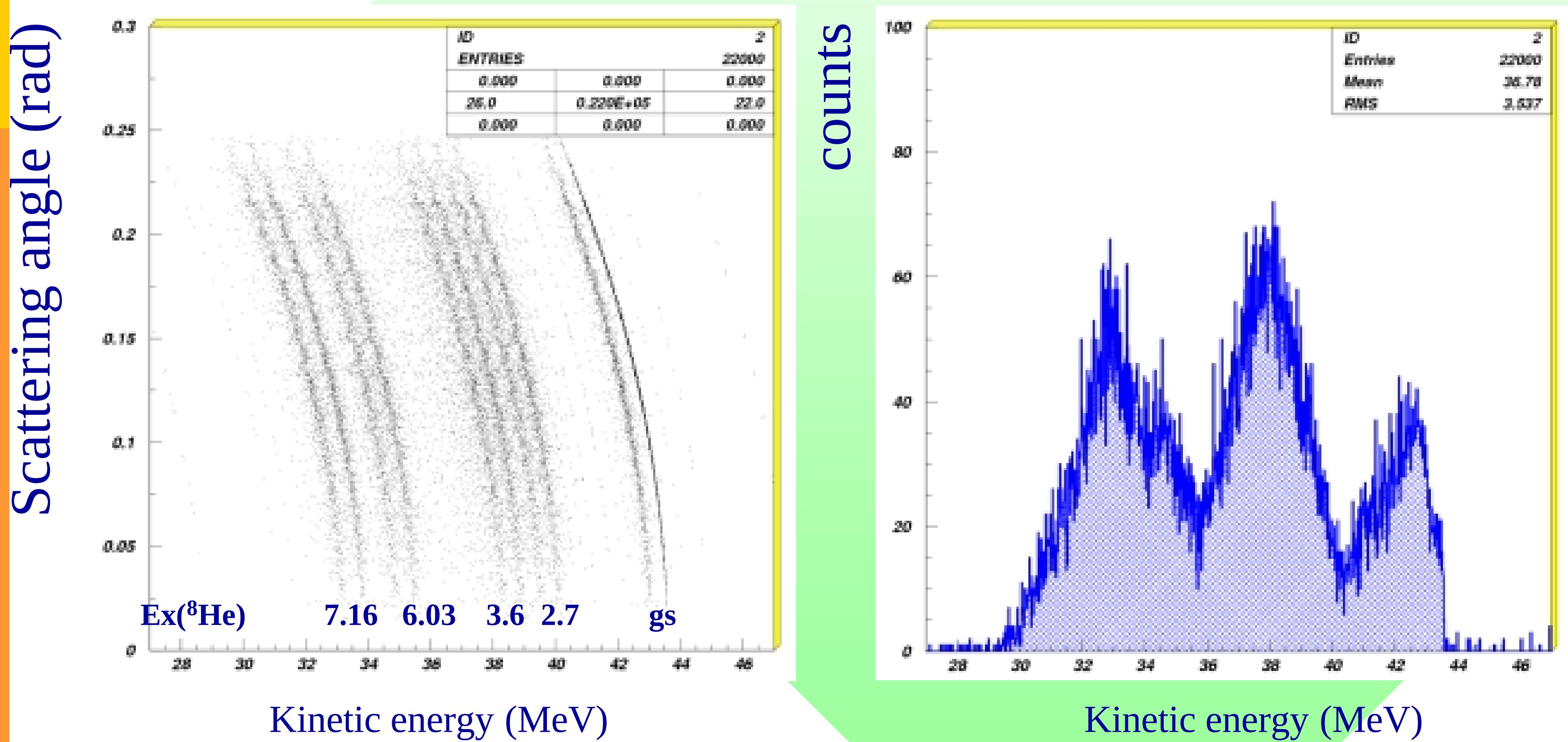
- Splitting of $p_{1/2}$ and $p_{3/2}$ s.p. levels decreases as n/p ratio increases – effect of weakening of spin-orbit interaction.

Some numbers

- ^{8}Li expected intensity of 1×10^{6} pps
- MAGNEX acceptance 51 msr
- Scattering angles accepted with a unique setting θ_{lab} = 1°÷15° corresponding to θ_{cm} = 1°÷35°
- Expected average cross section ~ 200 μb/sr for Gamow Teller transitions (from systematics)
- Rate/target thickness ~ 1.6 / (1 μm) counts/hour
- Effect of target on the energy resolution: ~ 28 keV / (1 μm)
- Strong kinematic effect (> 2 MeV in the accepted

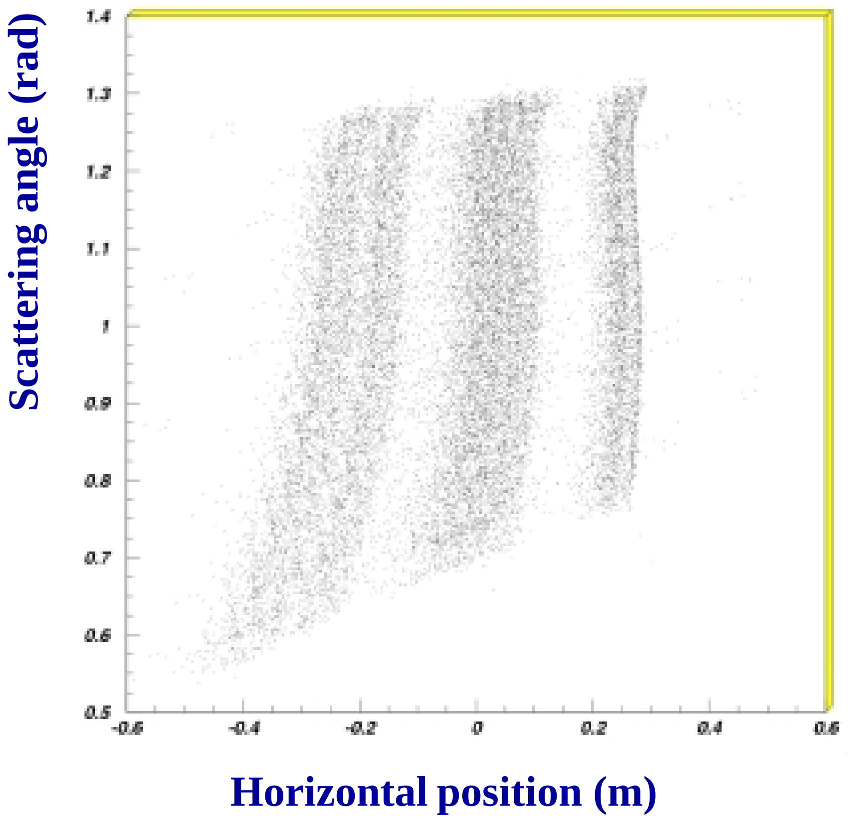
Cosymag simulations (initial conditions)

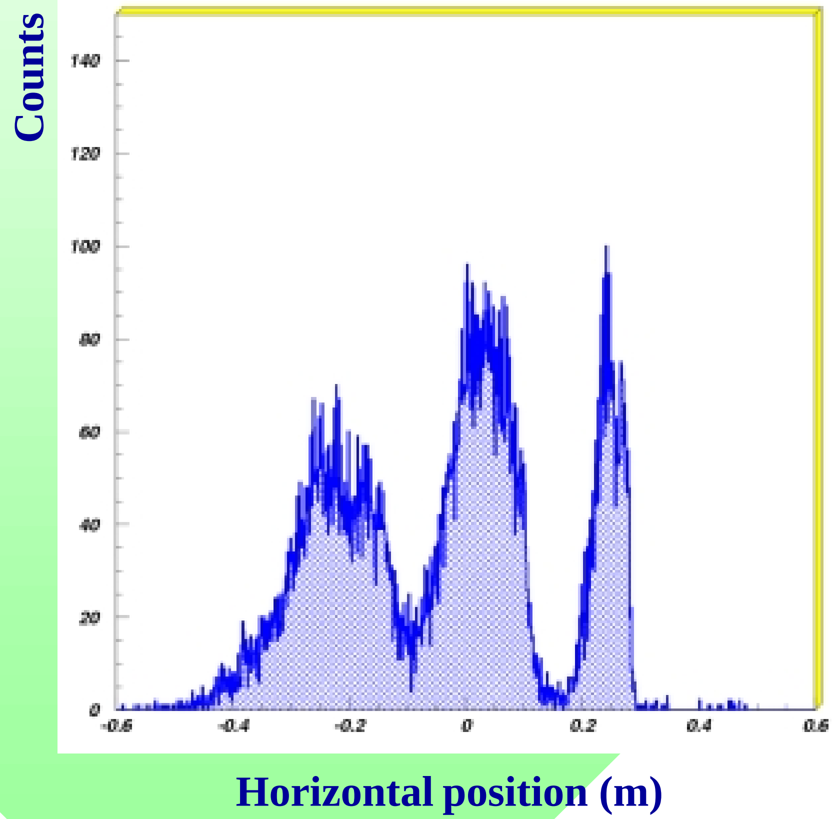
$^{7}Li(^{8}Li,^{7}Be)^{8}He$ at 57 MeV



Cosymag simulations (Observation at the focal plane)

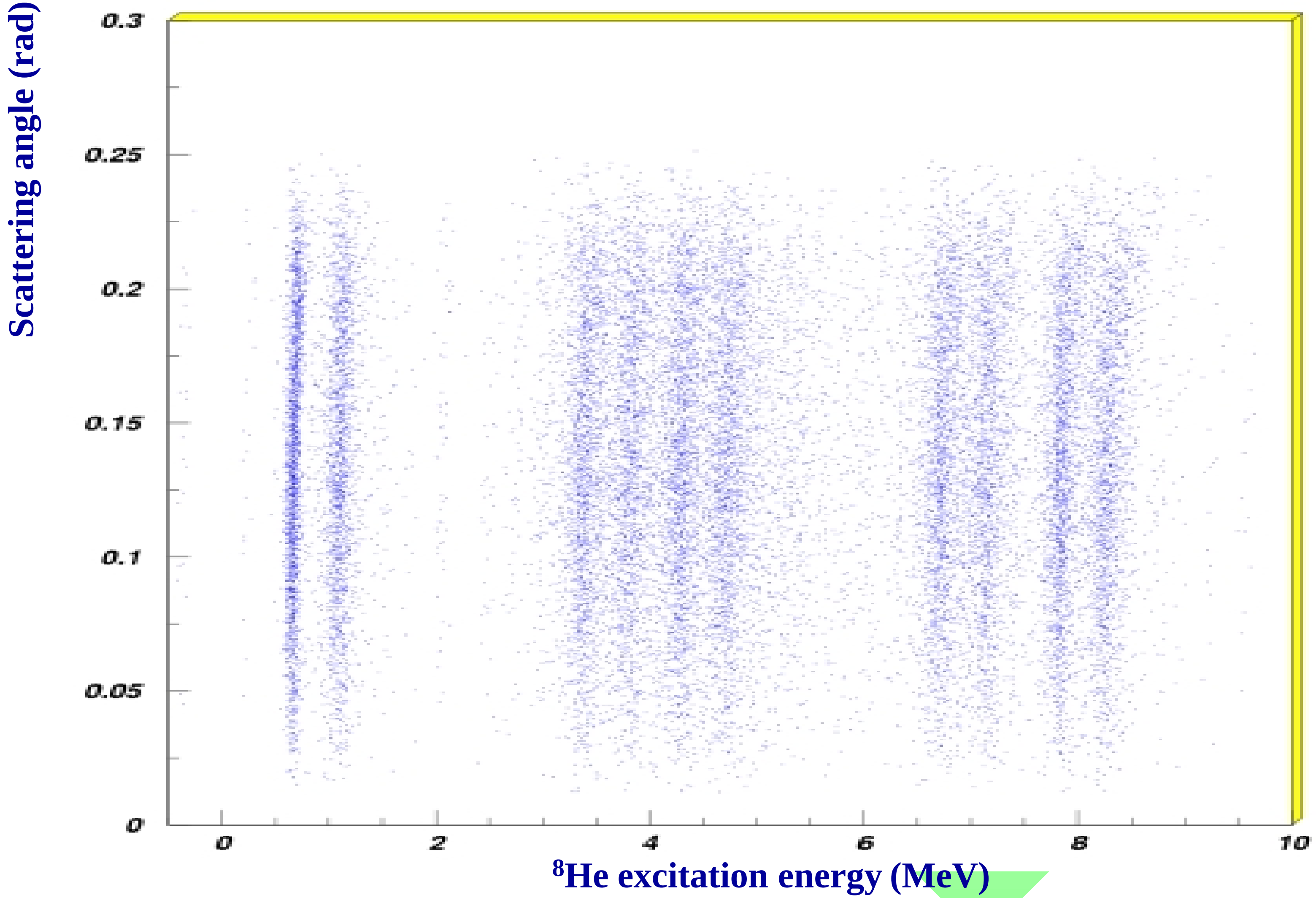
$^{7}Li(^{8}Li,^{7}Be)^{8}He$ at 57 MeV





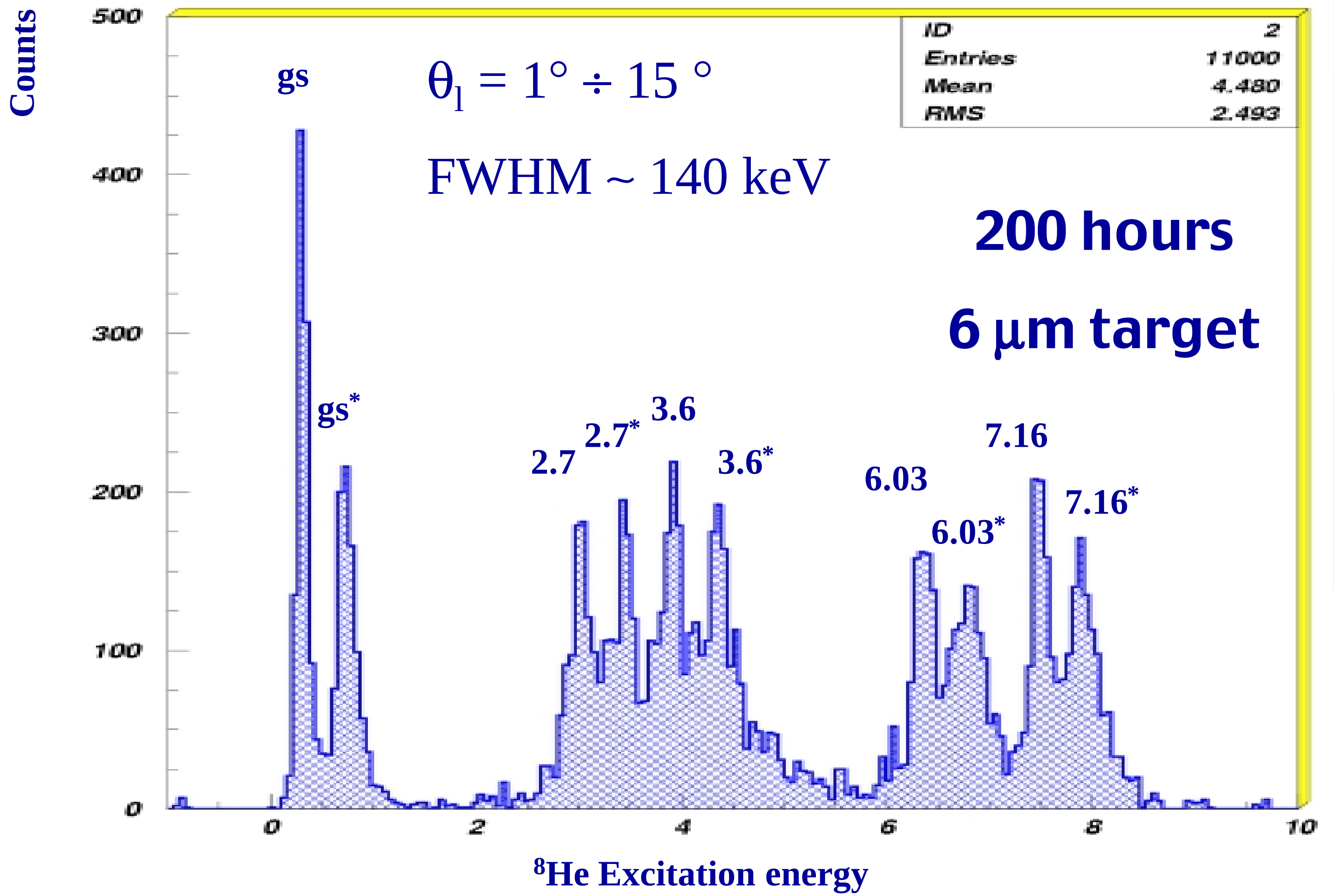
Cosymag simulations (11th order Reconstruction)

$^{7}Li(^{8}Li,^{7}Be)^{8}He$ at 57 MeV



11th reconstructed ^{8}He spectrum

^{7}Li(^{8}Li,^{7}Be)^{8}He at 57 MeV



Experiments with CS beams

- **Exploration of the (^{7}Li,^{7}Be) reaction at intermediate energies to study the reaction mechanism**

- **Study of the IVGMR via (^{7}Li,^{7}Be) on ^{40}Ca and ^{208}Pb at 50 MeV/u** (Nakayama et al. PRL 83 (1999) 690)

- **Transfer in the continuum by the $^{208}Pb(^{14}N,^{13}N)^{209}Pb$ reaction at 35 MeV/u (discussed by A.Bonaccorso and S.Gales)**

Experiments with ^{14}C beams at Tandem energies

- Single and double charge exchange at low energy

Example: $^{11}B(^{14}C,^{14}N)^{11}Be$ and $^{11}B(^{14}C,^{14}O)^{11}Li$

- Requires a specialyzed source due to contamination from the beam

Conclusions and Outlook

- An innovative instrument for nuclear spectroscopic research is under construction at the LNS laboratory
- First generation experiments planned with MAGNEX both with stable and radiocative beams starting at the end of this year
- Suggestions for possible experiments with MAGNEX will be warmly welcomed