Experimental study of ^{60}Fe destruction using the $d(^{60}Fe,p\gamma)^{61}Fe$ transfer reaction

Nicolas de Séréville

Institut de Physique Nucléaire (Orsay)

EURORIB'12 20-25 May, Padova

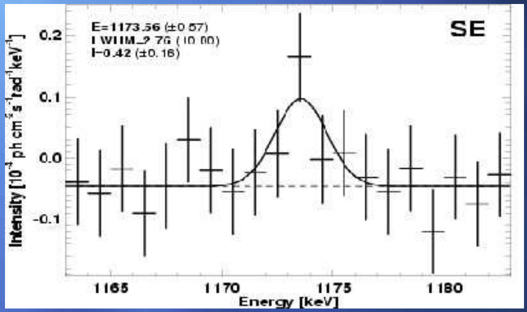
^{60}Fe observations

^{60}Fe ($T_{1/2}$ = 2.6 10^{6} yr): $^{60}Fe \xrightarrow{\beta^-} {}^{60}Co \xrightarrow{\beta^-} {}^{60}Ni^* \xrightarrow{\gamma} {}^{60}Ni$

1.173 + 1.332 MeV

γ-ray emission in our galaxy:

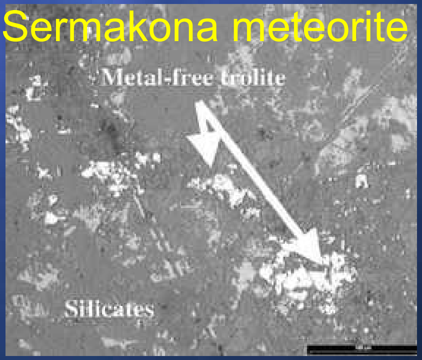
- First observation with RHESSI (Smith et al., 2004)
- Confirmed with INTEGRAL (Wang et al., 2007)
- ^{60}Fe/^{26}Al emission ratio ~ 0.15



Detection of ^{60}Ni in presolar grains:

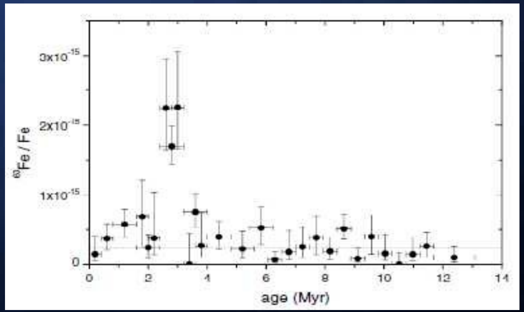
- Constraints on astrophysical conditions of Solar System formation
- Stellar or in-situ origin production?
- Other extinct radioactivities (^{26}Al, ^{10}Be, …) to be explained as well

Sermakona meteorite



^{60}Fe excess in deep ocean crust:

- Interpreted as a SN explosion 2.8 Myr ago a few 10th pc away (Knie et al., 2004)
- Not observed in marine sediments (Fitoussi et al., 2008)



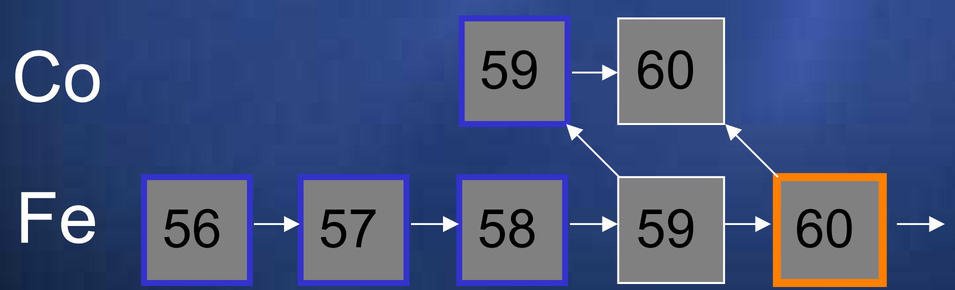
^{60}Fe nucleosynthesis

Production sites:

- low mass stars (AGB) (Lugaro et al., MNRAS 2007)
  - He-rich inter-shell of Thermally Pulsing AGB stars
- massive stars ($> 8M_{\odot}$) (e.g. Limongi et al., ApJ 2006)
  - convective He-shell burning
  - convective C-shell burning
  - very small contribution from explosive phase

^{60}Fe nucleosynthesis (s-process):

- Production $^{59}Fe(n,\gamma)^{60}Fe$ and destruction $^{60}Fe(n,\gamma)^{61}Fe$



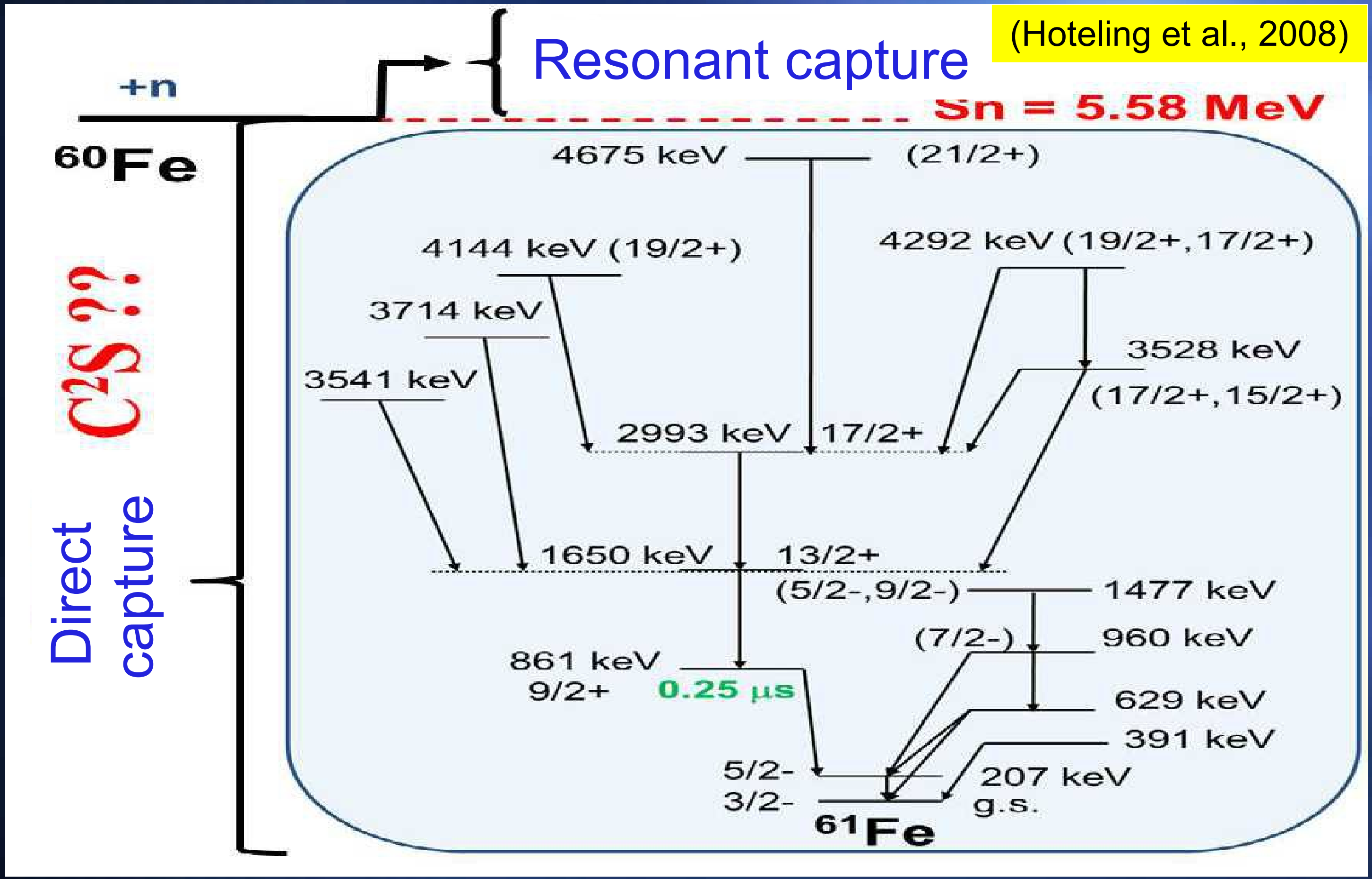
- need to bypass ^{59}Fe ($T_{1/2}$ = 44.5 d) bottleneck $\rightarrow \sim 3\ 10^{10}$ n/cm^3 for $T_9 > 0.5$

Other nuclear uncertainties:

- $^{22}Ne(\alpha,n)^{25}Mg$ (Kappeler et al., 1994)
- 3α, $^{12}C(\alpha,\gamma)^{16}O$ (Tur et al., 2010)

$^{60}Fe(n,\gamma)^{61}Fe$ status

Reaction rate: HF calculations (resonant capture) + shell-model (direct capture)



Previous experiments
- β-decay
- Coulomb excitation
- deep-inelastic

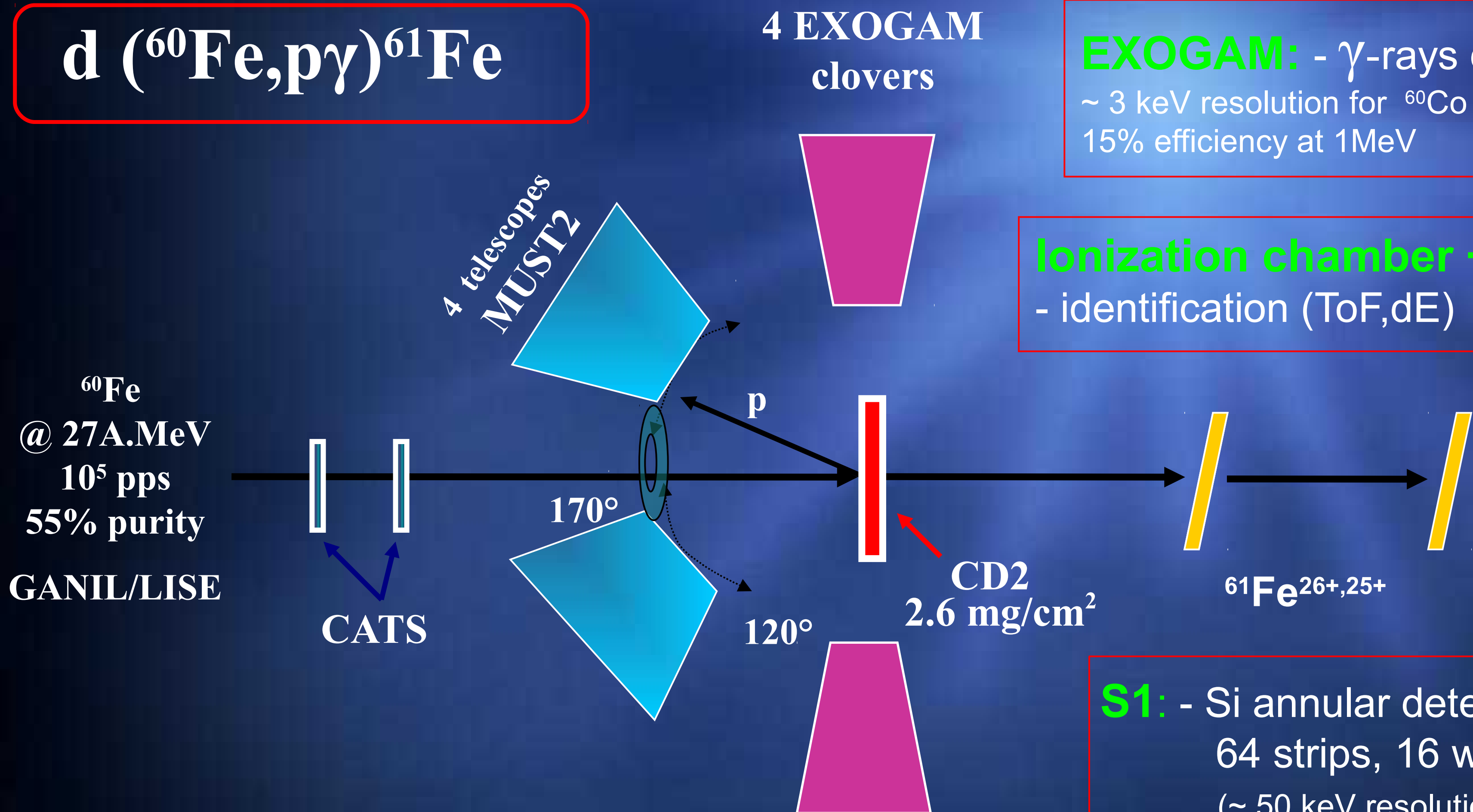
Direct capture: capture on bound ^{61}Fe states → E_x, l, C^2S

→ (d,p) transfer reaction

Note: Recent $^{60}Fe(n,\gamma)^{61}Fe$ activation measurement (Uberseder et al, 2009)

Experimental set-up

d (^{60}Fe,pγ)^{61}Fe



EXOGAM: - γ-rays detection
~ 3 keV resolution for ^{60}Co source
15% efficiency at 1MeV

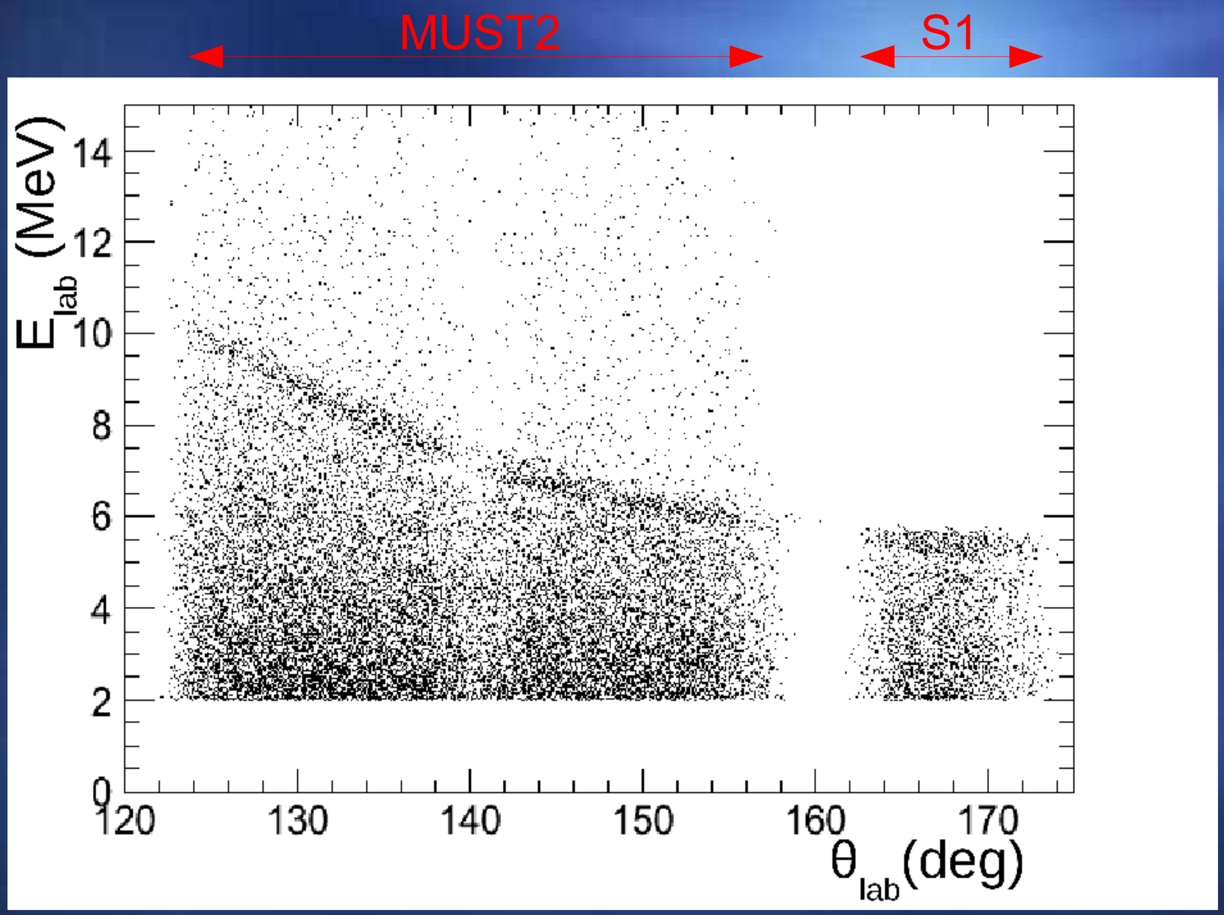
Ionization chamber + plastic:
- identification (ToF,dE)

S1: - Si annular detector (500μm)
64 strips, 16 wedges
(~ 50 keV resolution)

CATS: - **MWPC**
-proton emission point
-Start time of flight
(<1mm resolution in position)

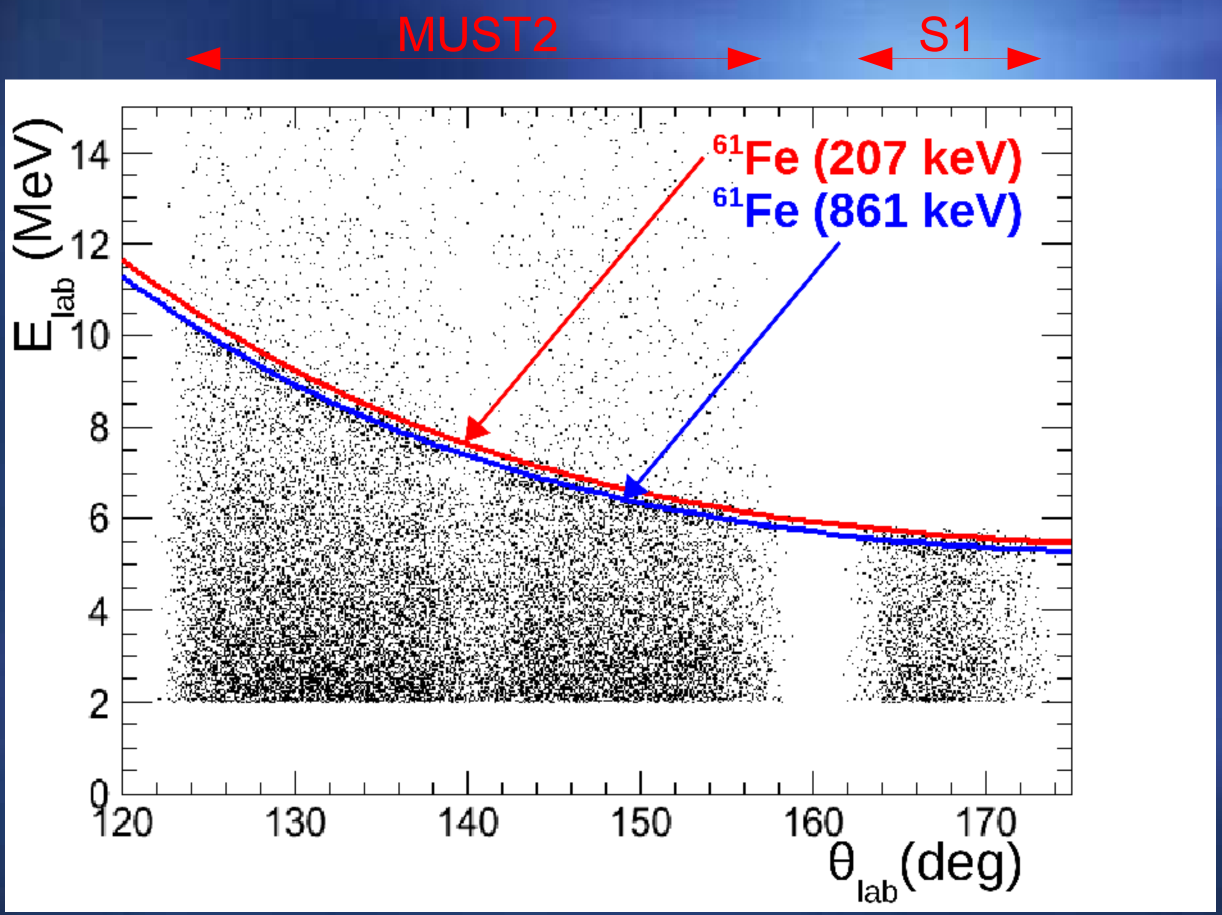
MUST2: - **Si** strips (300μm)+ **SiLi** (4.5 mm) detectors
-**impact** localization (strip pitch : 0.07 mm)
-**energy** measurement
(~ 35 keV resolution for ^{241}Am α-source)

Kinematic lines



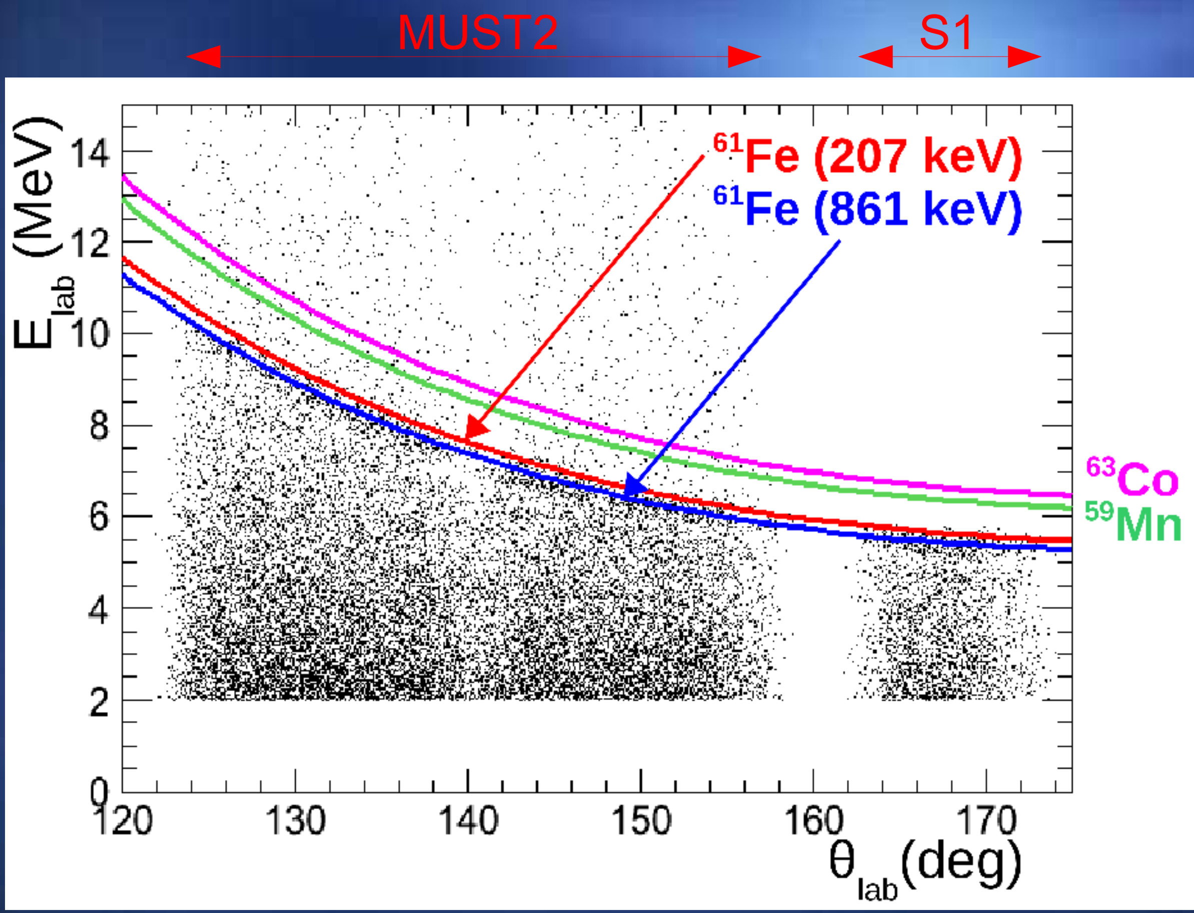
Energy corrections: energy loss in target and detectors dead layer

Kinematic lines



Energy corrections: energy loss in target and detectors dead layer

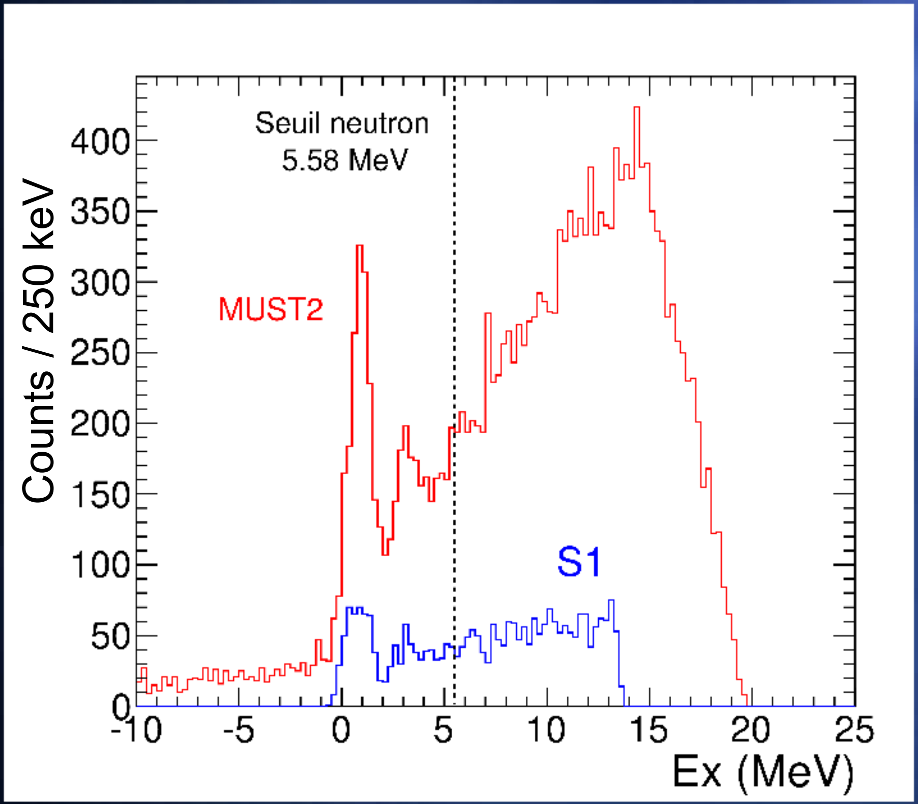
Kinematic lines

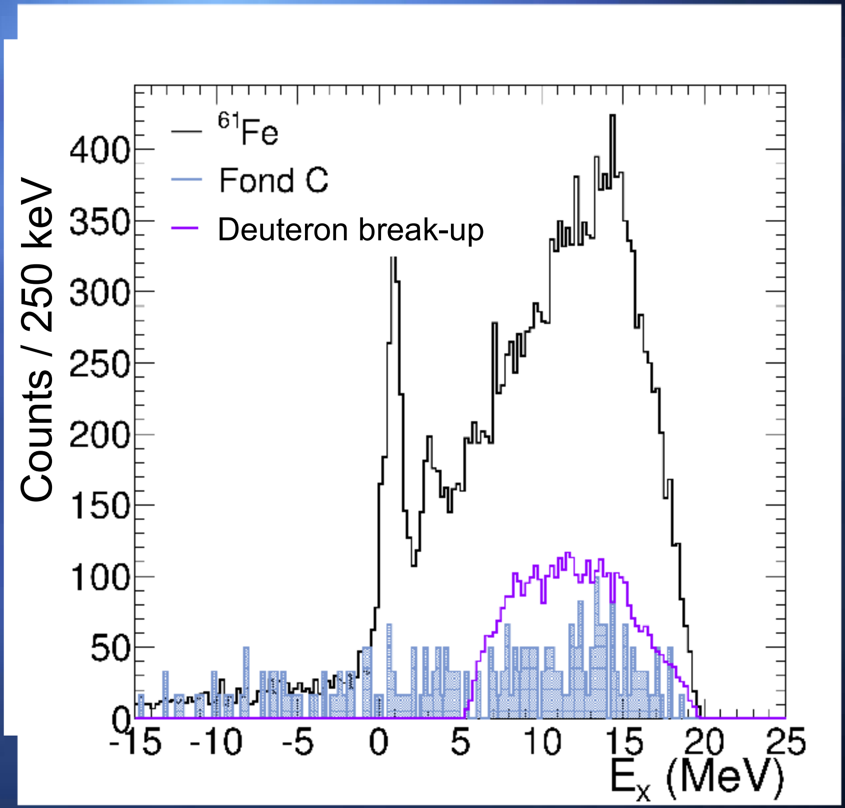


Energy corrections: energy loss in target and detectors dead layer

→ Negligible contribution from beam contaminants

Excitation energy





- Two large peaks below neutron threshold

FWHM ~ 1.5 – 2 MeV

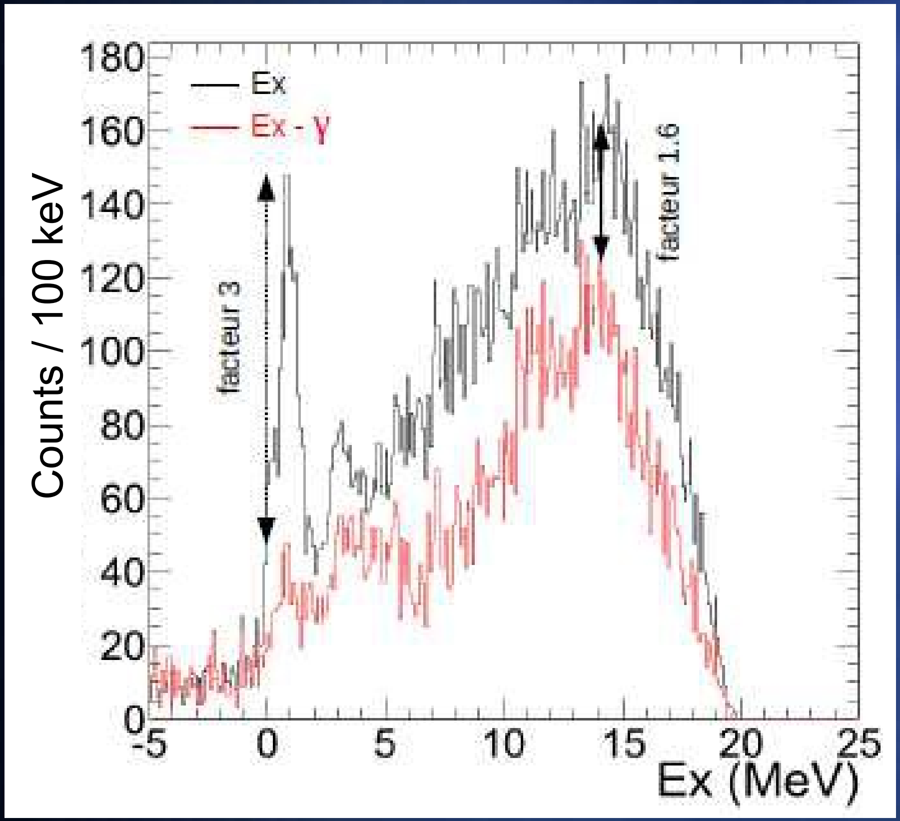
- MC simulations give width of ~ 800 keV

Several components:

- Carbon background (data)
- Deuteron break-up (calculation)

Levels identification

Single / coinc MUST2 spectra

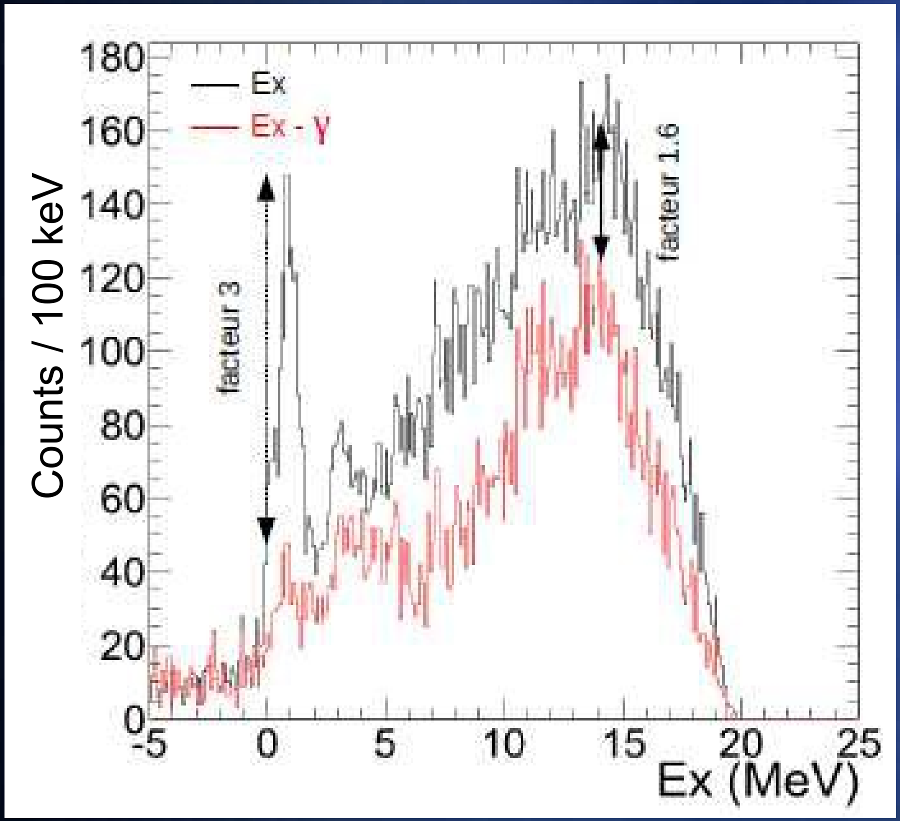


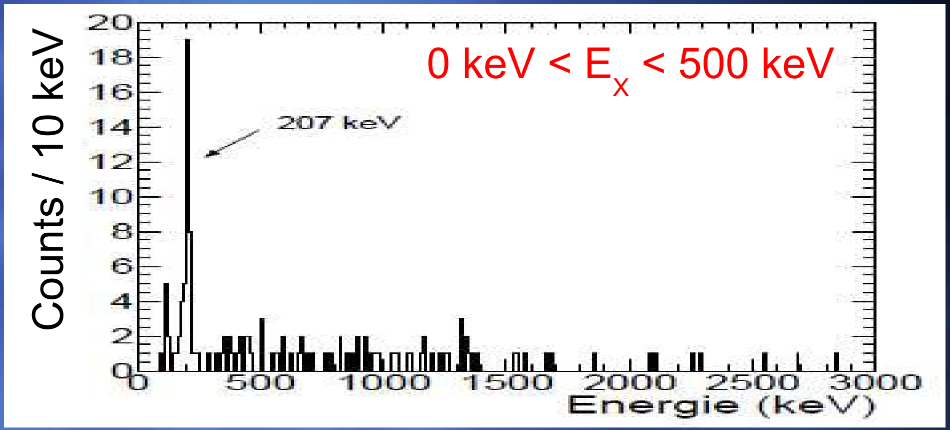
Isomeric level at 861 keV:

- $T_{1/2}$ = 0.25 μs >> tof ~ 14 ns
- Very small detection efficiency

Levels identification

Single / coinc MUST2 spectra





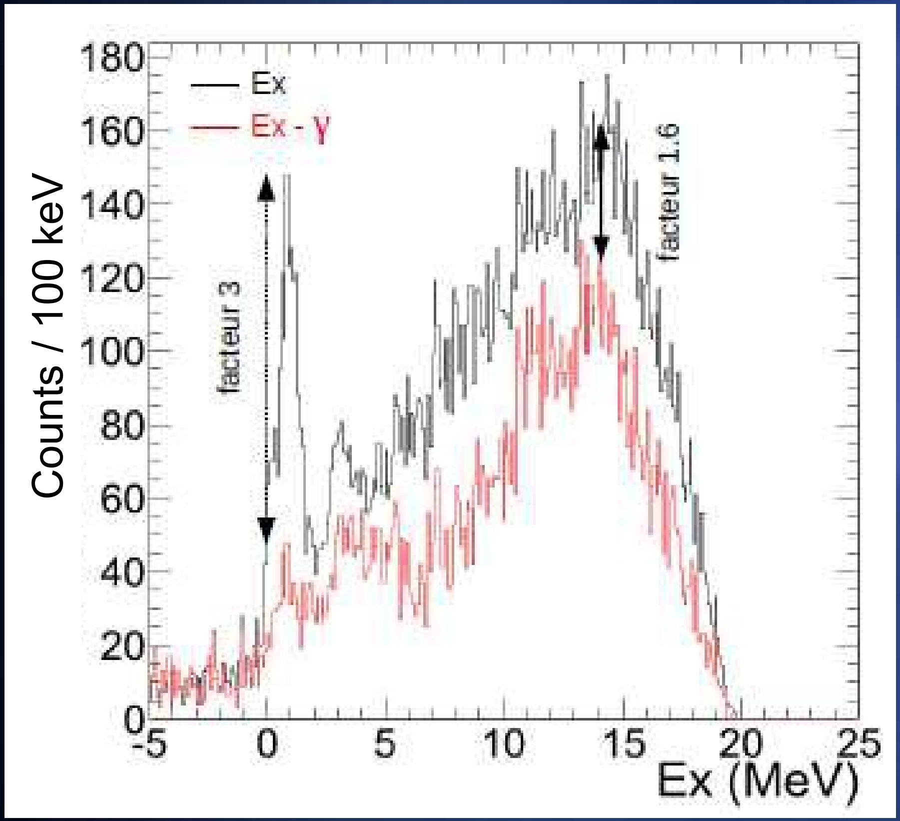
Direct population of the 207 keV level

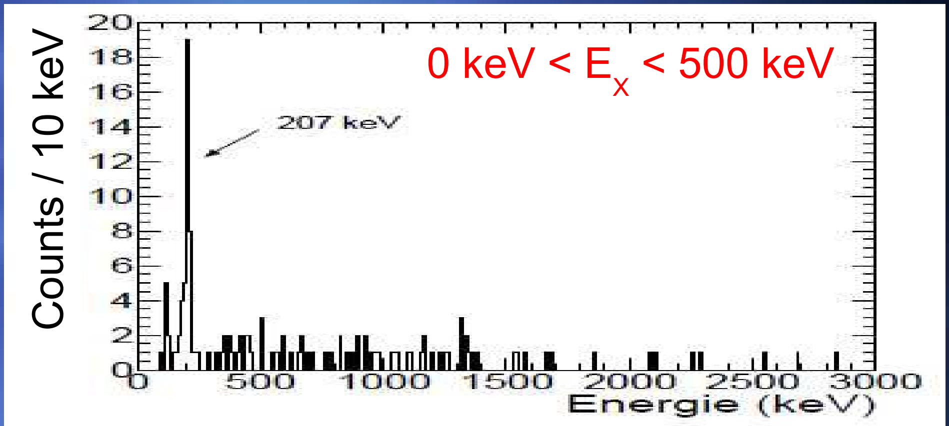
Isomeric level at 861 keV:

- $T_{1/2}$ = 0.25 μs >> tof ~ 14 ns
- Very small detection efficiency

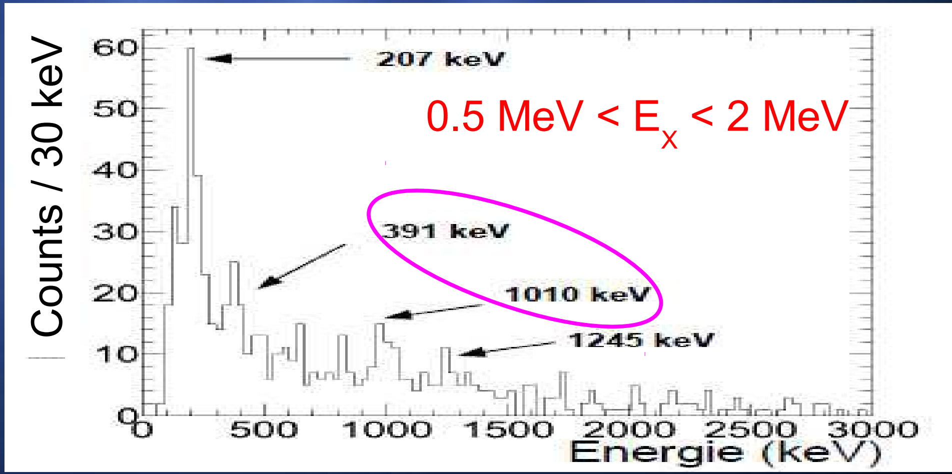
Levels identification

Single / coinc MUST2 spectra





Direct population of the 207 keV level

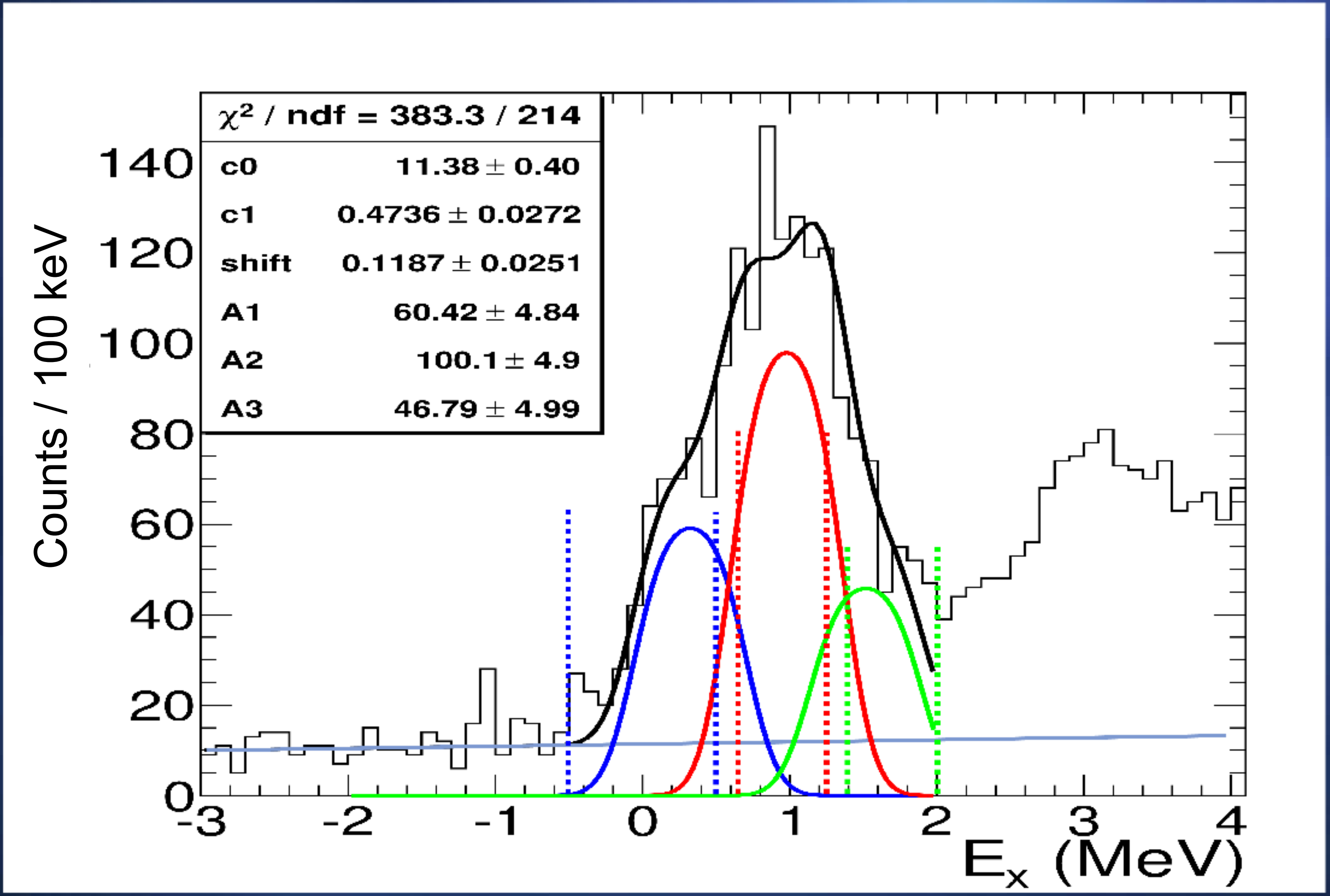


Isomeric level at 861 keV:

- $T_{1/2}$ = 0.25 μs >> tof ~ 14 ns
- Very small detection efficiency

Cascade between 391 keV and 1010 keV transitions → level at 1401 keV

Peak deconvolution



Fit constraints:

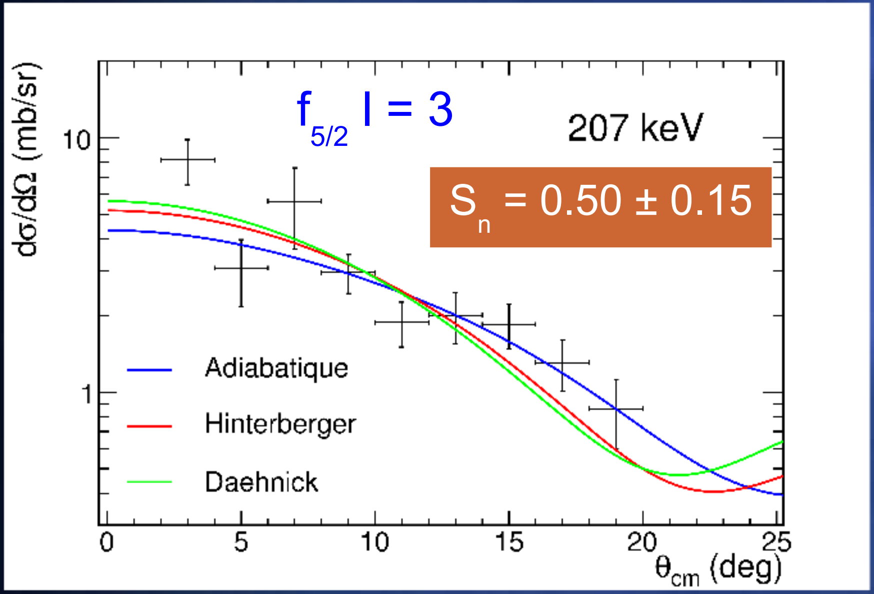
- Peak shape from simulation
- Known level energies

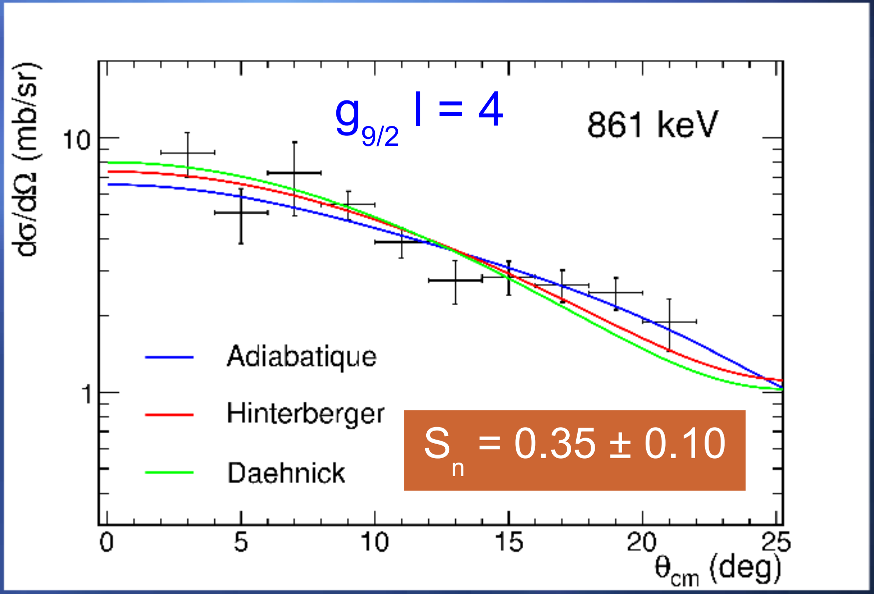
Free parameters:

- Peak amplitudes
- Global energy shift
- Linear carbon background from $E_X < 0$

Differential cross-sections 207 keV and 861 keV

Known orbital for these two levels → test for optical potentials





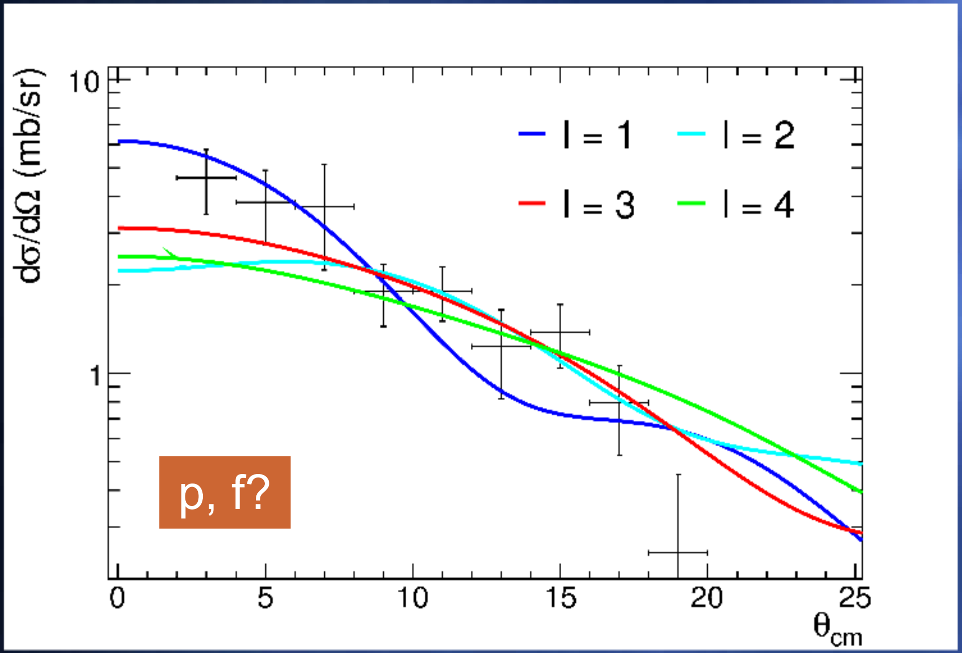
Optical potentials:

- ^{60}Fe + d channel
  → Global parametrization
  (Hinterberger et al., 1968, Daehnicket al., 1980)
- ^{61}Fe + p channel
  → CH89 (Varner et al., 1991)

Zero-range calculations (DWUCK4):

- DWBA
- DWBA using adiabatic prescription
  → for deuteron break-up
  (Wales & Johnson, 1976)

Cross-sections: 1401 keV



Previous work: $^{58}Fe(d,p)^{59}Fe$ (McLean et al., 1972; Klema et al., 1967)

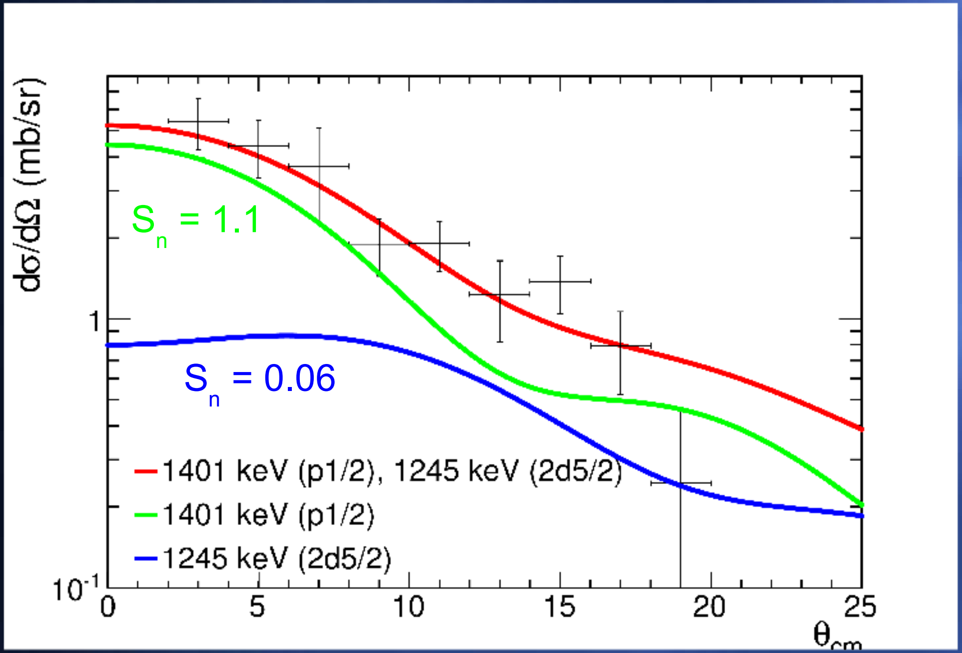
- $p_{1/2} \rightarrow E_X$ = 1214 keV S_n = 0.60 / 0.81
- $p_{3/2} \rightarrow E_X$ = 728 keV S_n = 0.08 / 0.13

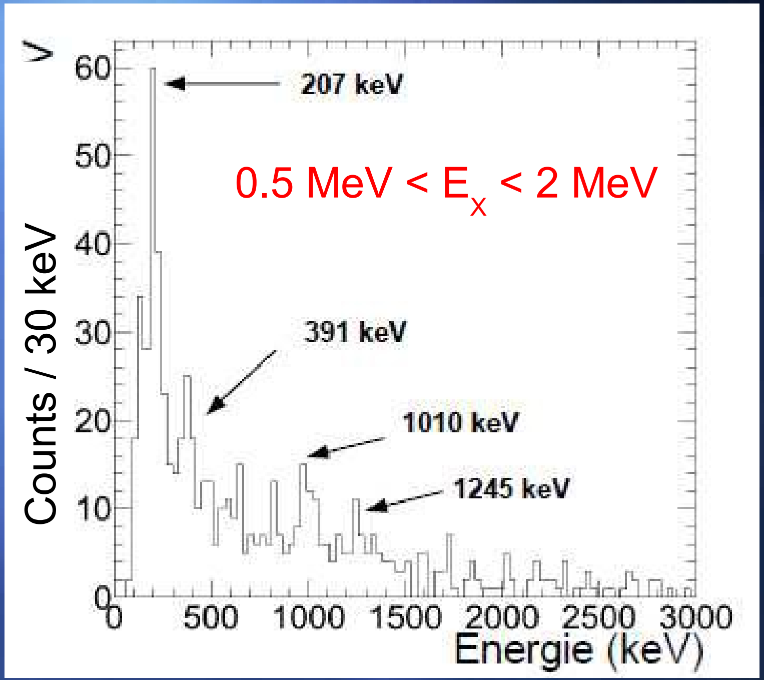
If p-shell:

- $p_{1/2} \rightarrow S_n$ = 1.56
- $p_{3/2} \rightarrow S_n$ = 0.78

$p_{1/2}$ favored

Cross-sections: 1401 keV





Previous work: $^{58}Fe(d,p)^{59}Fe$ (McLean et al., 1972; Klema et al., 1967)

- $p_{1/2} \rightarrow E_X$ = 1214 keV S_n = 0.60 / 0.81
- $p_{3/2} \rightarrow E_X$ = 728 keV S_n = 0.08 / 0.13

If p-shell:

- $p_{1/2} \rightarrow S_n$ = 1.56
- $p_{3/2} \rightarrow S_n$ = 0.78

$p_{1/2}$ favored

Deconvolution with level at 1245 keV

- Possible orbitals: d, f or g
- g-orbital does not reproduce data

	1245 keV	1401 keV
$f_{5/2}$	0.16	0.92
$2d_{5/2}$	0.06	1.1

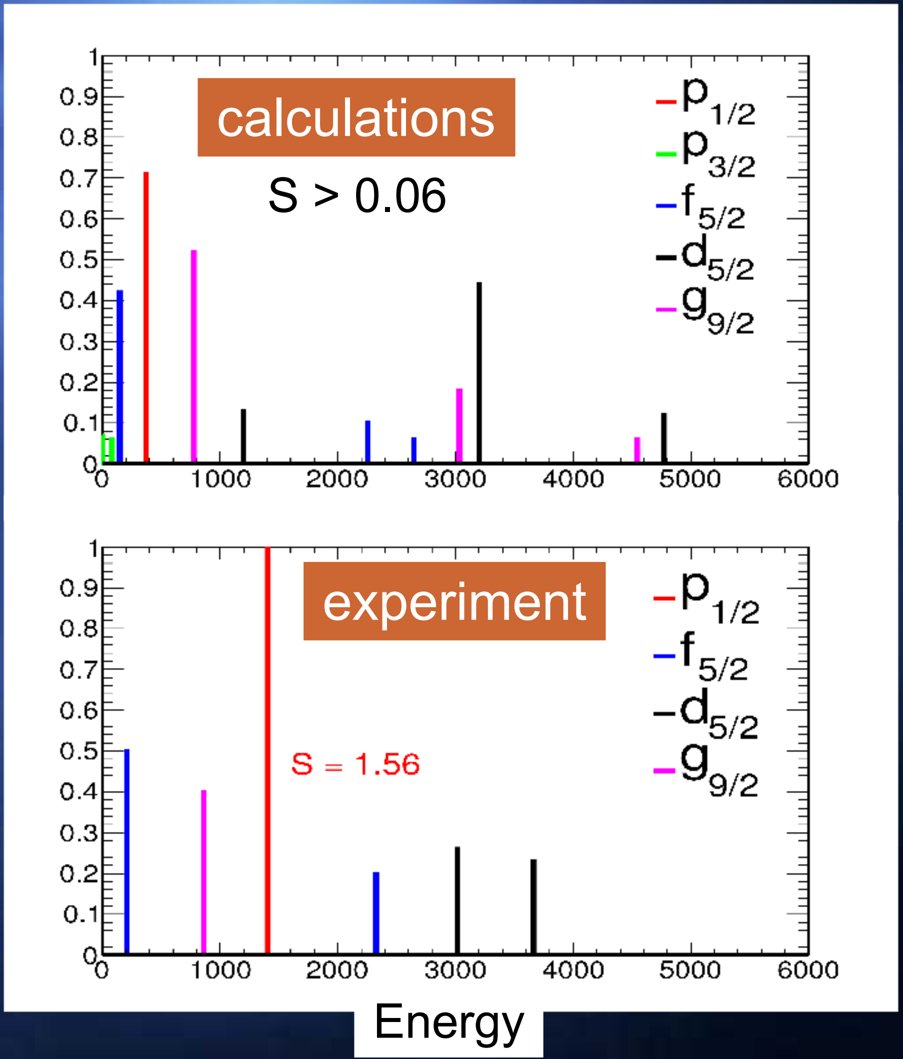
Comparison with shell-model calculations

Calculations: (K. Sieja)

- ^{48}Ca core
- Valence space: fp (π) and fpgd (ν)
- Based on LNPS effective interaction
  (Lenzi et al., 2010, Sieja et al., priv. com.)

Results:

- Good agreement for $f_{5/2}$ and $g_{9/2}$
- Ground-state not populated
  $p_{3/2}$ orbital → small S_n
- Level at 1401 keV
  - Most likely configuration → $p_{1/2}$
  - Large difference in energy
- Level at 1245 keV ($2d_{5/2}$) ?



Conclusions

- Study of the ^{60}Fe destruction through the d(^{60}F,pγ)^{61}Fe transfer reaction
- Complex experimental set-up with CATS/MUST2-S1/EXOGAM
- Indications of a new l = 1 state at 1401 keV with a large C^2S_n
- Level at "1245 keV" on $2d_{5/2}$ shell (?)
- Neutron spectroscopic factor measurement for the 207-, 861-, 1401- and "1245" keV states
- General good agreement with shell-model calculations except for the $p_{1/2}$ shell

Collaboration

S. Giron, F. Hammache, N. de Séréville,
D. Beaumel, S. Franchoo, J. Guillot, F. Maréchal, A. Matta, Y. Matea, L. Perrot,
J. A. Scarpaci, I. Stefan
(IPN-Orsay)

J. Burgunder, L. Caceres, E. Clement, G. De France, B. Fernandez, S. Grevy,
R. Raabe, O. Sorlin, C. Stoedel, J.C. Thomas
(GANIL-Caen)

F. Flavigny, A. Gillibert, V. Lapoux, L. Nalpas, A. Obertelli
(SPhN Saclay)

G. Duchene, M. Moukaddam (IRES-Strasbourg)

J. Gibelin (LPC-Caen)

Y. Togano, M.Takechi (Riken)

M. Heil (GSI-Darmstadt)

J. Kiener (CSNSM)

D. Galaviz-Redondo, L. Gasques (FCT-Lisboa)