前方角の陽子非弾性散乱で探る原子核のM1,E1励起

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坂口先生と私

- 京都大学　学生実験(1990)
- 京都大学　大学院
  - 58Niからの弾性散乱のQパラメータ測定(1992-1993)
  - FPP用のデータ収集システムの開発(1993-, 1995-実用開始)
  - 0度での12C(p,p’)偏極移行量測定(1996-1997)
  - 反応機構 NN有効相互作用のVσ成分の研究(学位1999)
- 高分解能低B.G.での前方角陽子非弾性散乱測定(2003-)
  M1,E1励起強度分布の測定

Contents

- High-Resolution (*p*,*p*’) measurement at close to zero degrees
  - Physics Motivations
  - Experimental Method
  - Representative Spectra
- Isoscalar and Isovector M1 Excitations in N=Z Nuclei
- M1,E1 strength in ^{208}Pb
- Summary

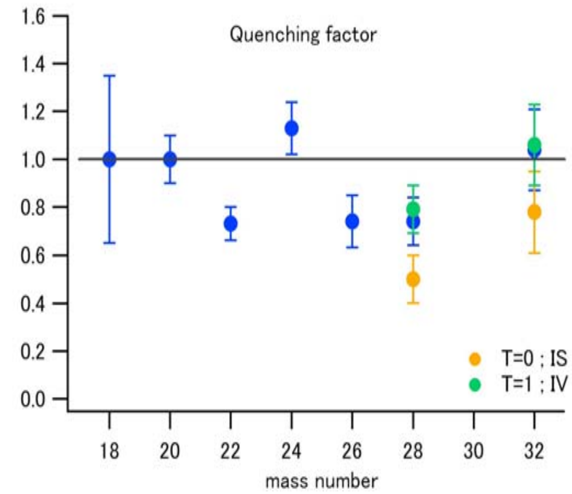
High-Resolution (*p*,*p’*) measurement at close to zero degrees

Physics Motivations

Motivations

Determination of M1 and E1 strength distribution of stable nuclei with high-resolution and high-sensitivity

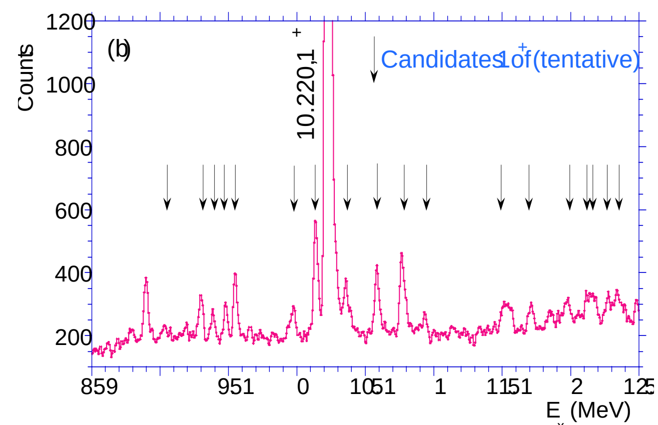
1. M1 strength distribution and quenching
   for each isoscalar (ΔT=0) and isovector (ΔT=1) excitation
   over the sd-shell region
   Isovector M1 B(σ) ⇔ B(GT) ... analogous



G.M. Crawley et al.,PRC39(1989)311

2. M1&E1 strength in ^{208}Pb (^{120}Sn, ^{90}Zr,...)

3. Fragmentation of the excitation strengths:
   giant resonances and M1 exitation



^{48}Ca(p,p’) at IUCF at 0 deg., Y. Fujita *et al.*

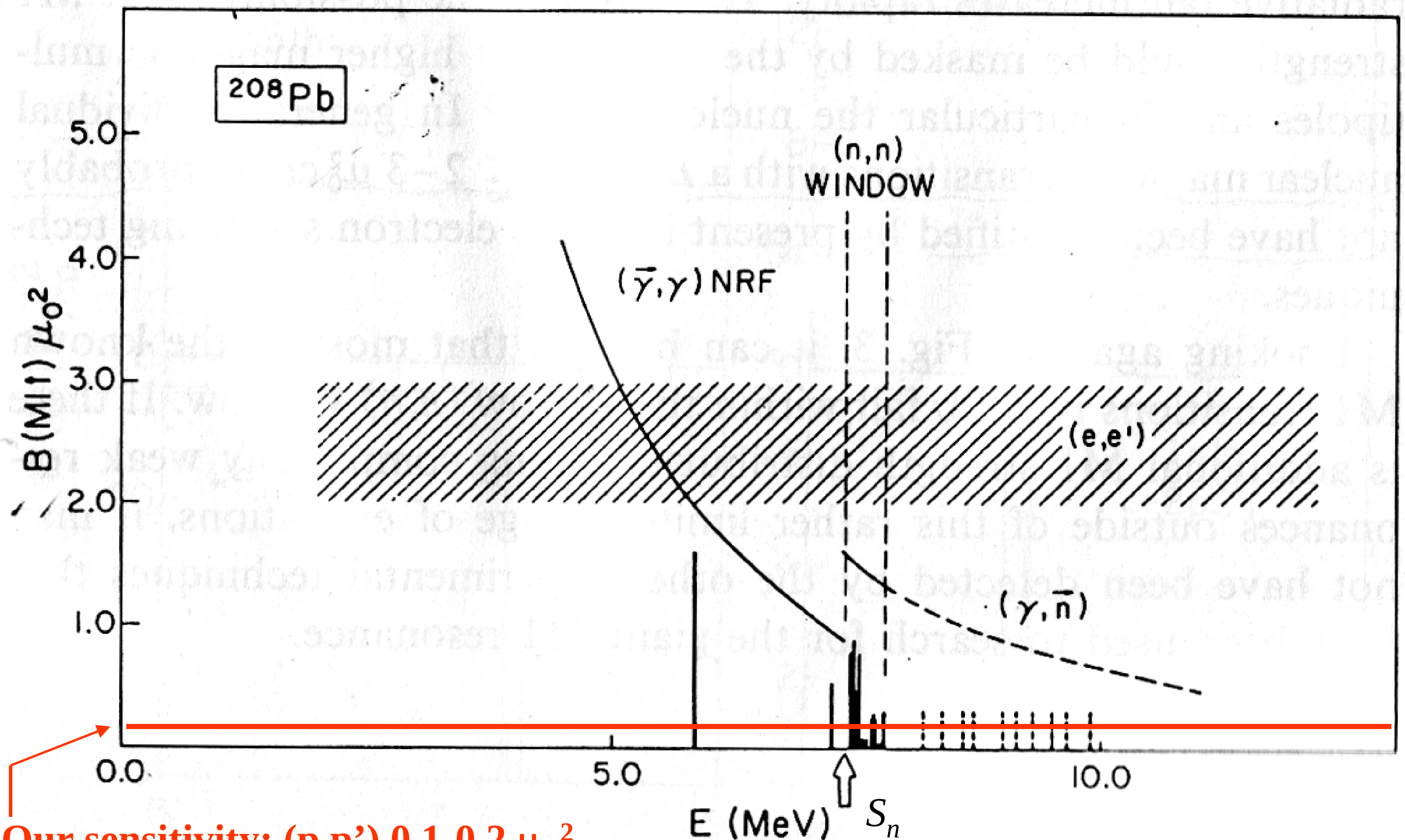
Motivations

4. nuclear excitation mode:
   troidal E1 excitation
   pygmy dipole resonance
   ... oscillation of neutron skin against core?

5. Astrophysical interest:
   nuclear matrix element B(σ) for (ν,ν’)
   E1 strength distribution around neutron separation energy

Experimental sensitivity

Sensitivity of various reactions for isolated peaks



Our sensitivity: (p,p') 0.1-0.2 μ_N^2

for the J^π determination by 3σ

R.M. Laszewski and J. Wambach, Comments Nucl. Part. Phys. 14 (1985) 321.

Merits of measuring proton inelastic scattering at 0 deg.

- The M1 strength can be studied by a "single shot measurement" over a wide E_x range.
- The detection efficiency is high (0.85~0.9) and independent of E_x.
- Total M1(E1) strength is measured (independent of decay channels).

- $d\sigma/d\Omega$ is maximum at 0° for $\Delta L=0$ excitations.
- ΔL can be identified from the angular distribution of $d\sigma/d\Omega$ at forward angles.
- $d\sigma/d\Omega$ at 0° is approximately proportional to the reduced matrix elements.

$$\frac{d\sigma}{d\Omega} = K \cdot N \cdot \left| J^{ST}(q) \right|^2 \cdot B^{ST}(q,\omega)$$

- M1 and E1 (by Coulomb ex.) can be model-independently decomposed by measuring polarization transfer coefficients at 0°

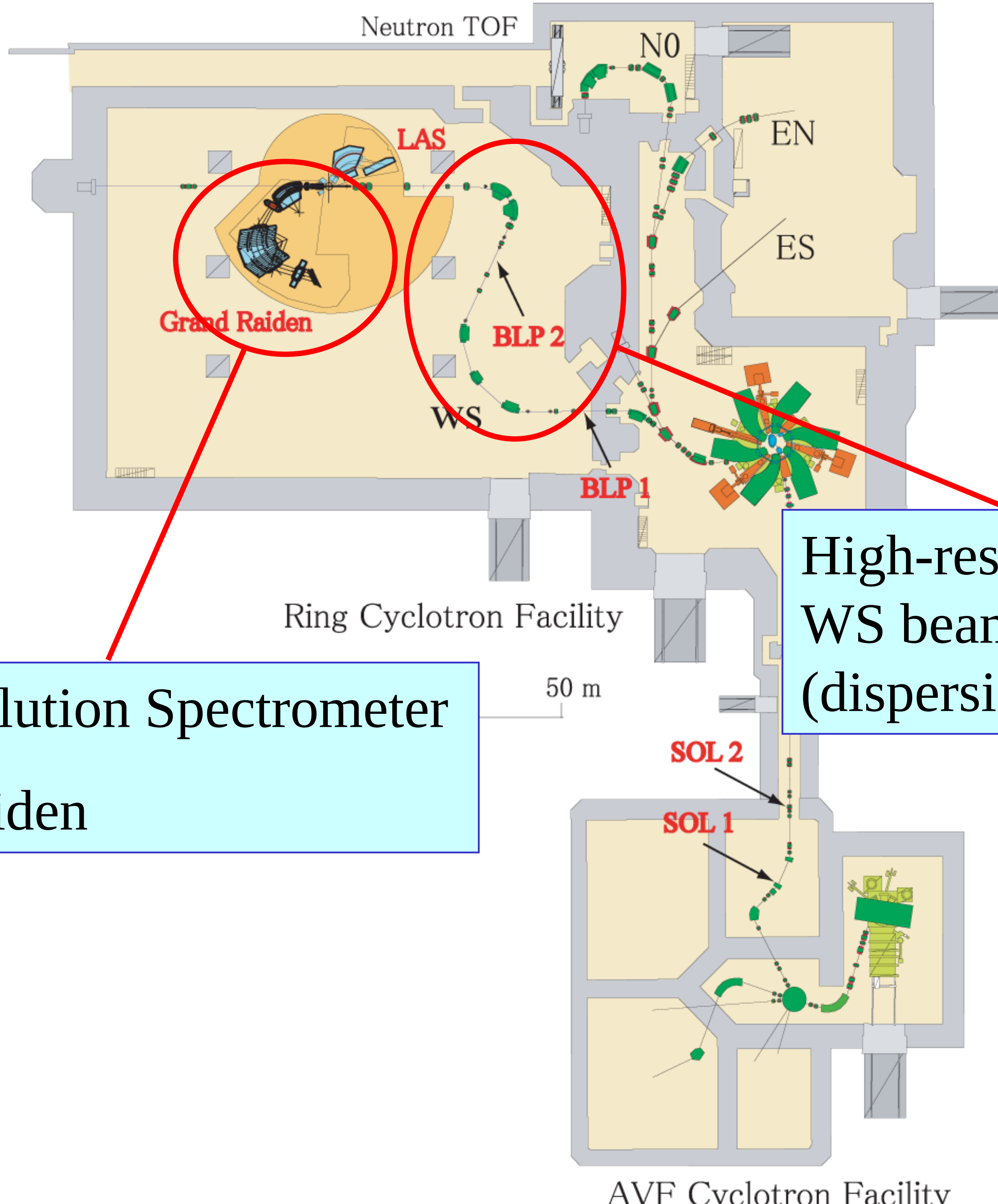
$$D_{SS} + D_{NN} + D_{LL} = \begin{cases} -1 \text{ for } \Delta S = 1 \\ 3 \text{ for } \Delta S = 0 \end{cases}$$

T.Suzuki, PTP103(2000)859

High-Resolution (*p*,*p*’) measurement at close to zero degrees

Experimental Method

A. Tamii *et al*., submitted to NIM-A

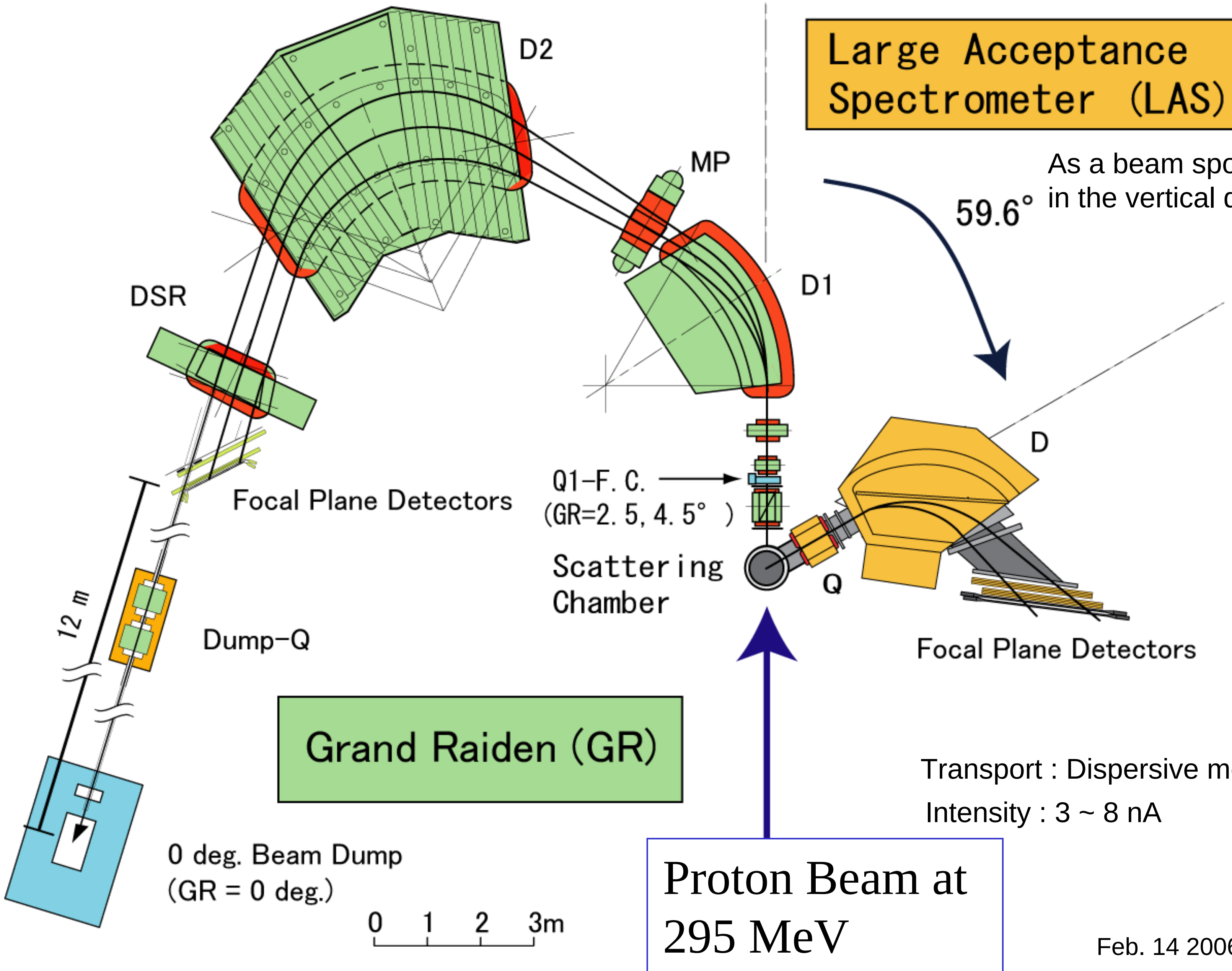


High-resolution
WS beam-line
(dispersion matching)

High-resolution Spectrometer

Grand Raiden

Spectrometers in the 0-deg. experiment setup

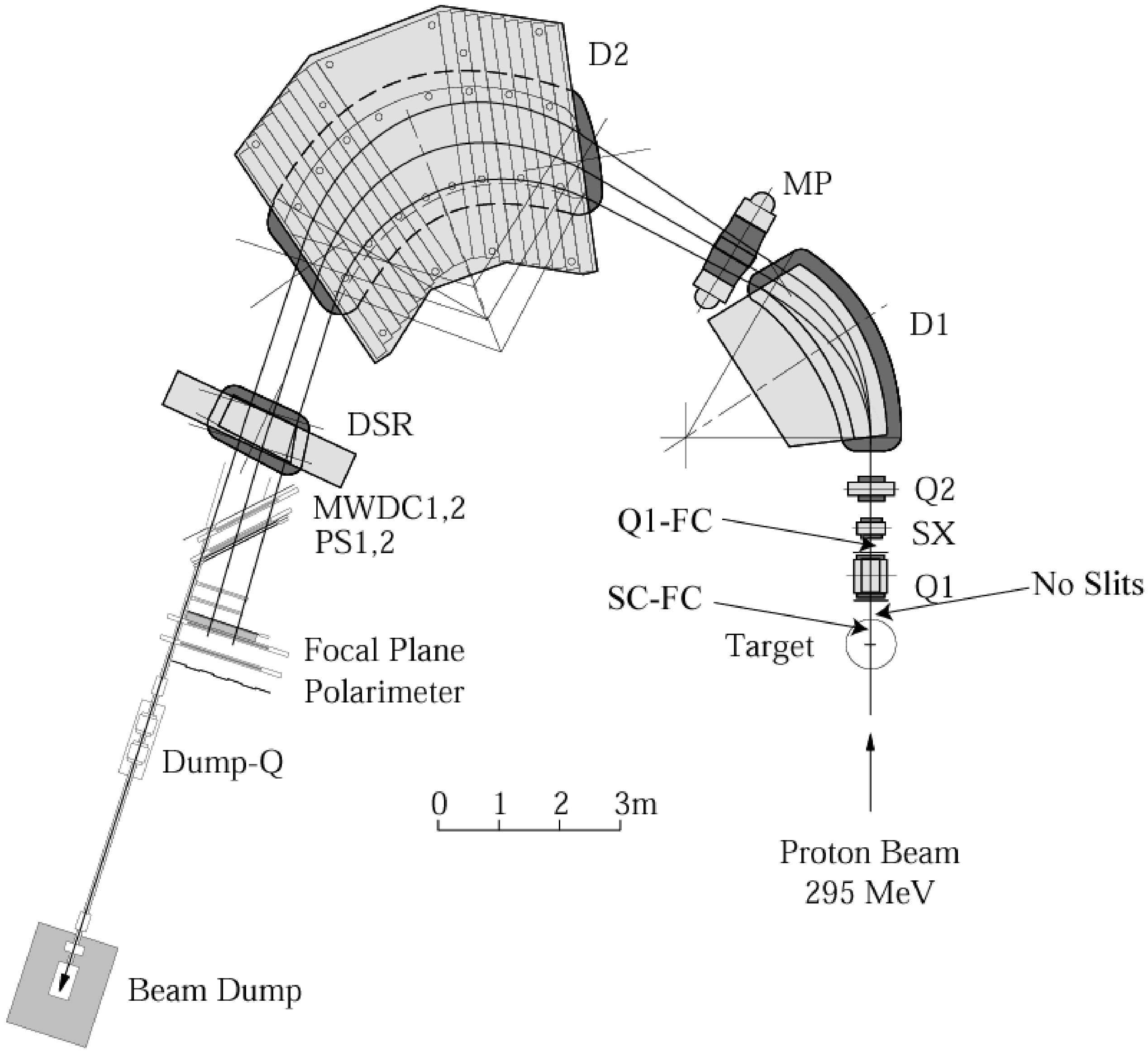


Transport : Dispersive mode

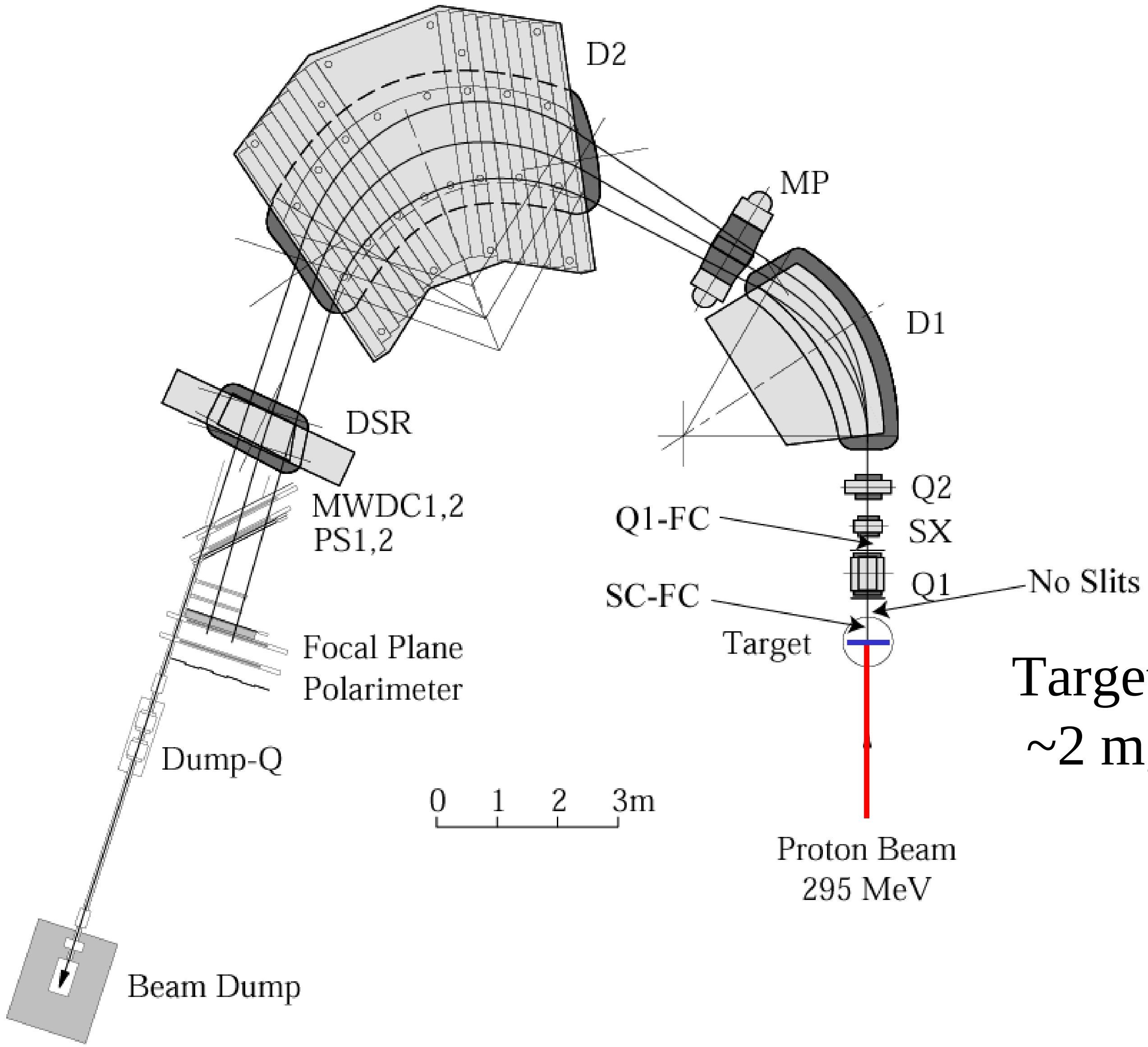
Intensity : 3 ~ 8 nA

Feb. 14 2006 defense

Grand Raiden in the 0deg Measurement Setup

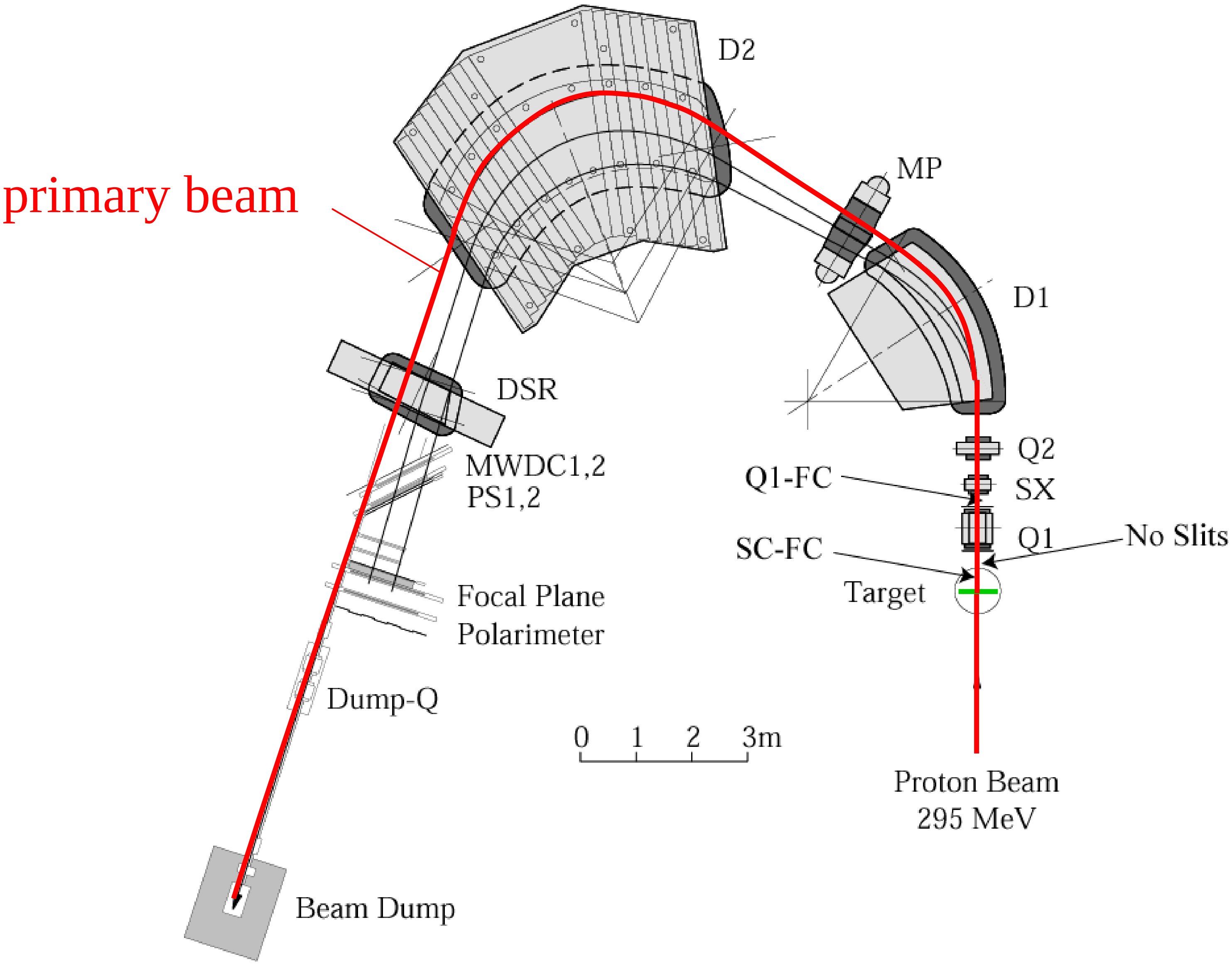


Grand Raiden in the 0deg Measurement Setup

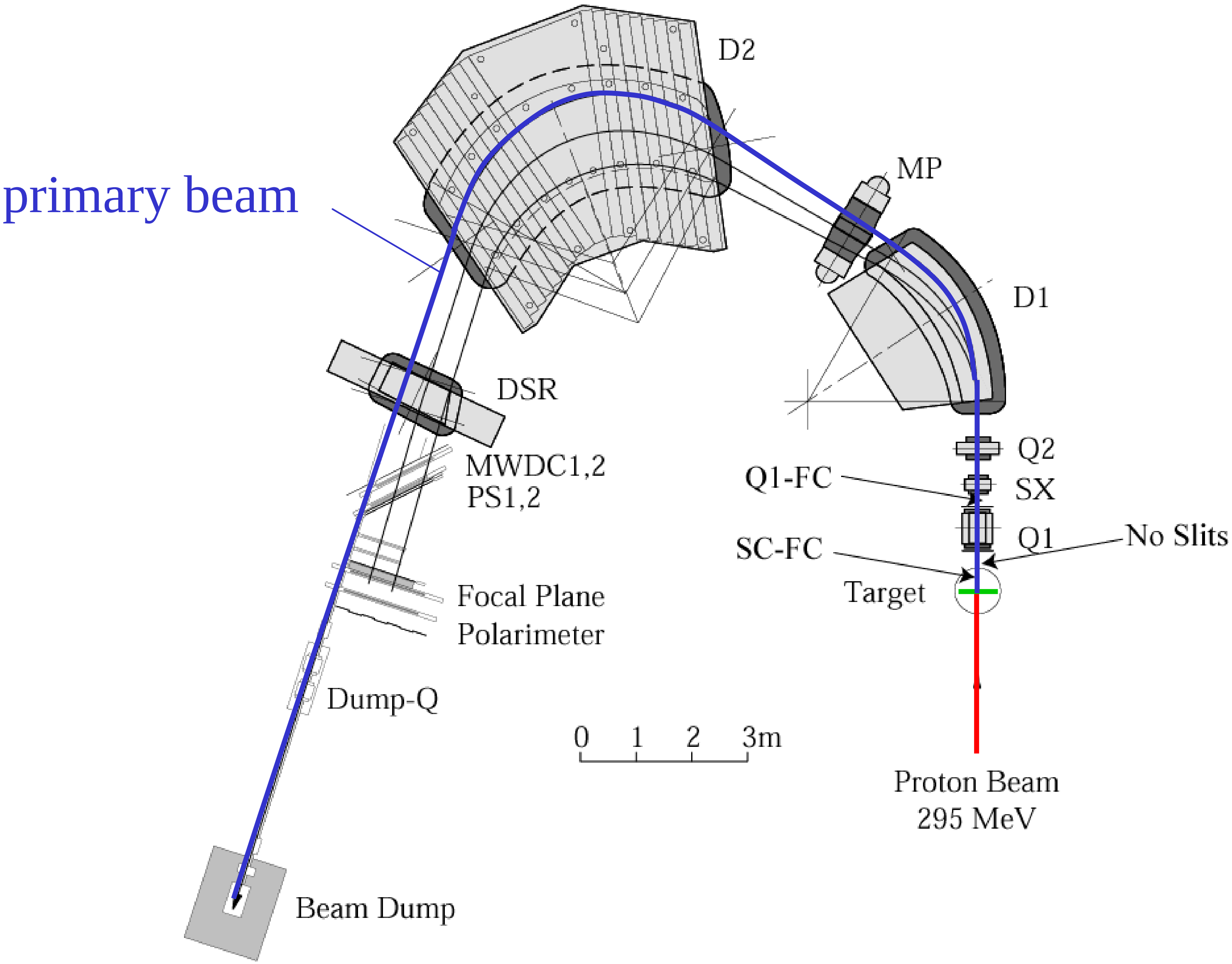


Target foil:
~2 mg/cm^2

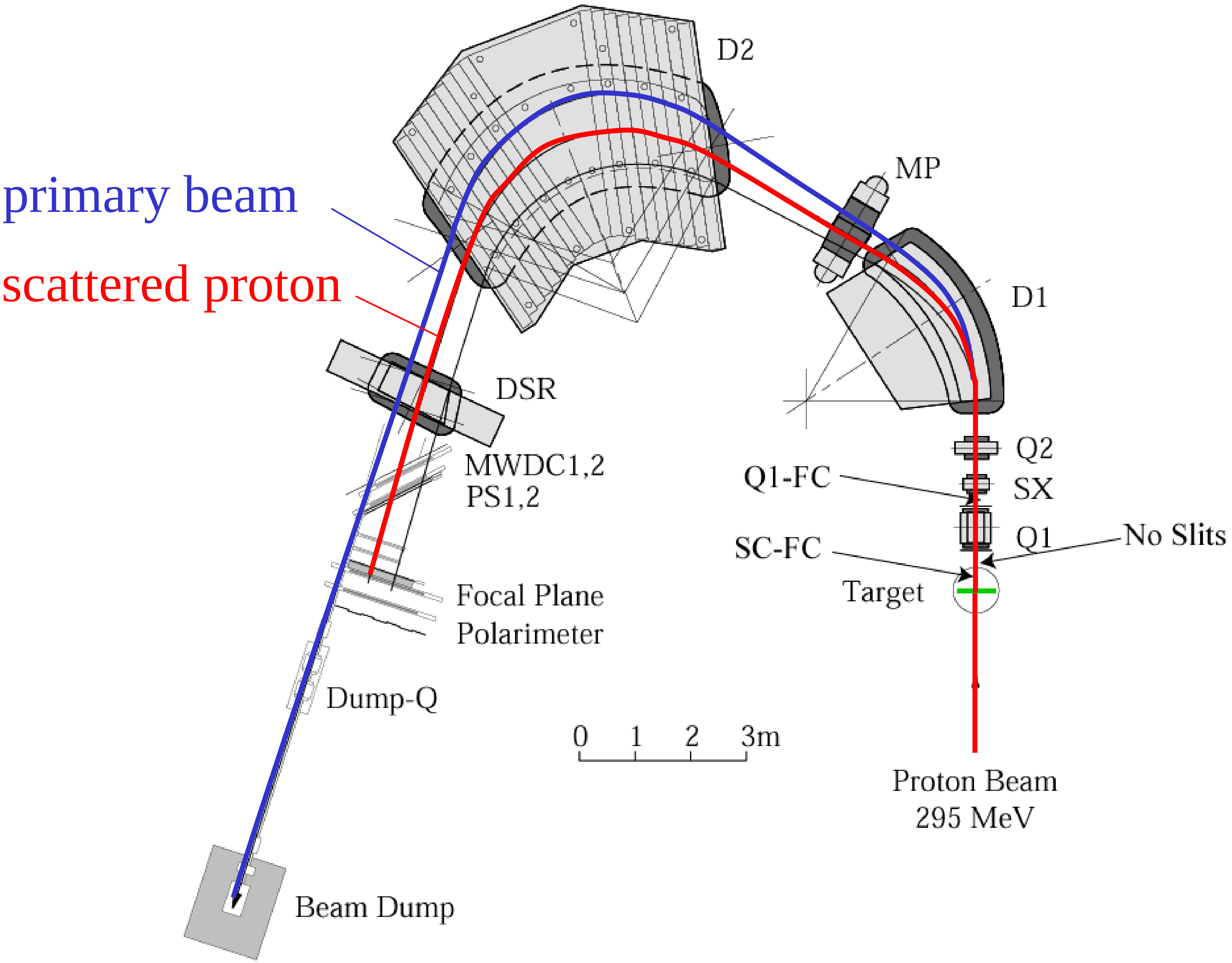
Grand Raiden in the 0deg Measurement Setup



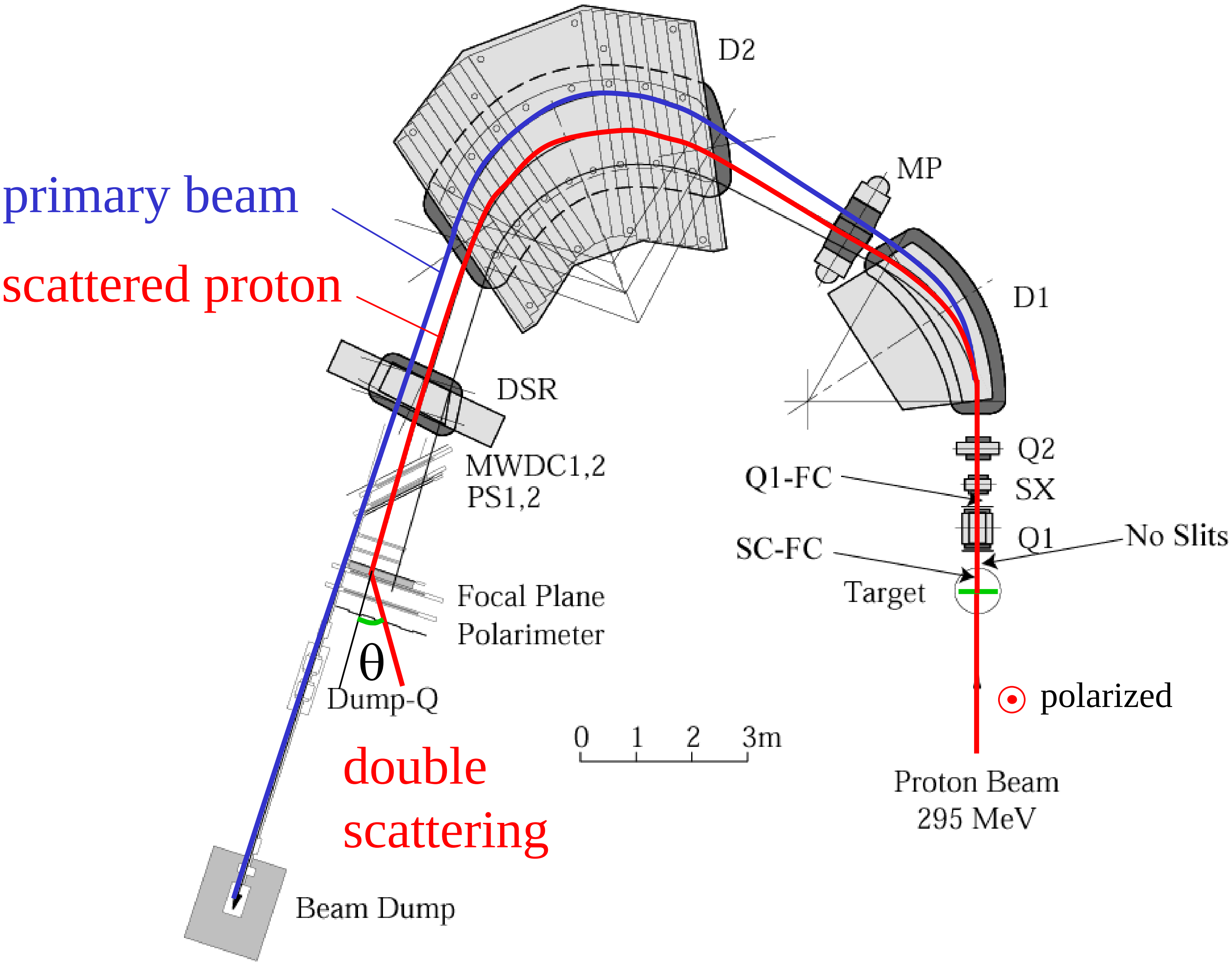
Grand Raiden in the 0deg Measurement Setup



Grand Raiden in the 0deg Measurement Setup



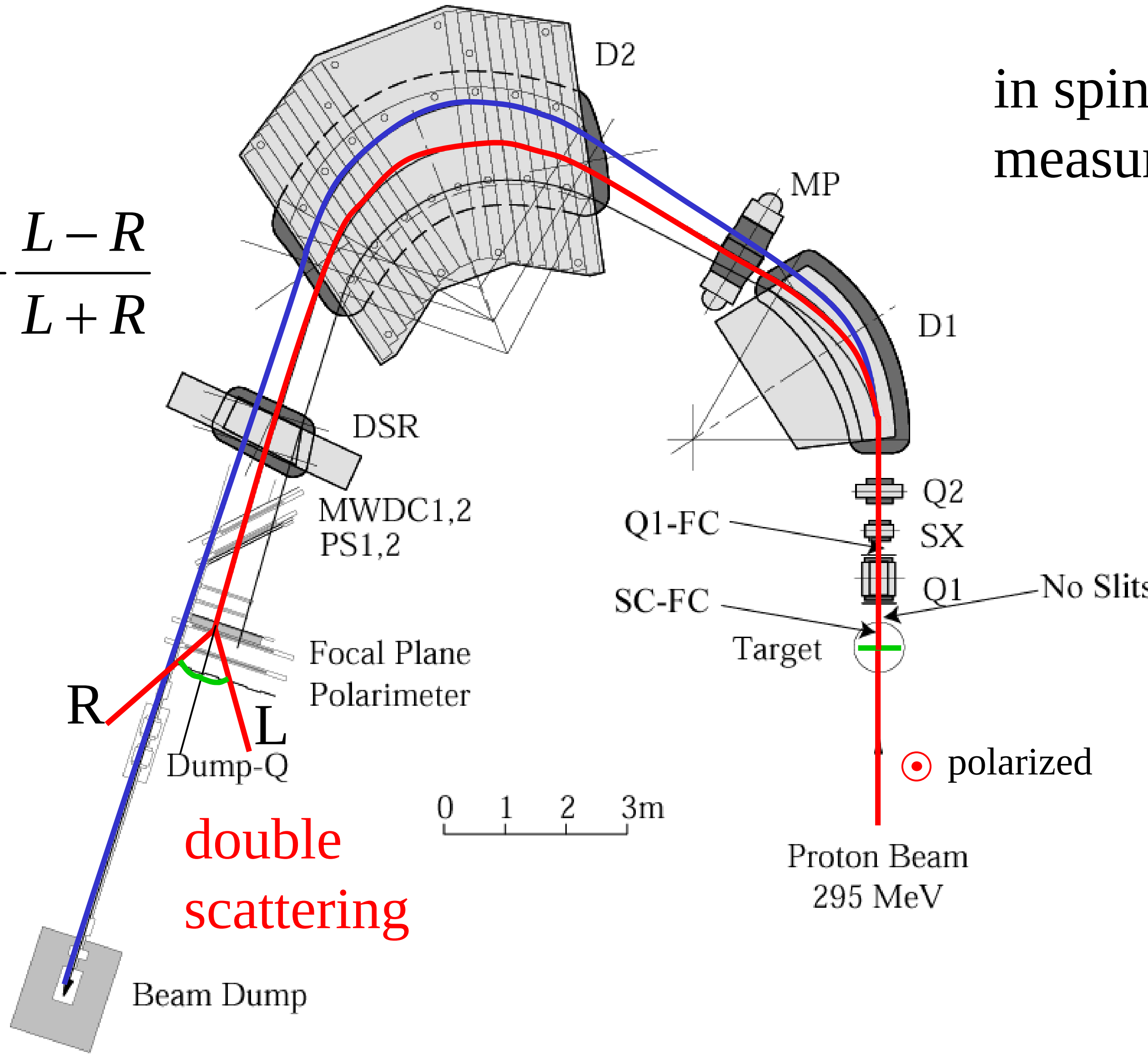
Grand Raiden in the 0deg Measurement Setup



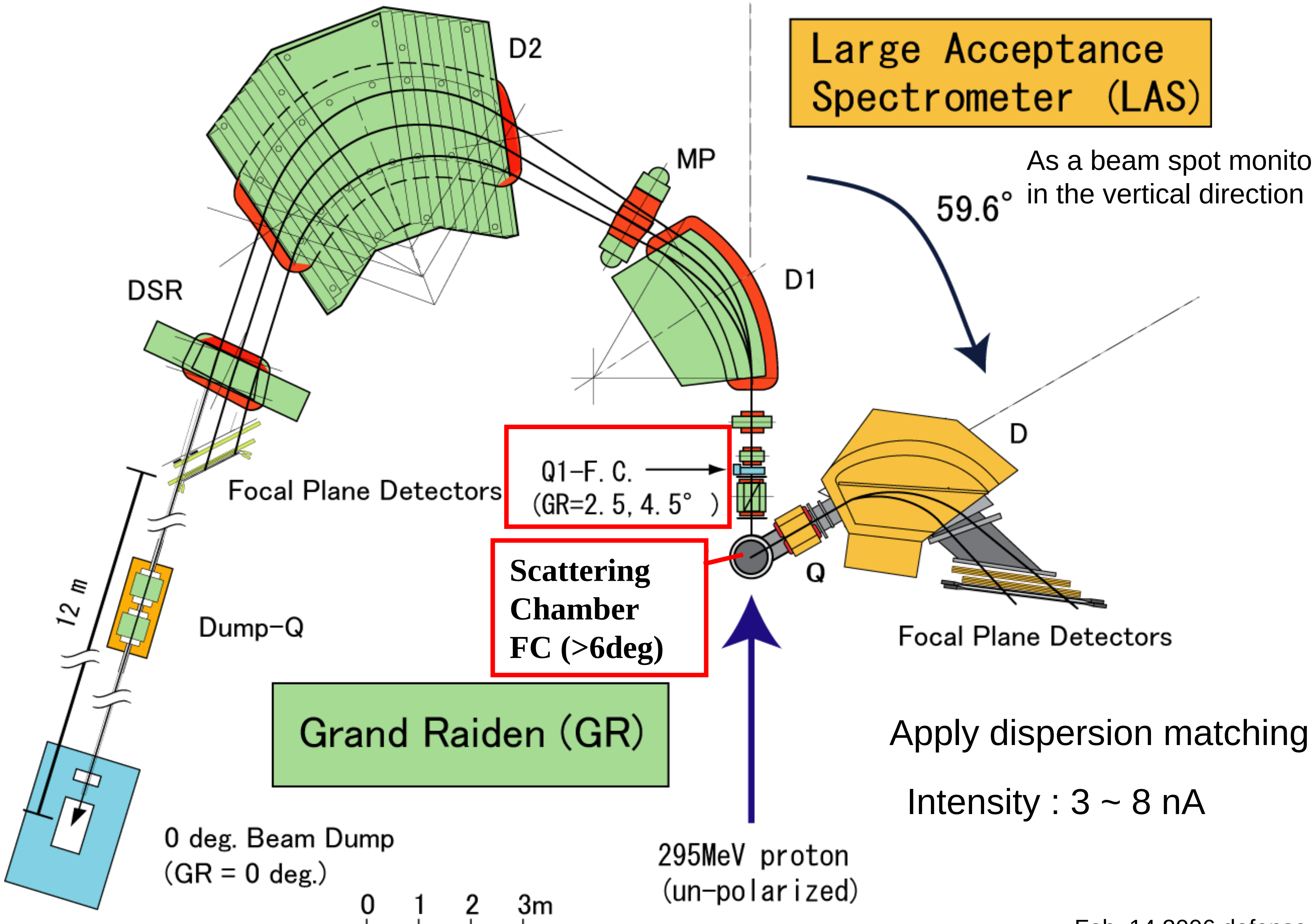
Grand Raiden in the 0deg Measurement Setup

in spin-transfer measurements

$$p_{y'} = \frac{1}{A_y}\frac{L-R}{L+R}$$



Spectrometers in the 0-deg. experiment setup

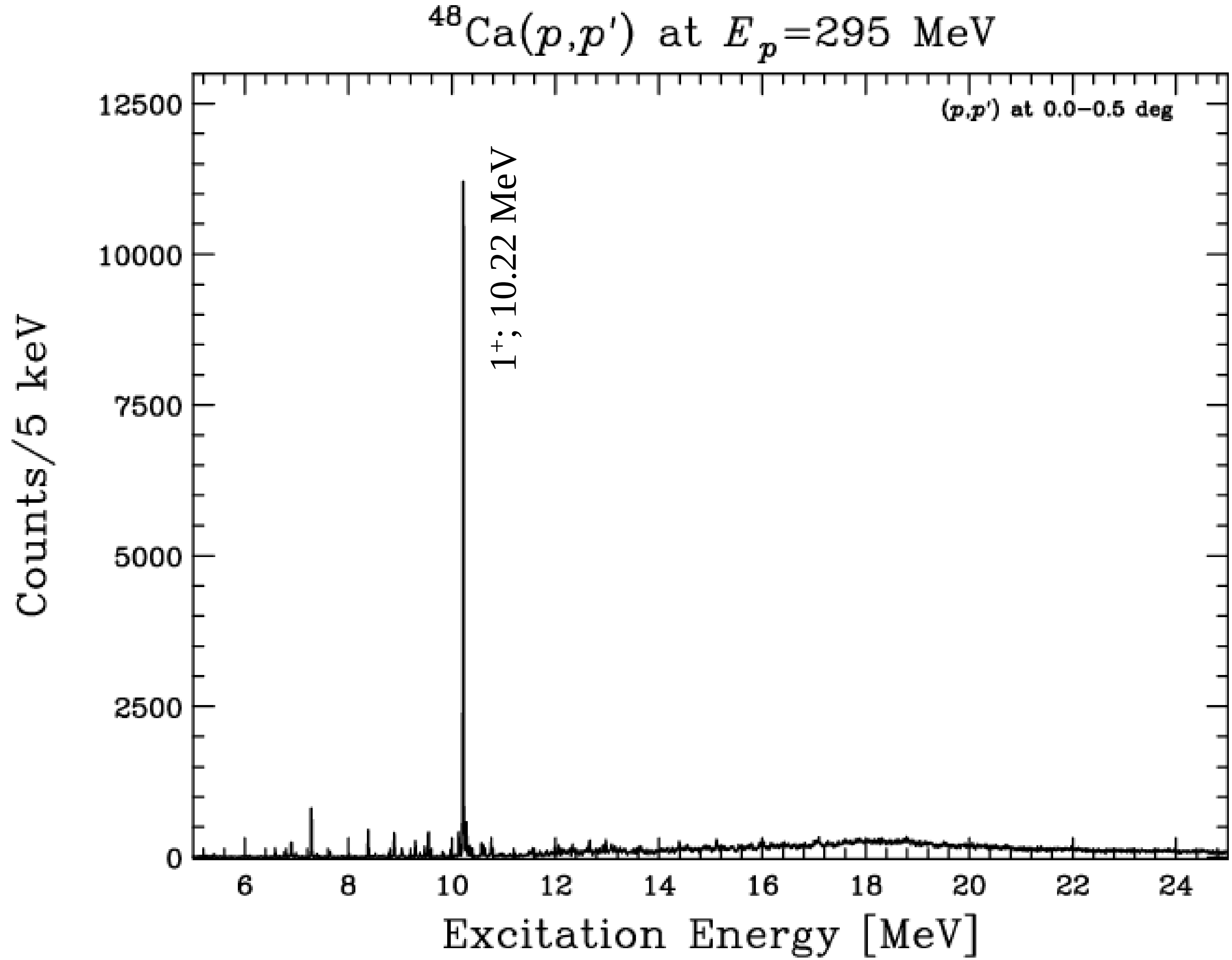


Apply dispersion matching

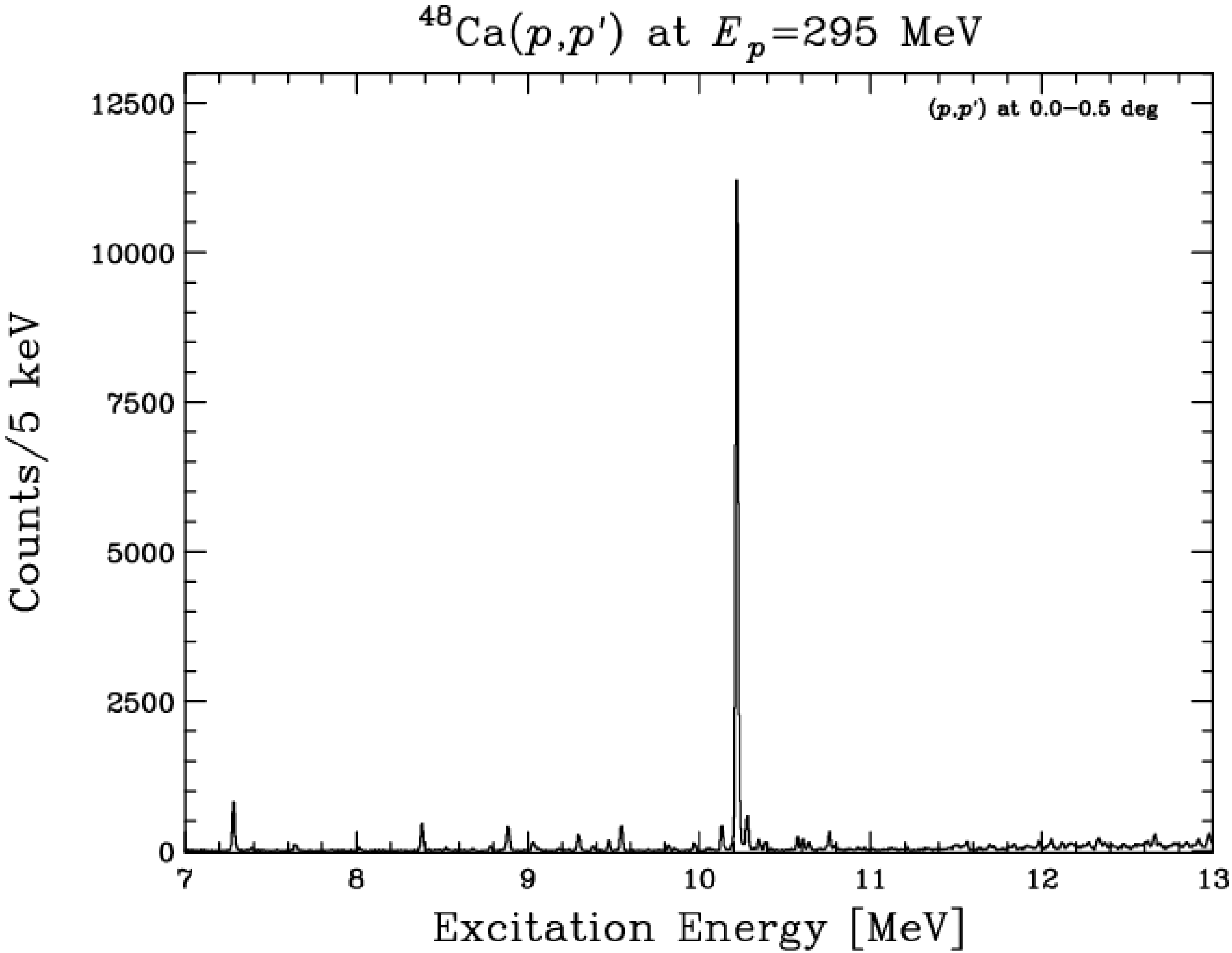
Intensity : 3 ~ 8 nA

1996–1997年頃

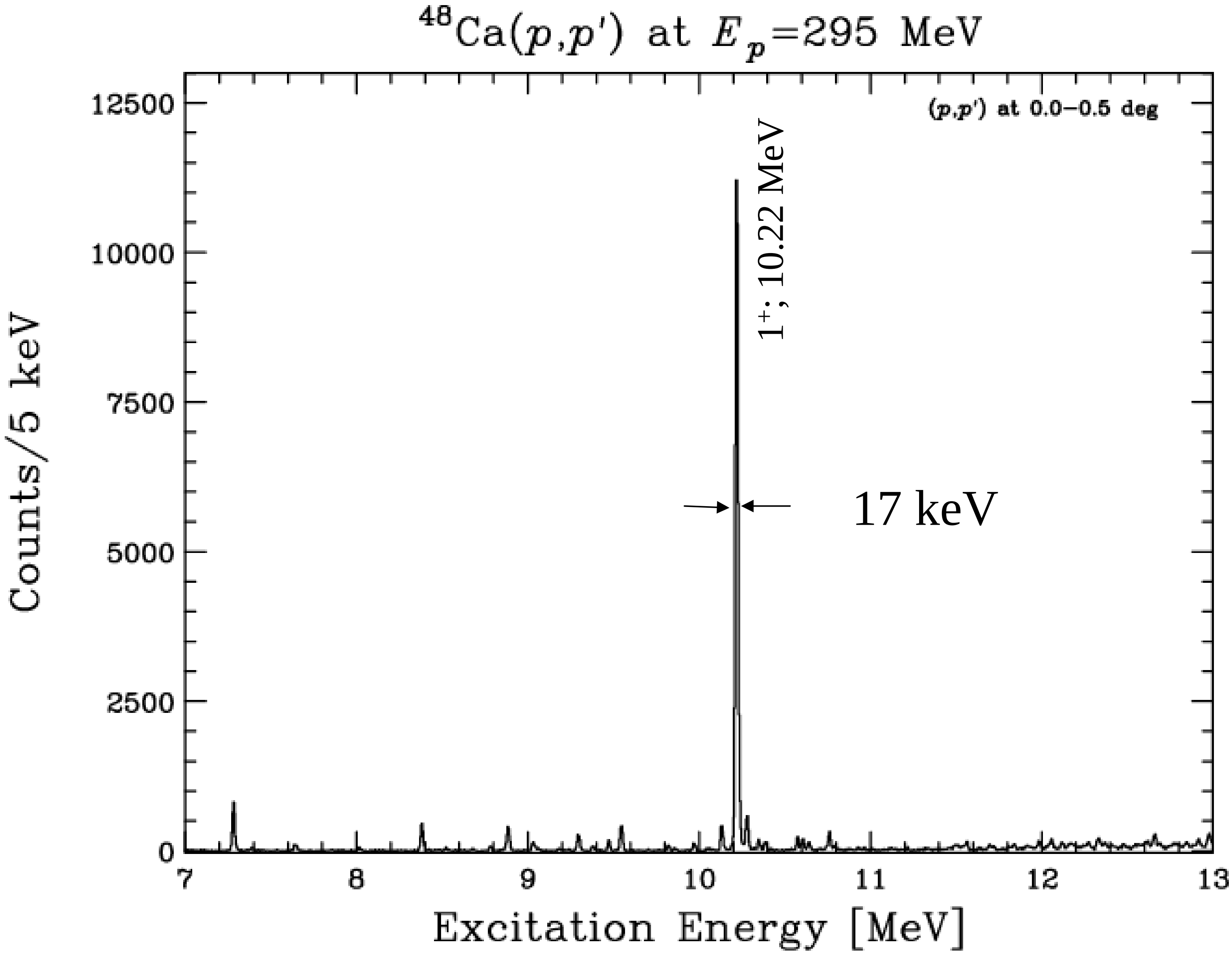
Representative Spectra



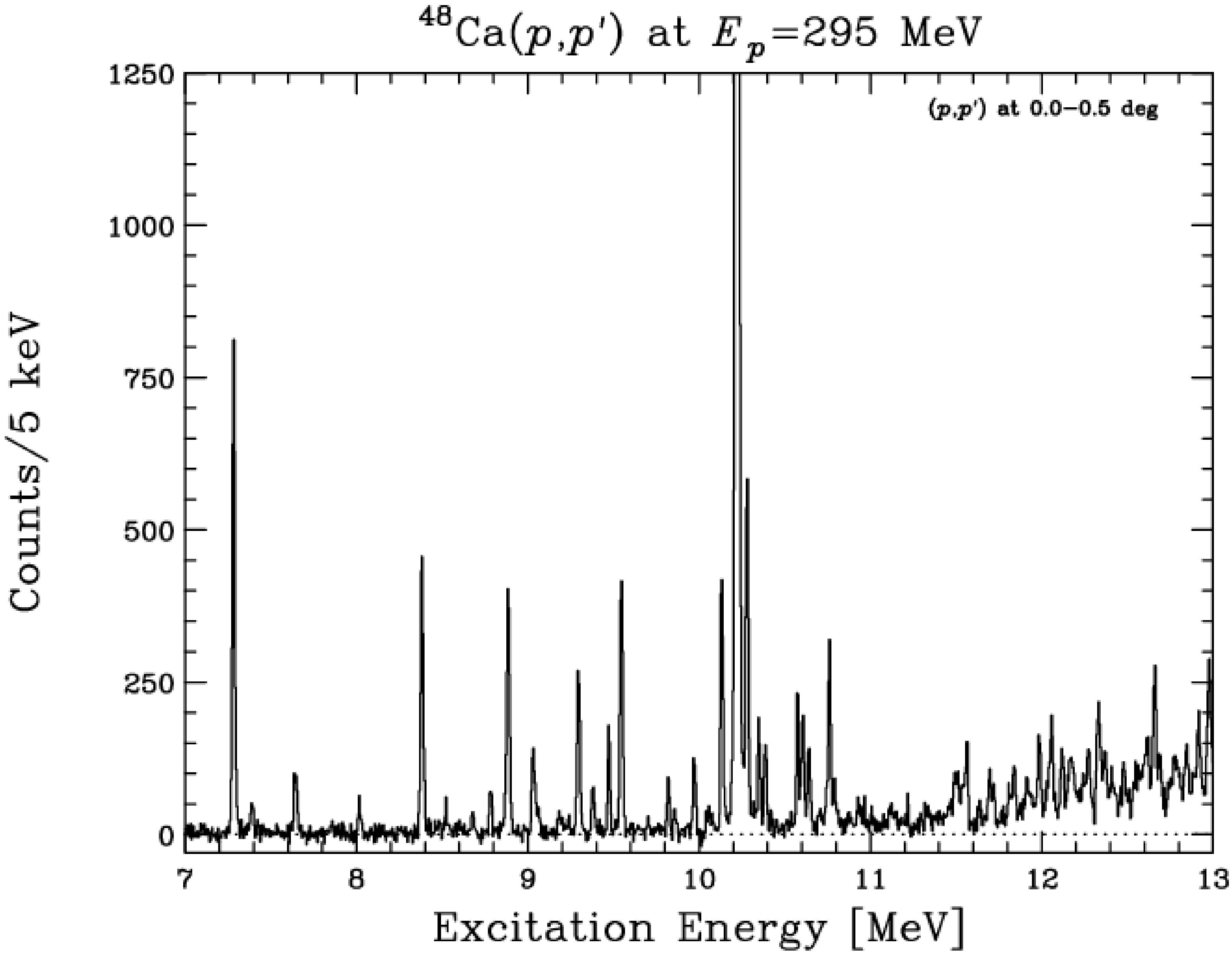
48Ca(p,p') at Ep=295 MeV
(p,p') at 0.0−0.5 deg
1+; 10.22 MeV
Counts/5 keV
Excitation Energy [MeV]
12500
10000
7500
5000
2500
0
6
8
10
12
14
16
18
20
22
24



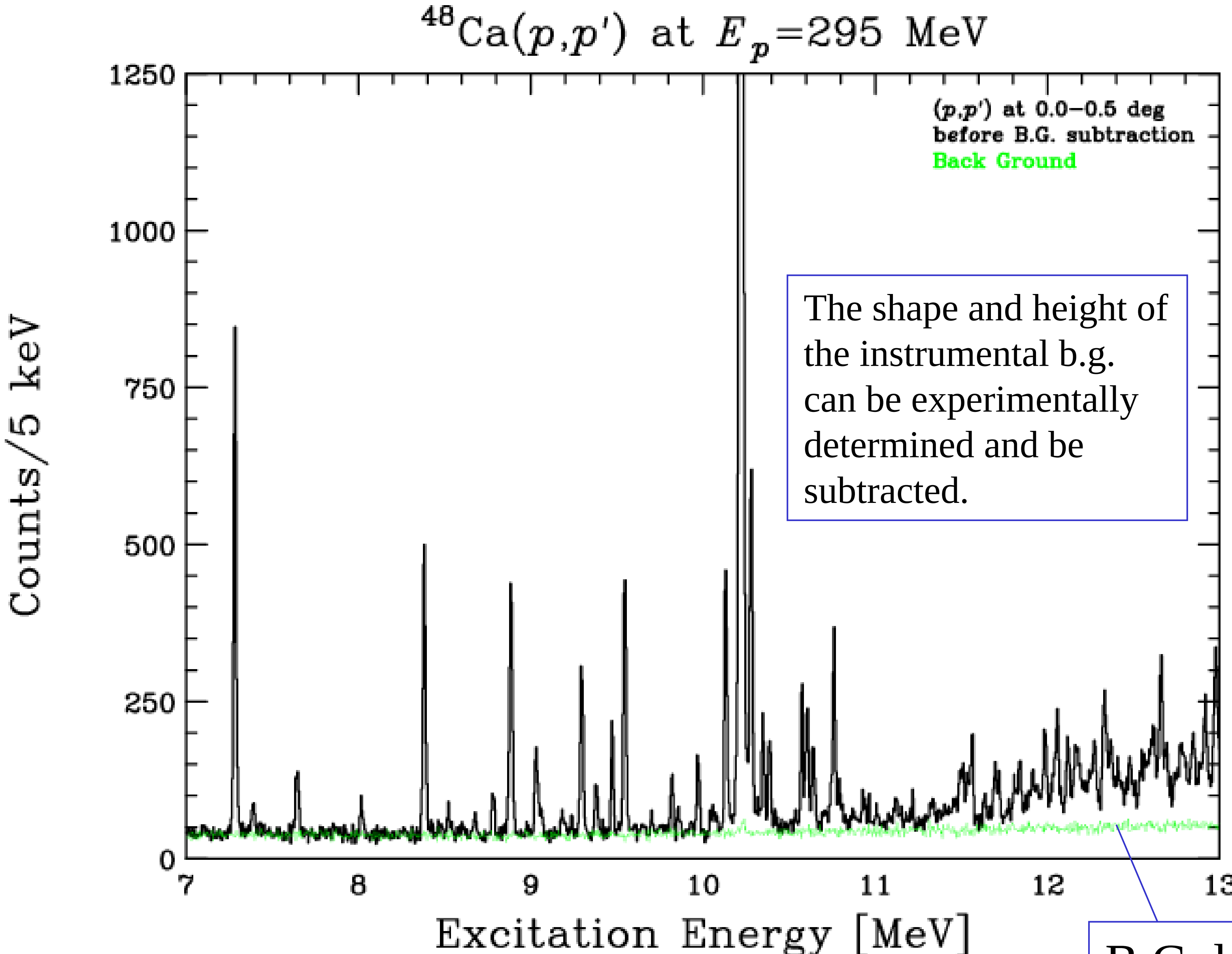
48Ca(p,p') at Ep=295 MeV
(p,p') at 0.0−0.5 deg
12500
10000
7500
5000
2500
0
7
8
9
10
11
12
13
Counts/5 keV
Excitation Energy [MeV]



48Ca(p,p') at Ep=295 MeV
(p,p') at 0.0−0.5 deg
1+; 10.22 MeV
17 keV
Counts/5 keV
Excitation Energy [MeV]
12500
10000
7500
5000
2500
0
7
8
9
10
11
12
13

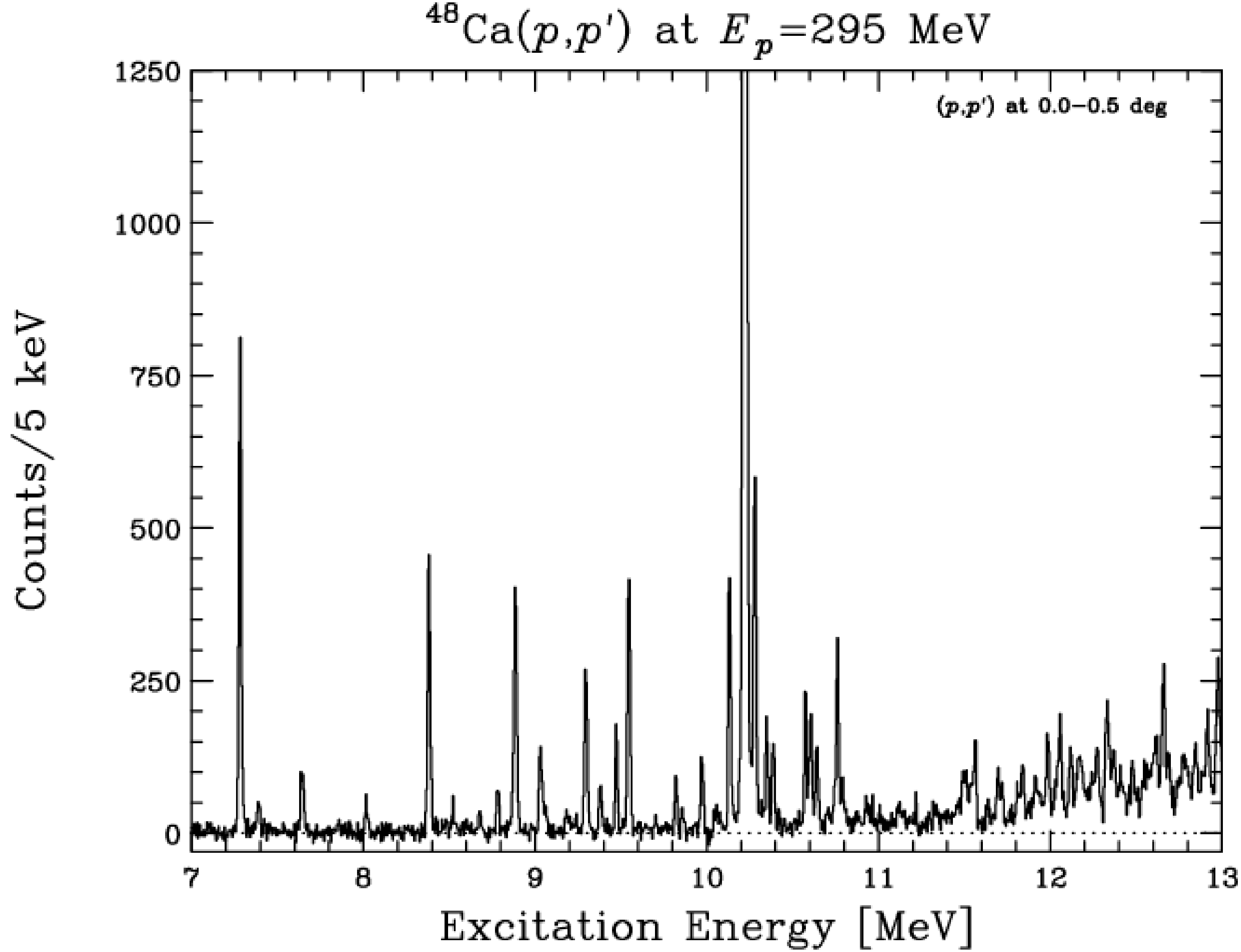


$^{48}Ca(p,p')$ at E_p=295 MeV
(p,p') at 0.0–0.5 deg
Counts/5 keV
Excitation Energy [MeV]
1250
1000
750
500
250
0
7
8
9
10
11
12
13

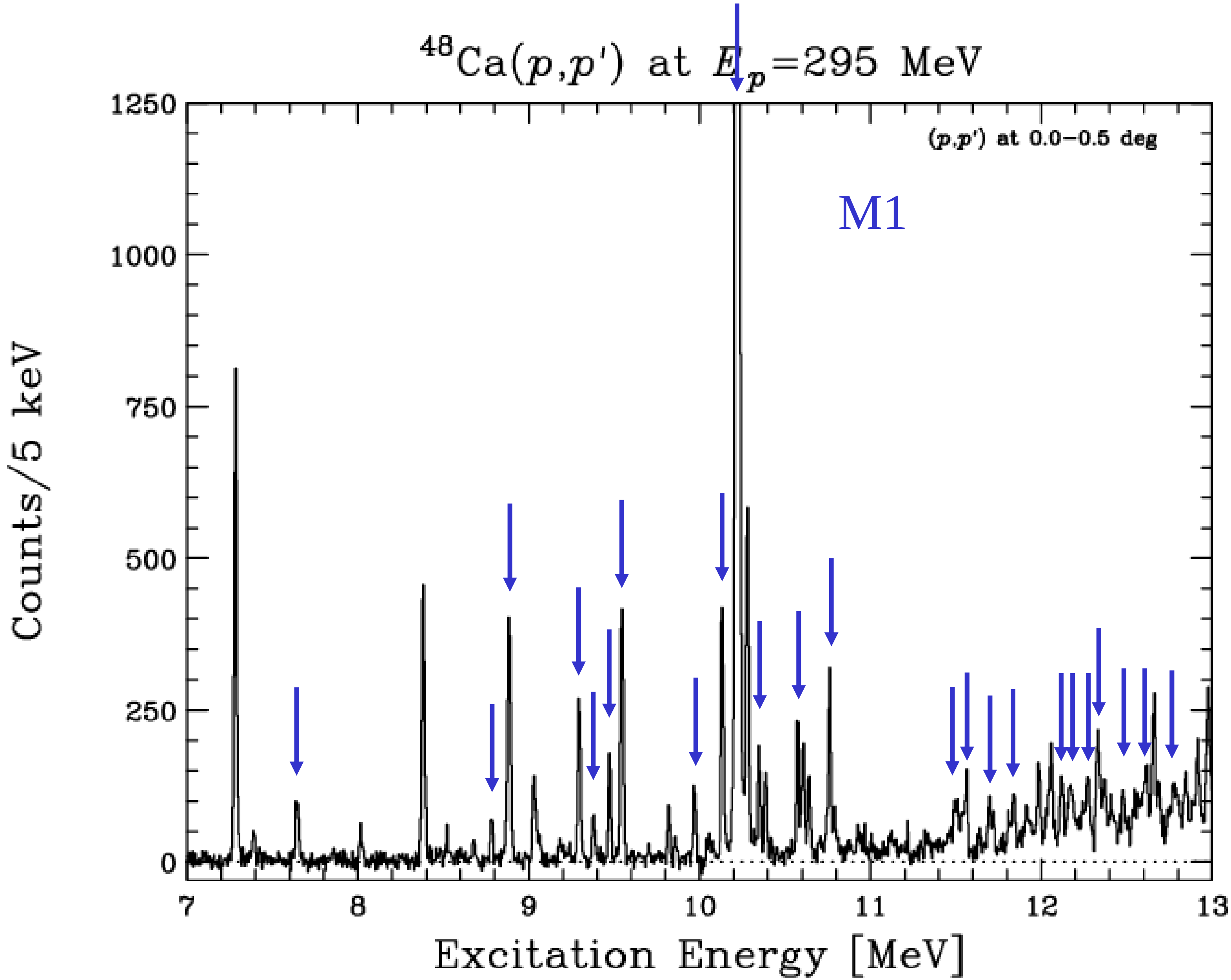


The shape and height of the instrumental b.g. can be experimentally determined and be subtracted.

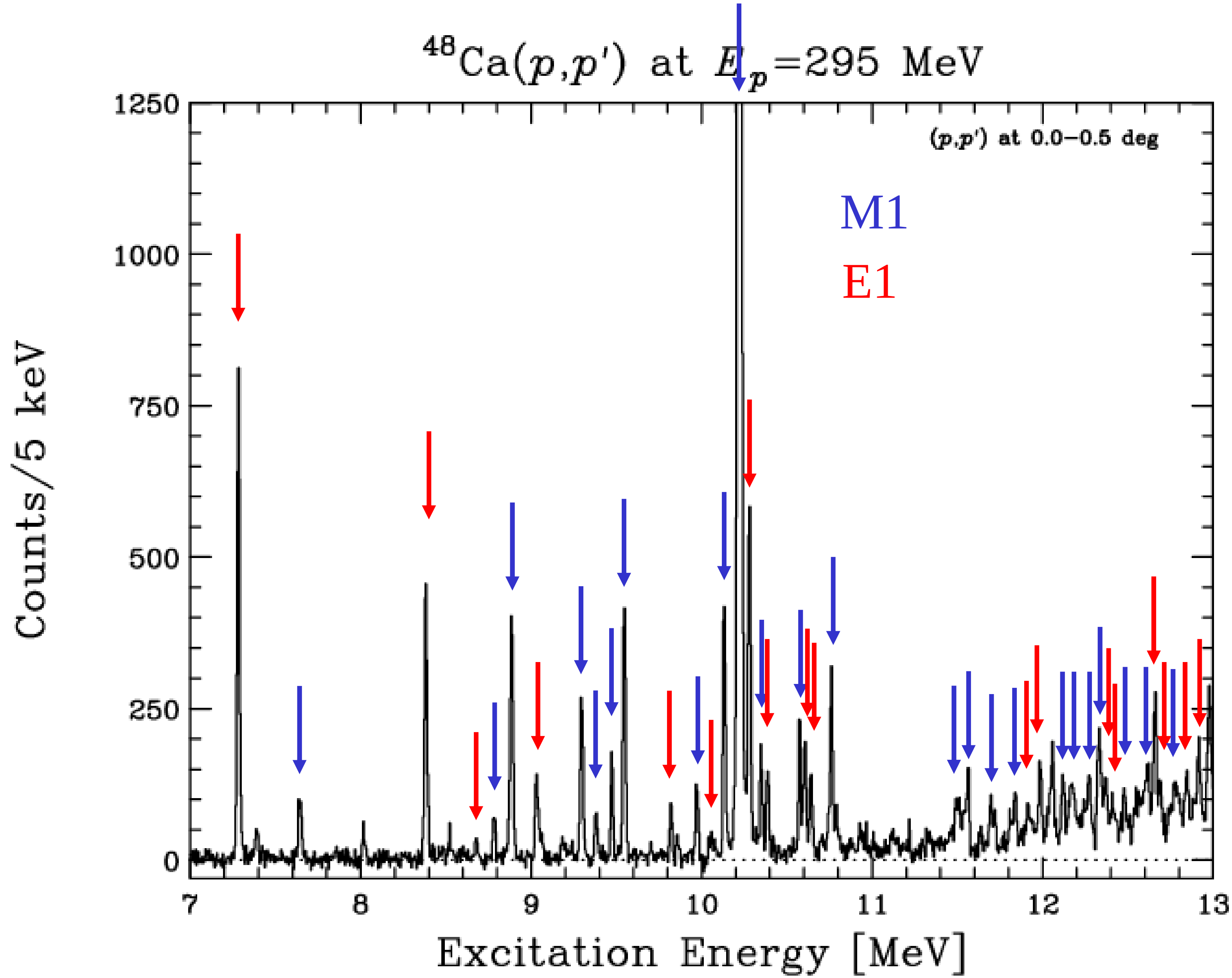
B.G. level



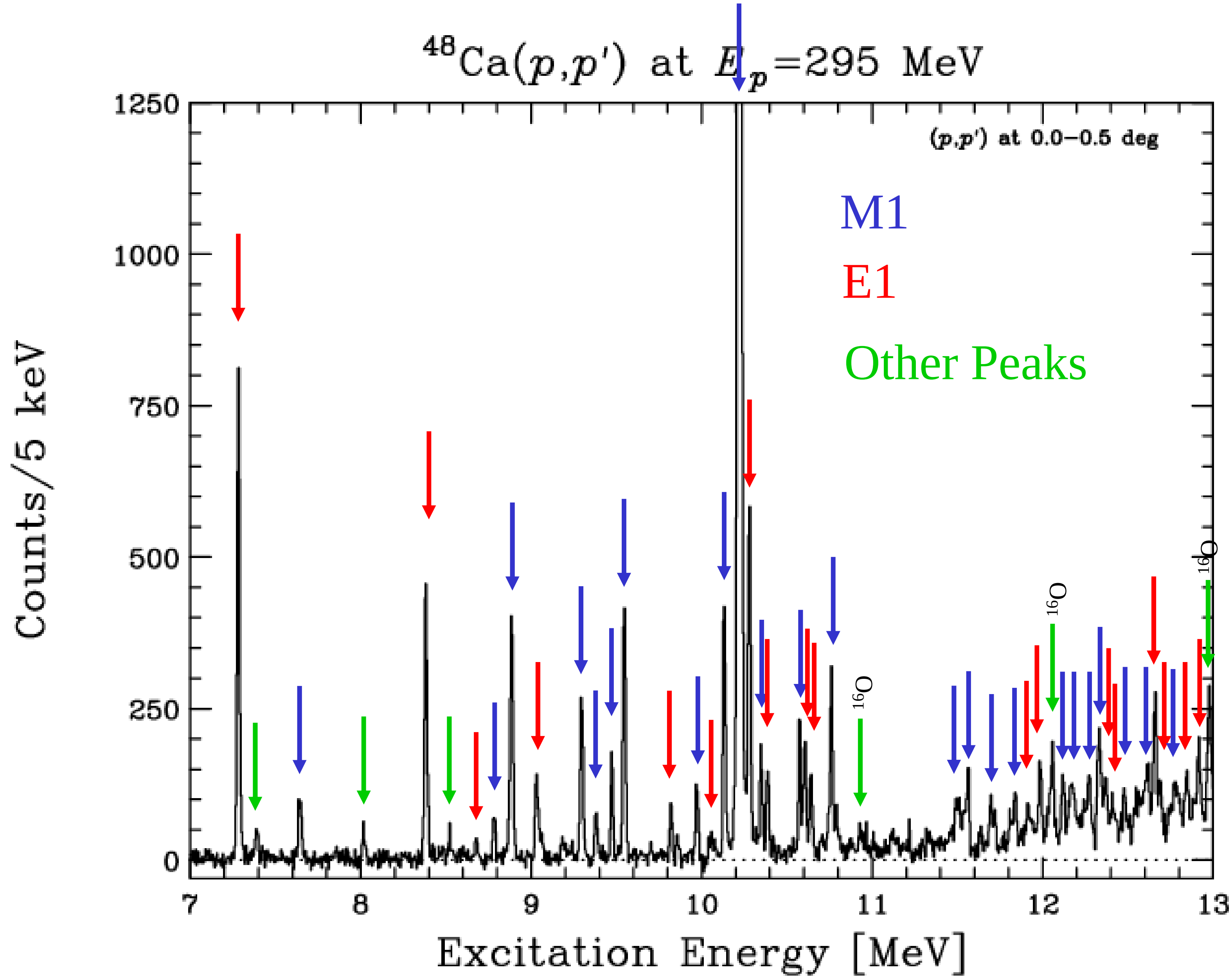
^{48}Ca(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
Counts/5 keV
Excitation Energy [MeV]
1250
1000
750
500
250
0
7
8
9
10
11
12
13



^{48}Ca(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
M1
Counts/5 keV
Excitation Energy [MeV]
1250
1000
750
500
250
0
7
8
9
10
11
12
13



^{48}Ca(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
M1
E1
Counts/5 keV
Excitation Energy [MeV]
0
250
500
750
1000
1250
7
8
9
10
11
12
13



48Ca(p,p') at Ep=295 MeV
(p,p') at 0.0–0.5 deg
M1
E1
Other Peaks
16O
16O
16O
Counts/5 keV
Excitation Energy [MeV]
0
250
500
750
1000
1250
7
8
9
10
11
12
13

Isoscalar and Isovector M1 Excitations in N=Z nuclei

H. Matsubara *et al*.

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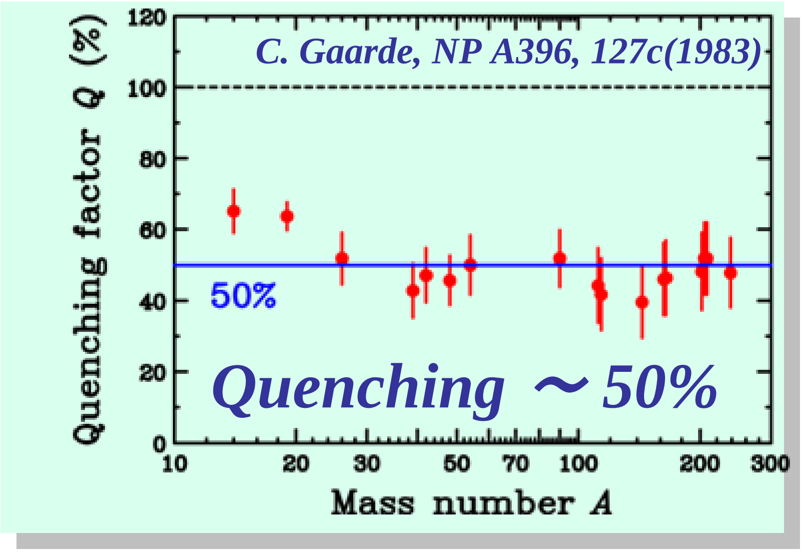
Quenching of the GT strengths

Gamow-Teller (GT) quenching problem:
The observed GT strengths are systematically smaller the sum-rule value.

GT sum rule : $S_{\beta^-} - S_{\beta^+} = 3(N - Z)$

Quenching Factor

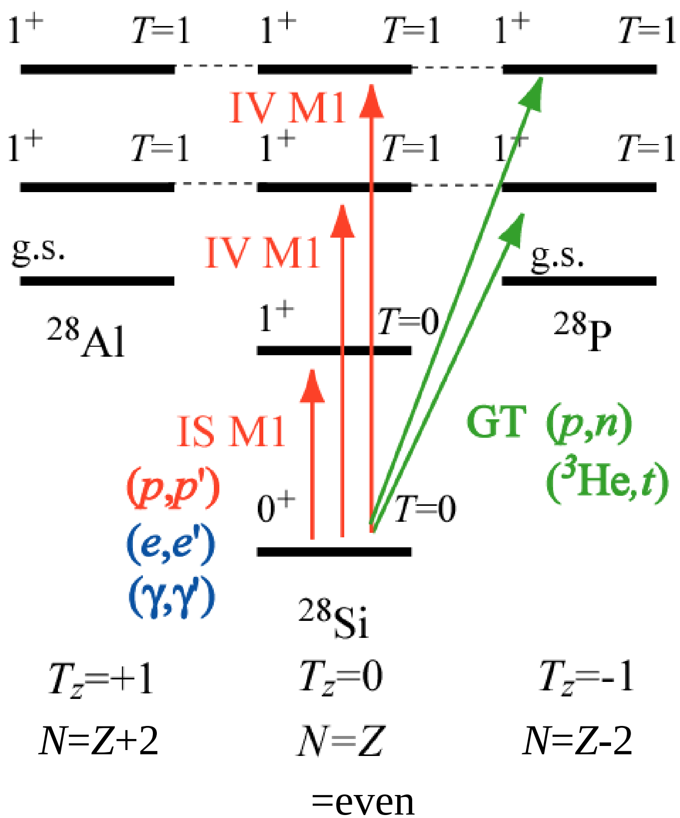
$$Q \equiv \frac{Strength(\text{exp.})}{Strength(theory)}$$



By sophisticated measurements and analysis of (p,n) and (n,p) reactions
50 → 88% of the strength was observed in ^{90}Zr upto E_x=50 MeV
T. Wakasa *et al*., PRC55(1997)2909 K. Yako *et al*., PLB615(2005)193

2 quenching schemes:
- Mixing of multi-particle multi-hole states ⟵ dominant contribution
- Mixing of Δ-hole states

M1 excitations and analogous excitations



IS: Isoscalar ΔT=0 σ

IV: Isovector ΔT=1 στ

Isovector (ΔT=1) M1 excitation is analogous to GT.

➡ Similar quenching is expected

Isoscalar (ΔT=0) M1 excitation: Δ-h mixing does not take place

➡ Different quenching between isoscalar and isovector excitations?

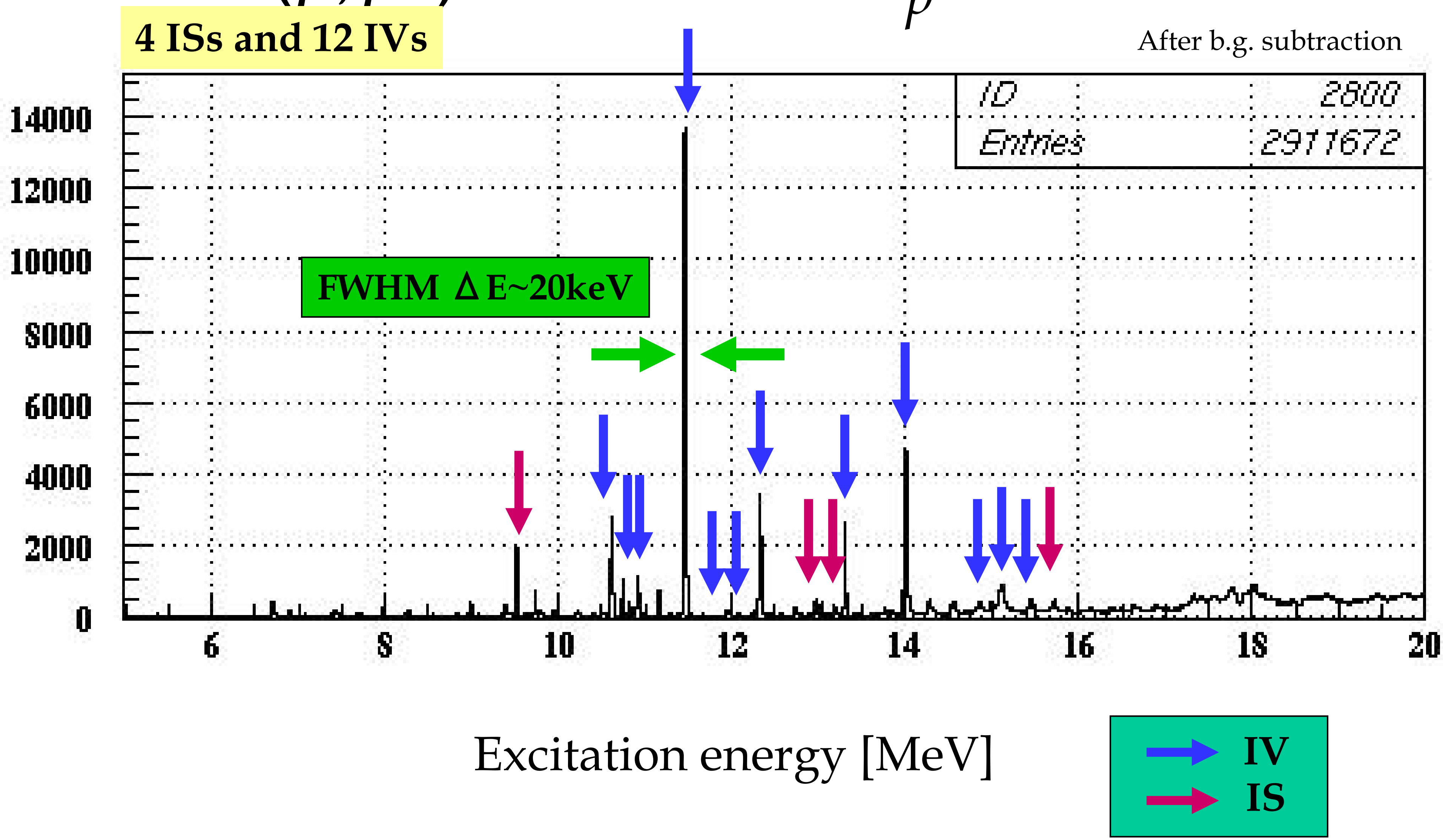
Study of isoscalar/isovector M1 excitations over the sd-shell region

For all the N=Z even-even stable nuclei over the sd-shell
(isoscalar/isovector excitations do not mix to each other)

^{16}O, ^{20}Ne, ^{24}Mg, ^{28}Si, ^{32}S, ^{36}Ar, ^{40}Ca

^{16}O: Ice target (H_2O)
^{32}S: Cooled target (for preventing sublimation)
^{36}Ar: Gas target
^{20}Ne: Cooled gas target

^{28}Si(p,p') at 0-0.5° E_p=300MeV



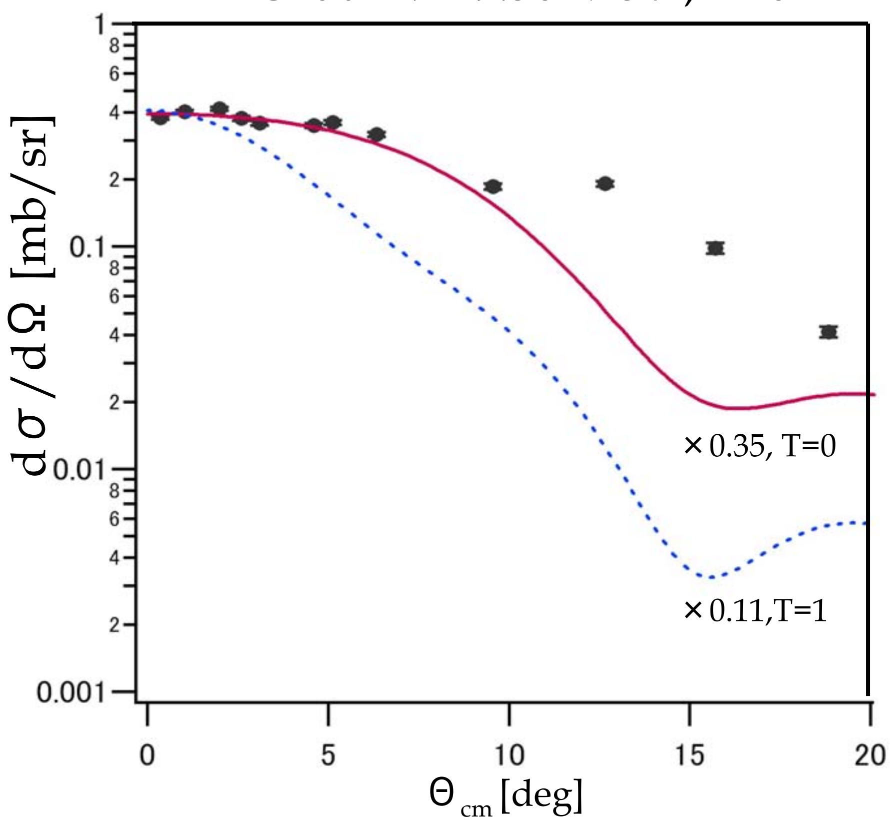
L and T assignments

- Distorted wave Born approximation (DWBA) by DW91

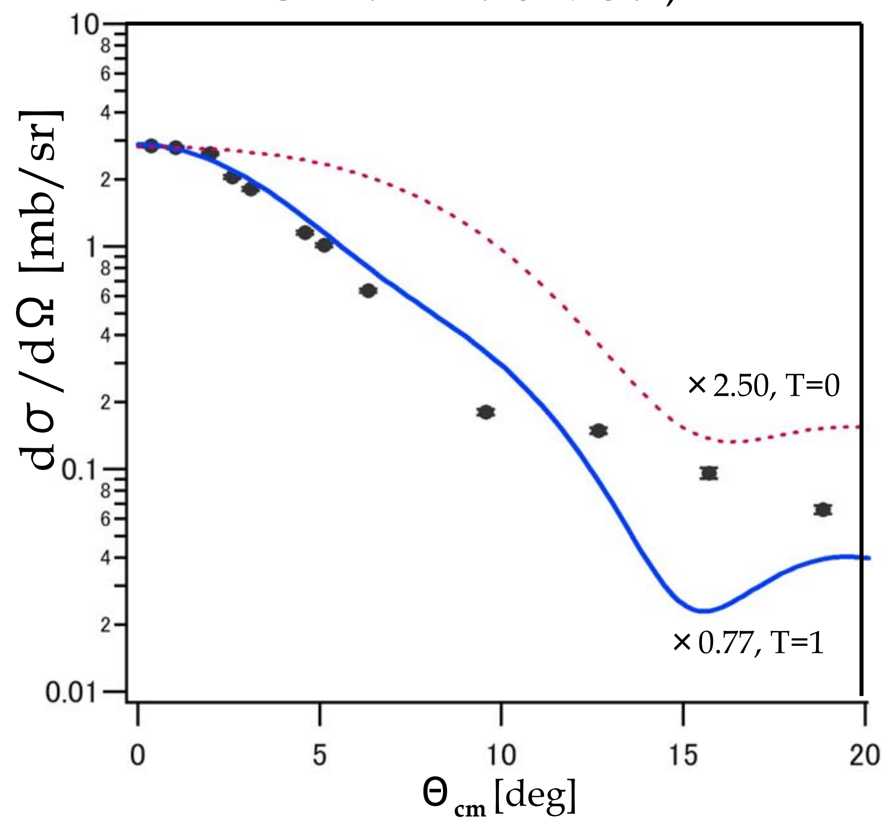
Trans. density : USD (from shell model calculation)
NN interaction. : Franey and Love, PRC31(1985)488. (325 MeV data)
Optical potential : K. Lin, M.Sc. thesis., Simon Fraser U. 1986.

T=0 ; IS
T=1 ; IV

^{28}Si at Ex = 9.50 MeV ; T=0



^{28}Si Ex = 11.45 MeV ; T=1



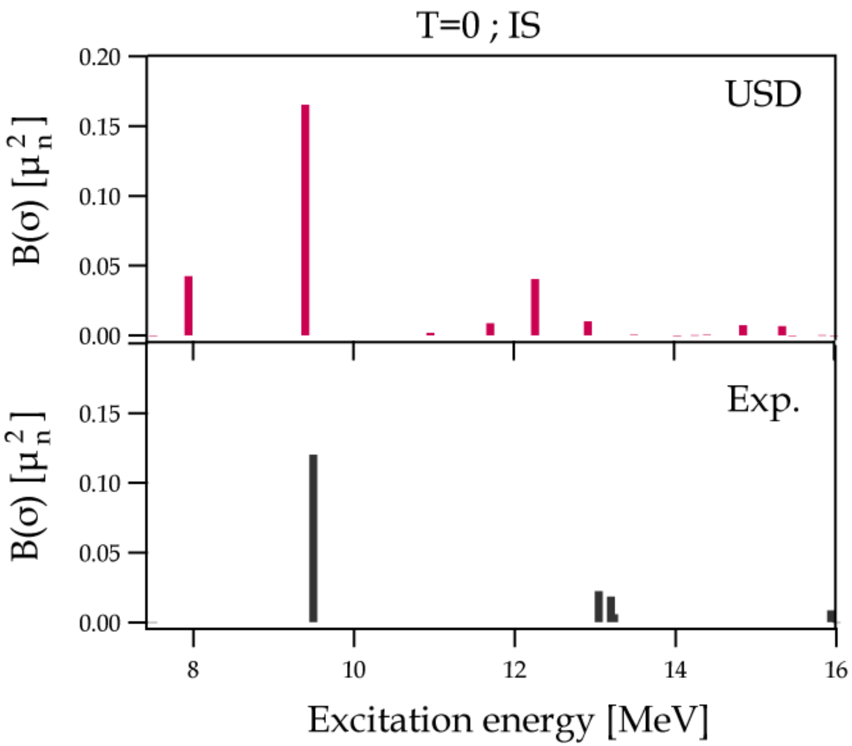
Isospin can be assigned from an angular distribution.

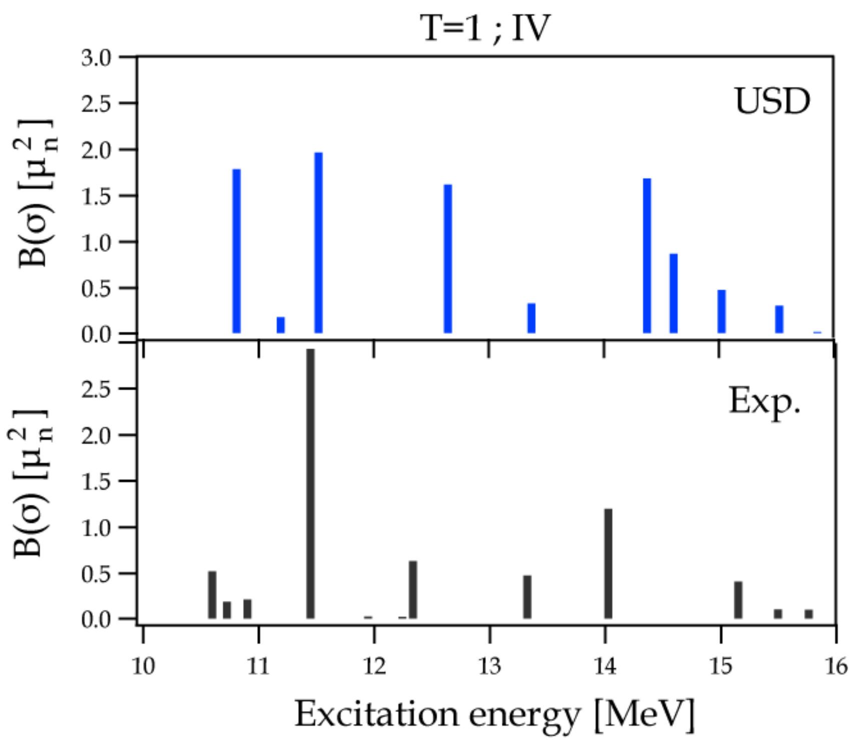
Strength distribution

preliminary

^{28}Si

shell model calculation:
OXBASH + USD interaction



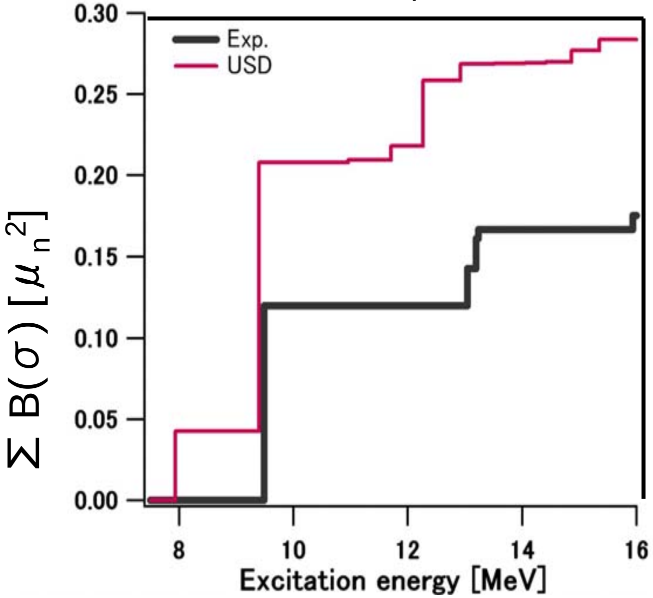


M1 strength in ^{28}Si

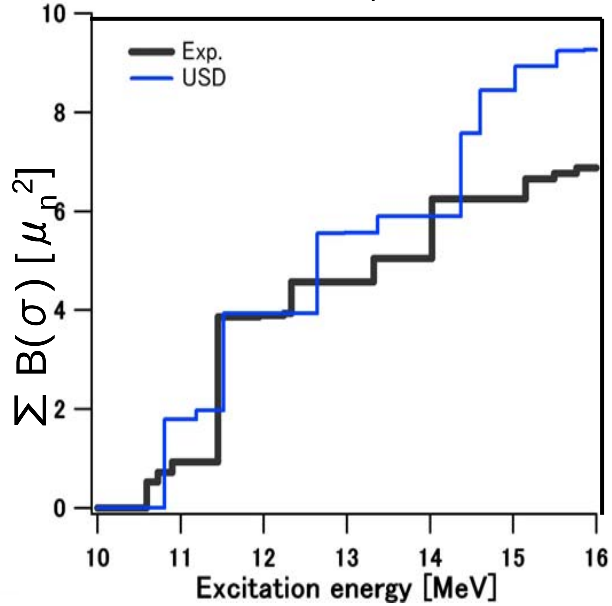
preliminary

Cumulative Sum

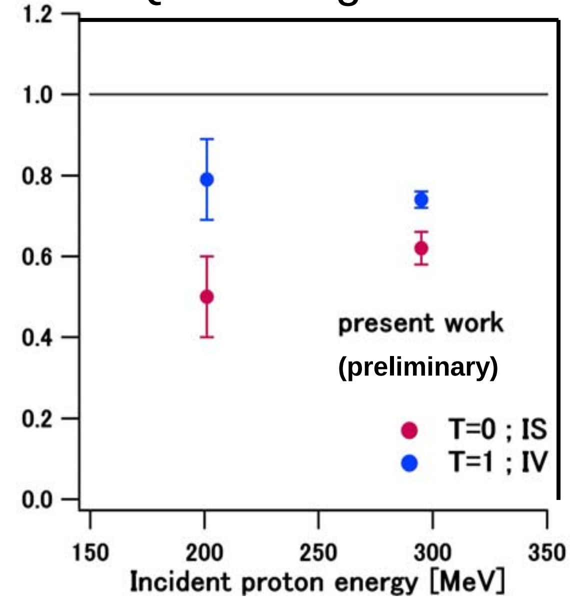
T=0 ; 1+



T=1 ; I+



Quenching factor



Followings should be checked more carefully.

- B(σ) is determined from dσ/dΩ(q=0) relying on the eff. interaction and DWIA calculation.

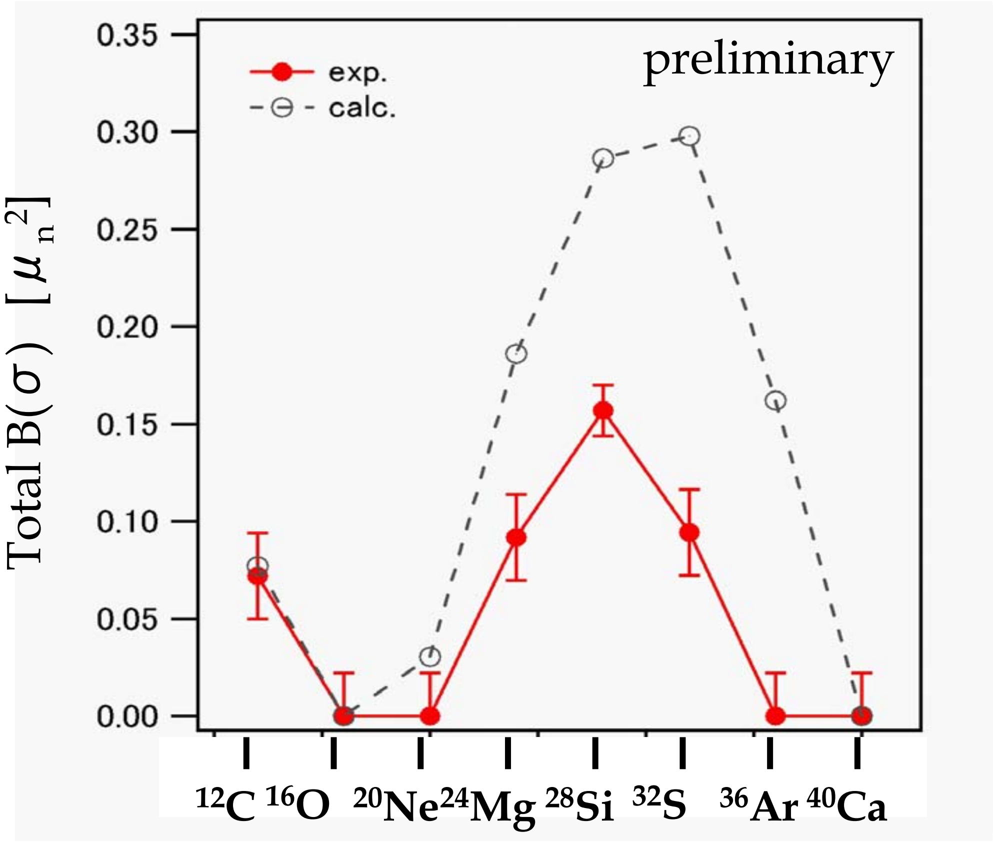
- Bare g-factor is used in the S.M. calculation.

$$Quenching\,Factor = \frac{\Sigma B(\sigma)_{\mathrm{exp}}}{\Sigma B(\sigma)_{shell-\mathrm{model}}}$$

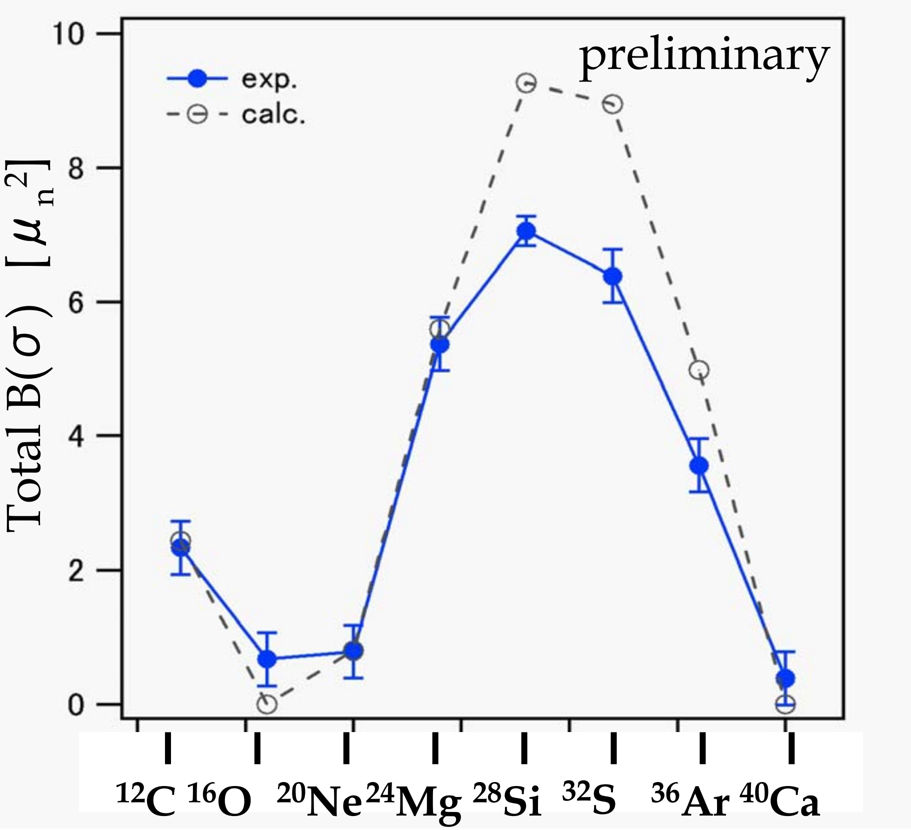
Total B(σ) strengths

very preliminary

IS



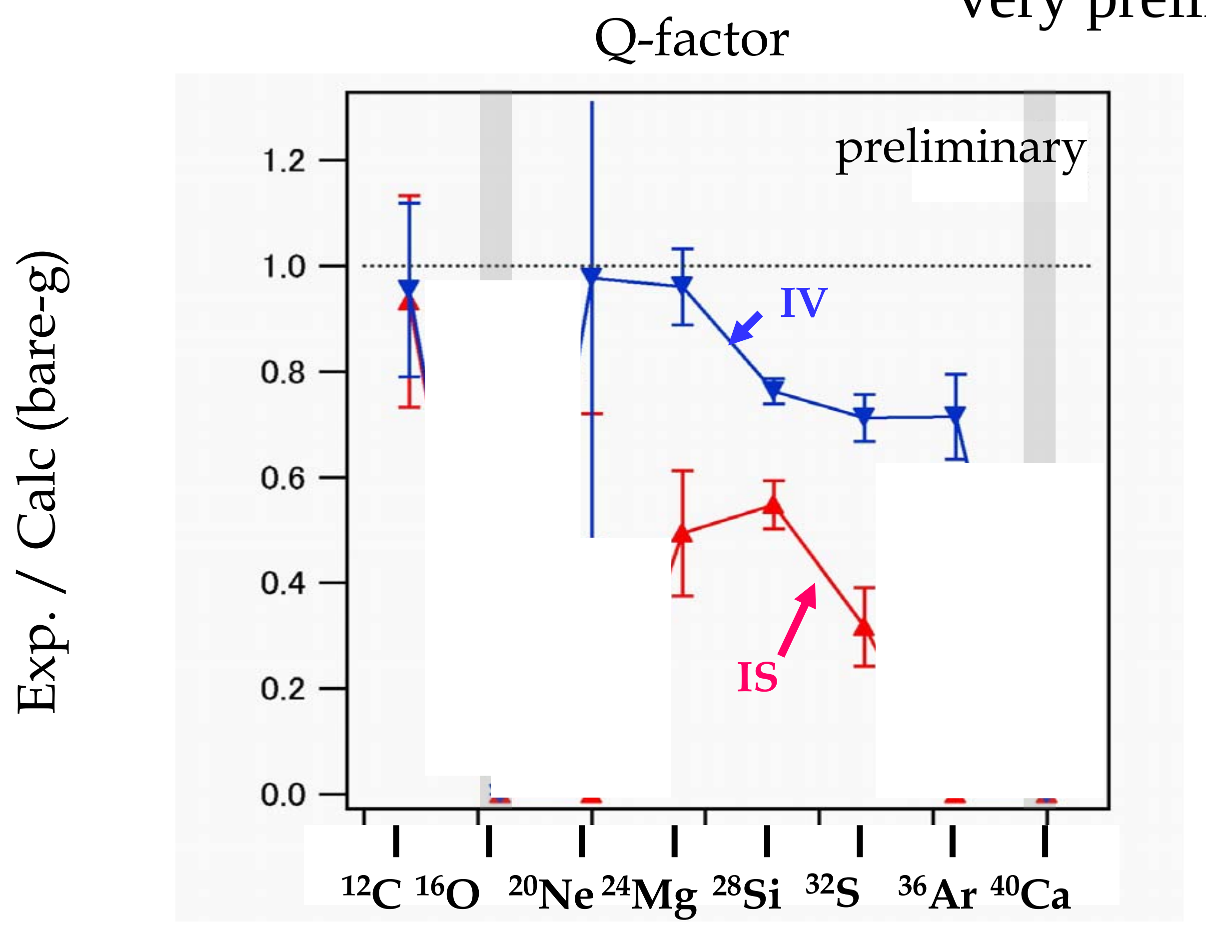
IV



Calc. = OXBASH shell model calculation (0 hw) with USD or CK int.
and the free-g factors.

Comparison of Q-factors IS and IV

very preliminary



IS seems generally to be less than IV in the sd-shell.

M1 strength in ^{208}Pb

Collaborators

E282

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Search for M1 strengths by experiments

Experimentally many reactions have been used to observe the M1 strengths:

^{208}Pb($\vec{\gamma}$,γ), ^{208}Pb(γ,$\vec{n}$), ^{207}Pb(*n*,*n*), ^{207}Pb(*n*,γ),

^{208}Pb(*e*,*e*’), and ^{208}Pb(*p*,*p*’)

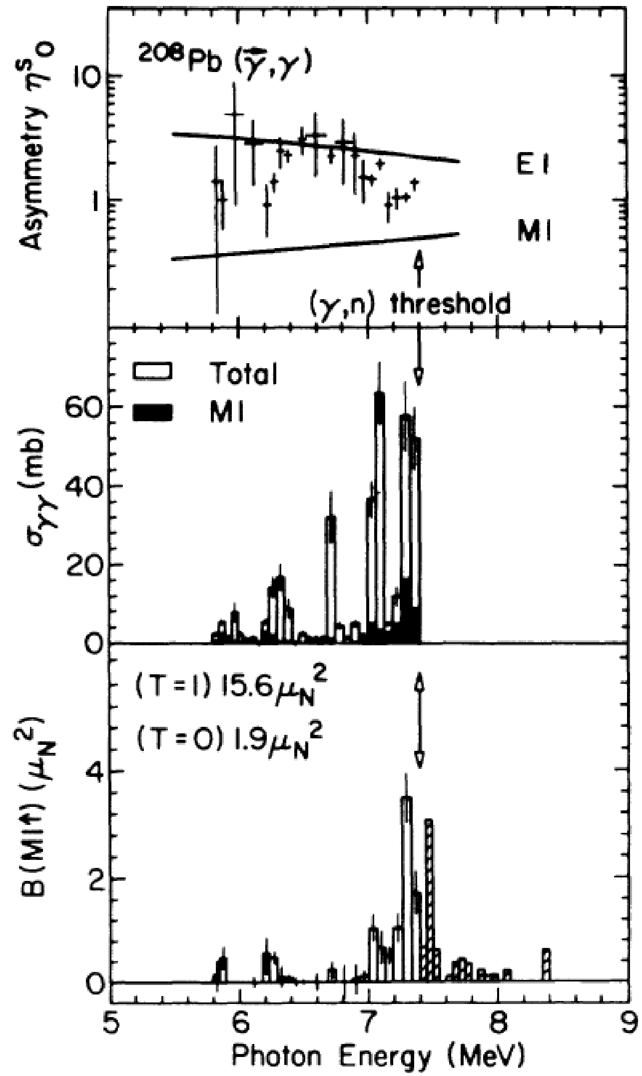
In 1988, R.M. Laszewsky et al. have identified

$8.8\mu_N^2$ below Sn by a ^{208}Pb($\vec{\gamma}$,γ) measurement.

In total the higher-lying strength became $15.6\mu_N^2$

which came closer to the “best” (smallest) theoretical prediction of $20\mu_N^2$.

Determination of the M1 strength distribution in ^{208}Pb over a large Ex range is important to know the M1 quenching mechanism.



R.M. Laszewski et al, PRL61(1988)1710

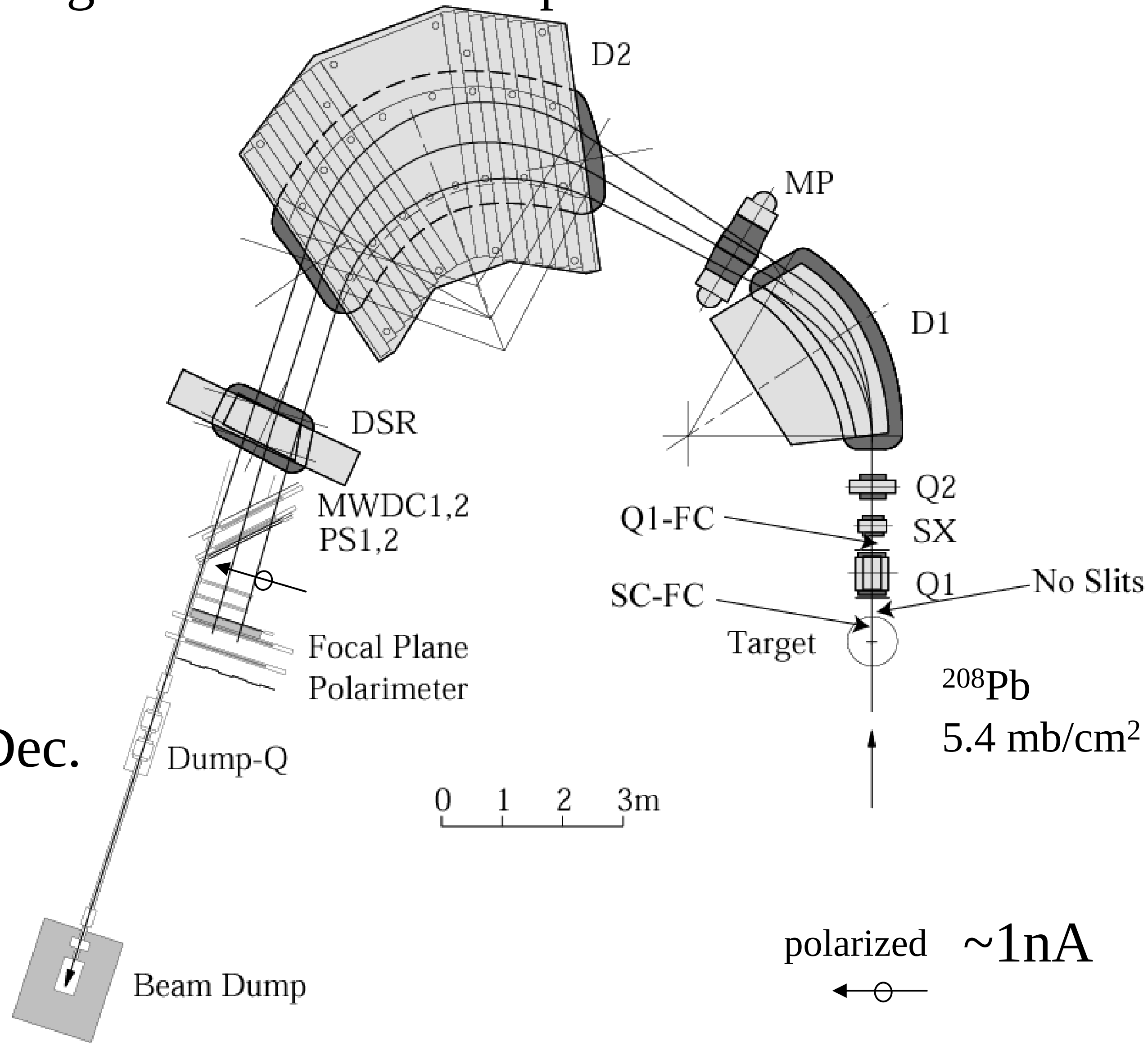
Prediction of the M1 strengths in ^{208}Pb

Many theoretical works have been done for reproducing
the observed M1 strengths

- spreading by the coupling to 2p-2h states: 20% of reduction
- ground state correlation: 20% of reduction
- coupling to Δ-h states and MEC: 20% of reduction

If all these mechanisms additively contribute,
"the best that be expected from theoretical predictions is 20 $\mu_N{}^2$"
I.S. Towner, Phys. Rep 155 (1987) 263.

Grand Raiden in the 0deg Measurement Setup



D_{LL} measurement is scheduled in Nov.-Dec. 2008.

D_{NN} (=D_{SS}) Measurement

ΔS can be model-independently extracted by measuring polarization transfer coefficients at 0°
(ΔS decomposition of the strengths)

T.Suzuki, PTP103(2000)859

$$2D_{NN} + D_{LL} = \begin{cases} -1 \text{ for } \Delta S = 1 & \text{M1} \\ 3 \text{ for } \Delta S = 0 & \text{E1 (Coulomb-Excitation)} \end{cases}$$

E1 and M1 strengths can be decomposed

The D_{NN} data were taken but D_{LL} were not.

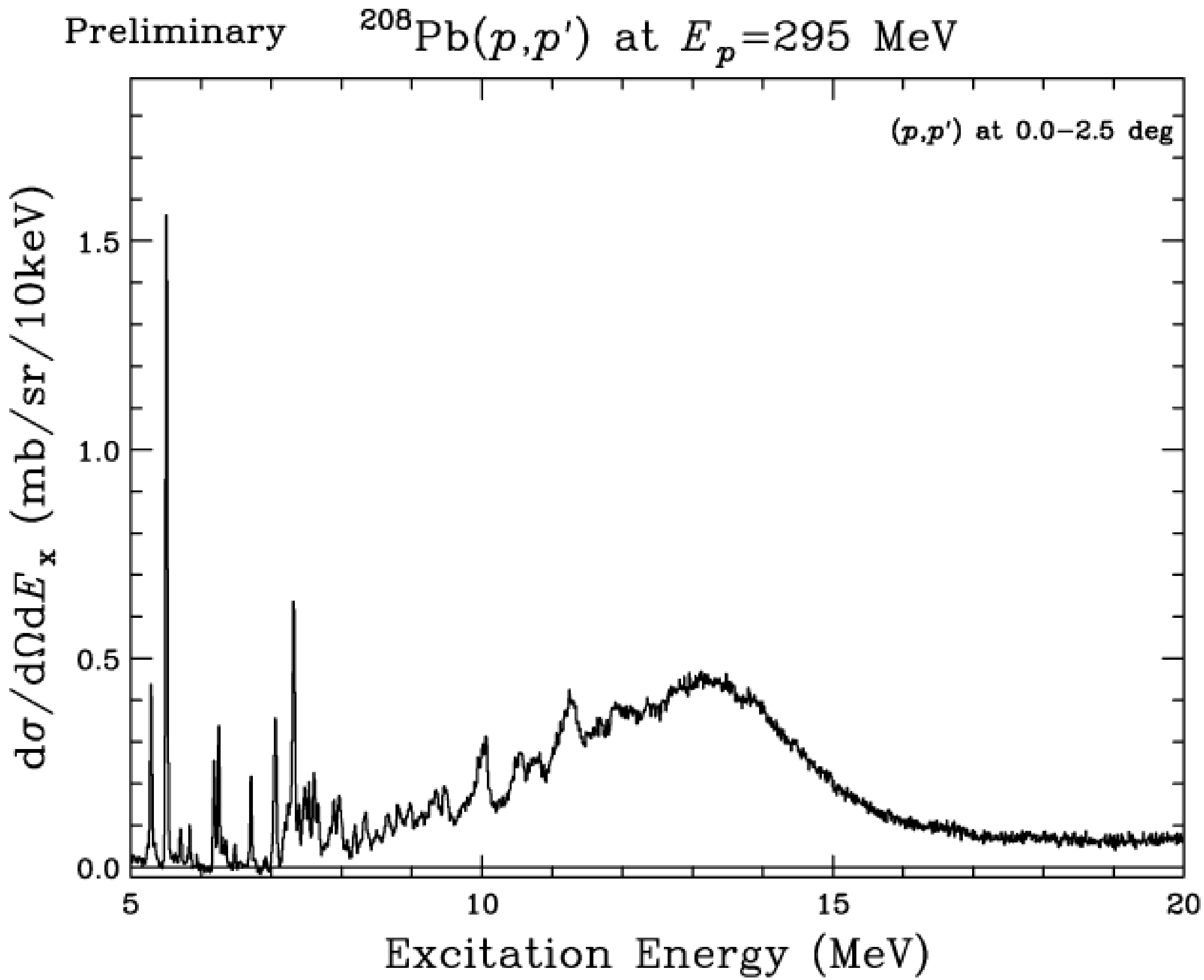
↓

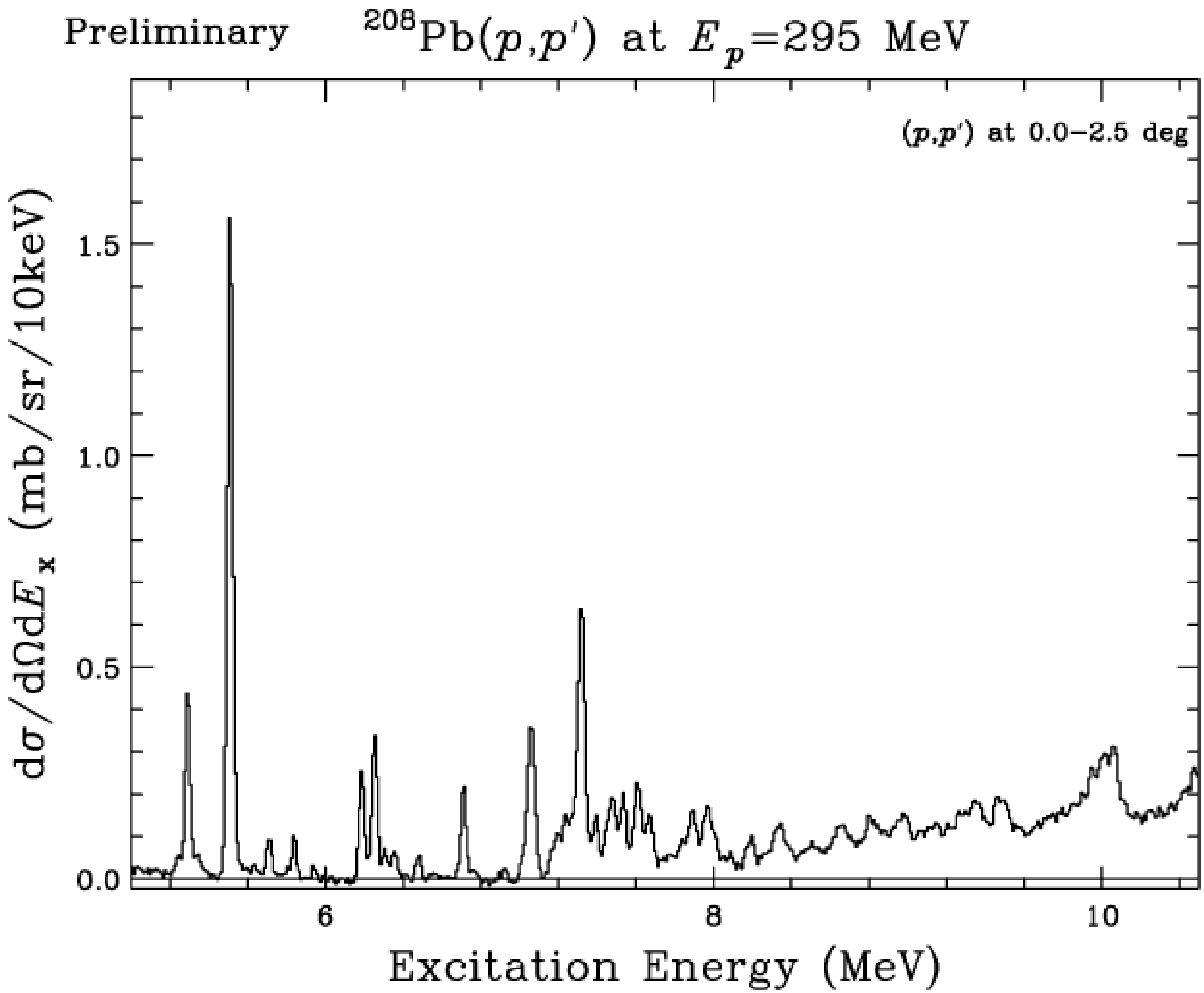
Here, we play a game assuming a constant

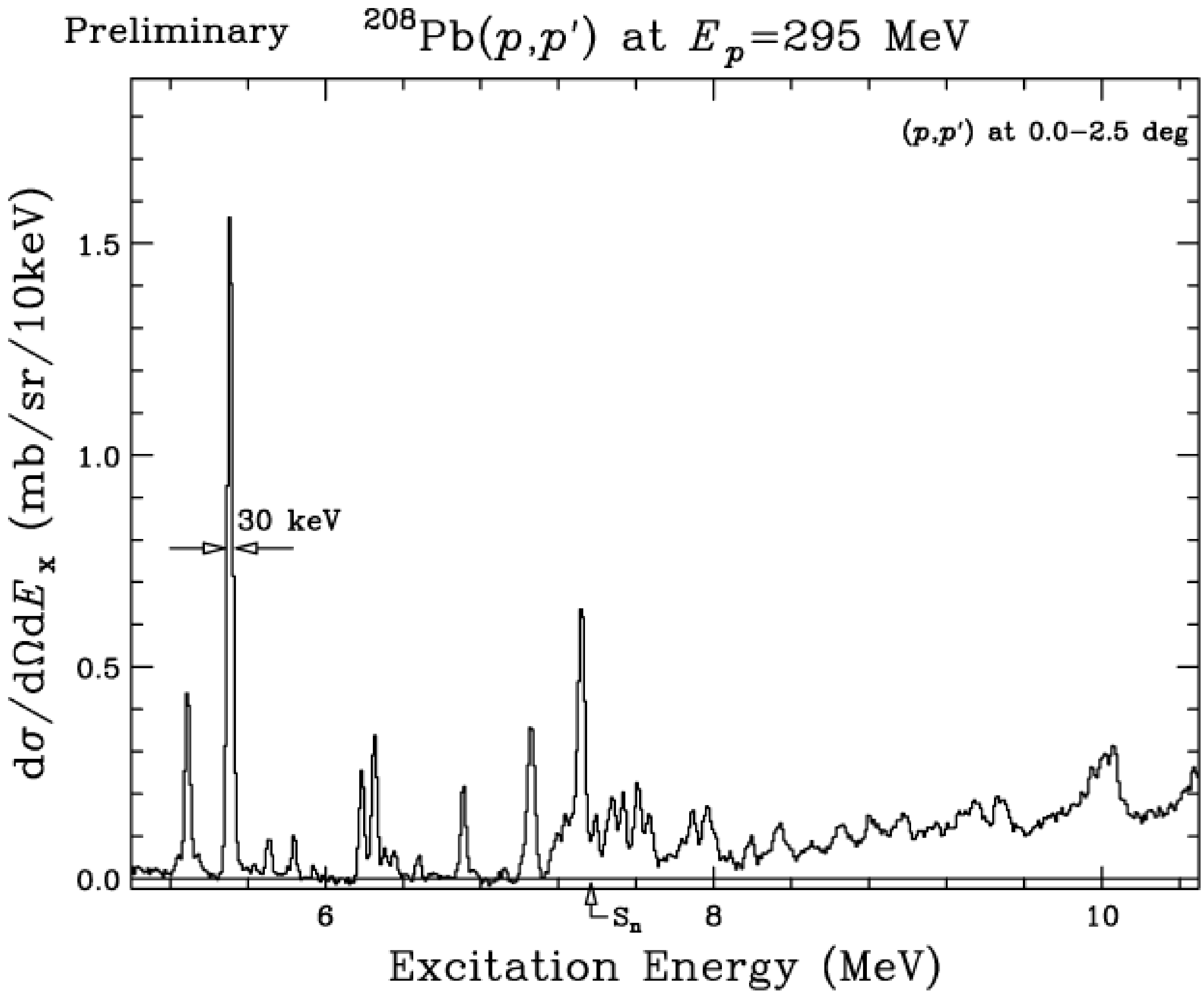
D_{NN} = -0.24 for M1 and +1 for E1 for the E1-M1 decomposition.

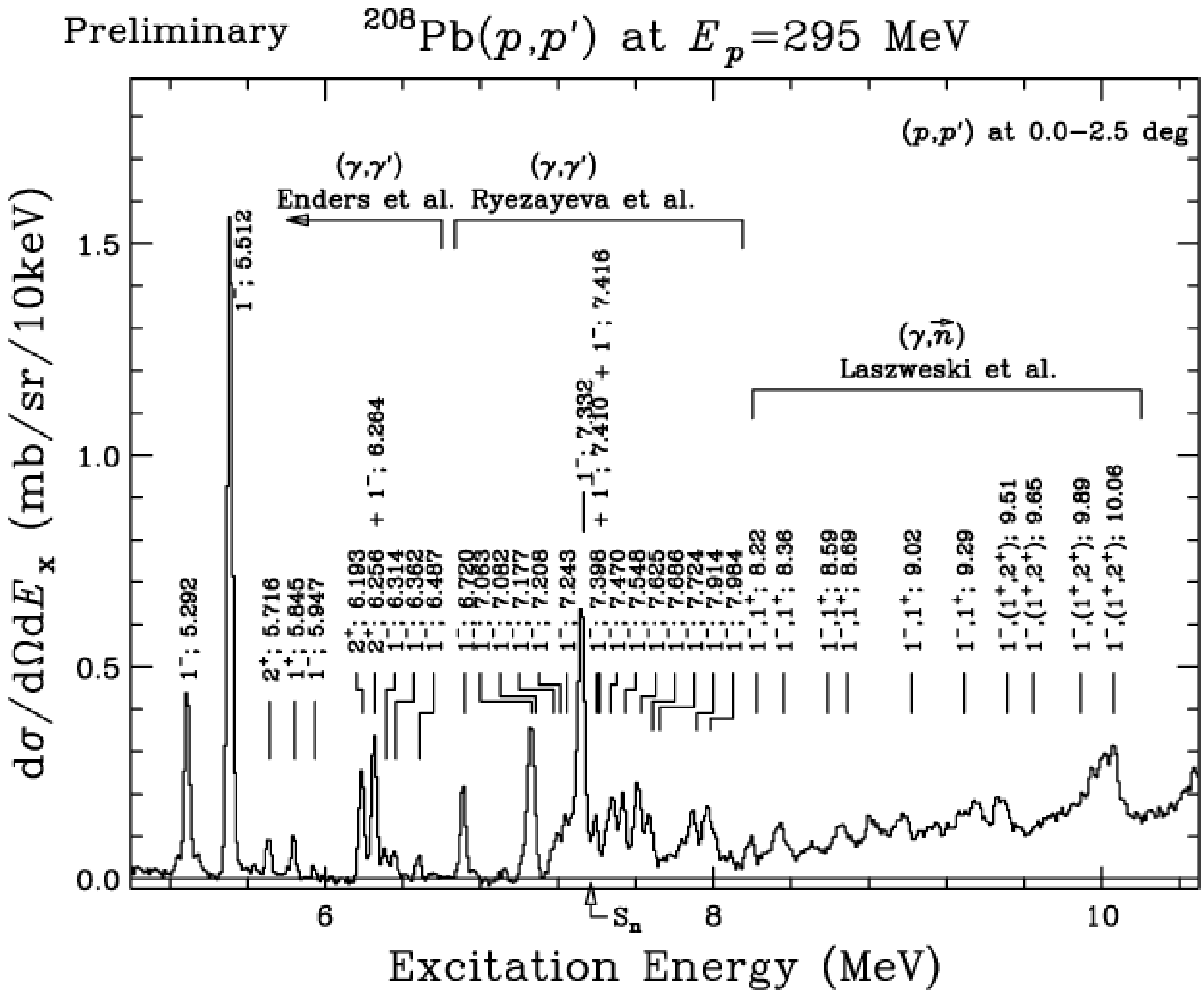
Normalization of B(σ) is not well determined

-0.24 is taken from T.Wakasa, M. Dozono *et al.*, for $^{12}C(p,n)^{12}N$(g.s) at 300 MeV at 0deg

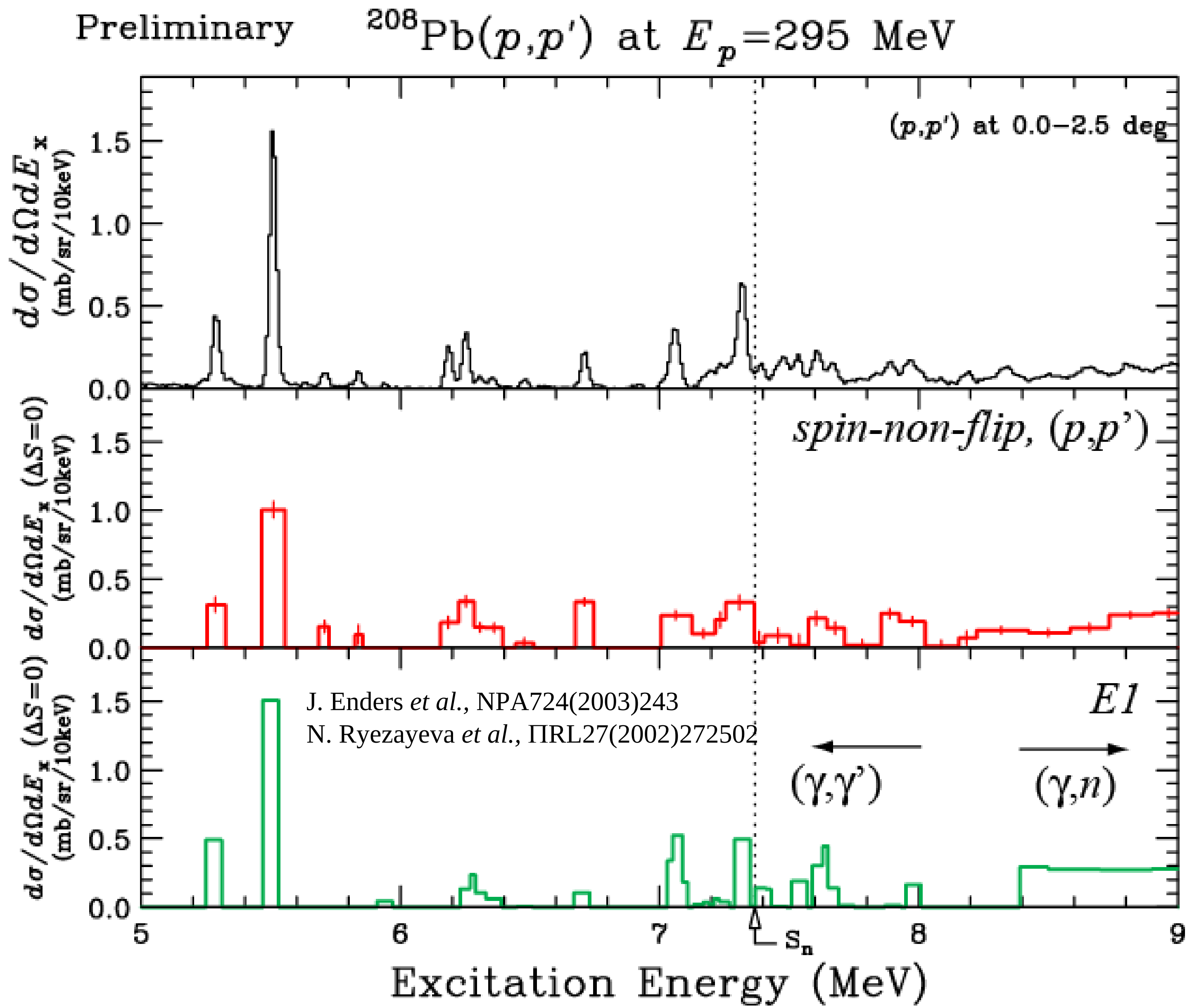

Preliminary
^{208}Pb(p,p') at E_p=295 MeV
(p,p') at 0.0−2.5 deg
dσ/dΩdE_x (mb/sr/10keV)
0.0
0.5
1.0
1.5
5
10
15
20
Excitation Energy (MeV)

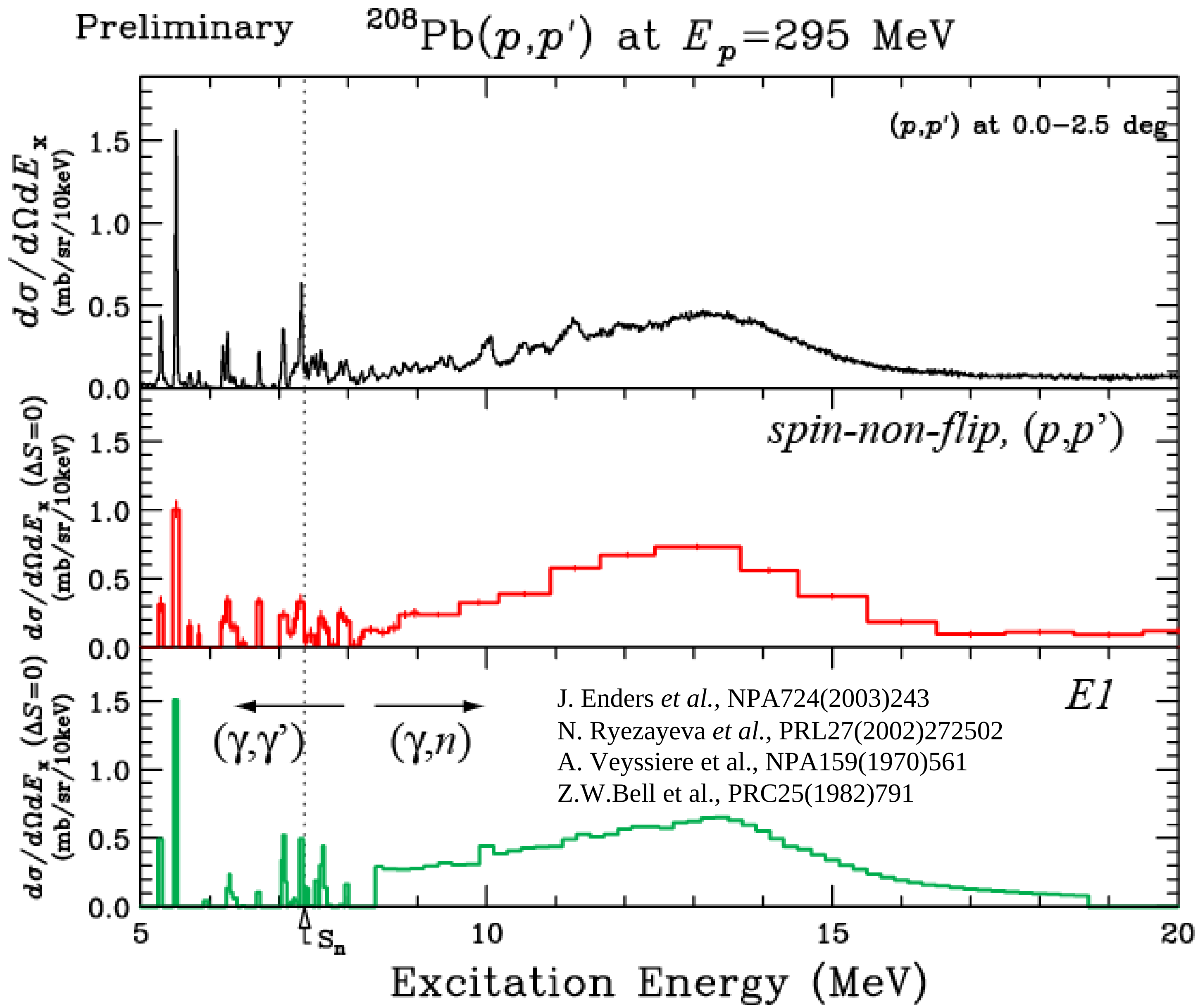

Preliminary
^{208}Pb(p,p') at E_p=295 MeV
(p,p') at 0.0–2.5 deg
dσ/dΩdE_x (mb/sr/10keV)
0.0
0.5
1.0
1.5
6
8
10
Excitation Energy (MeV)


Preliminary
^{208}Pb(p,p') at E_p=295 MeV
(p,p') at 0.0–2.5 deg
30 keV
dσ/dΩdE_x (mb/sr/10keV)
0.0
0.5
1.0
1.5
6
8
10
S_n
Excitation Energy (MeV)

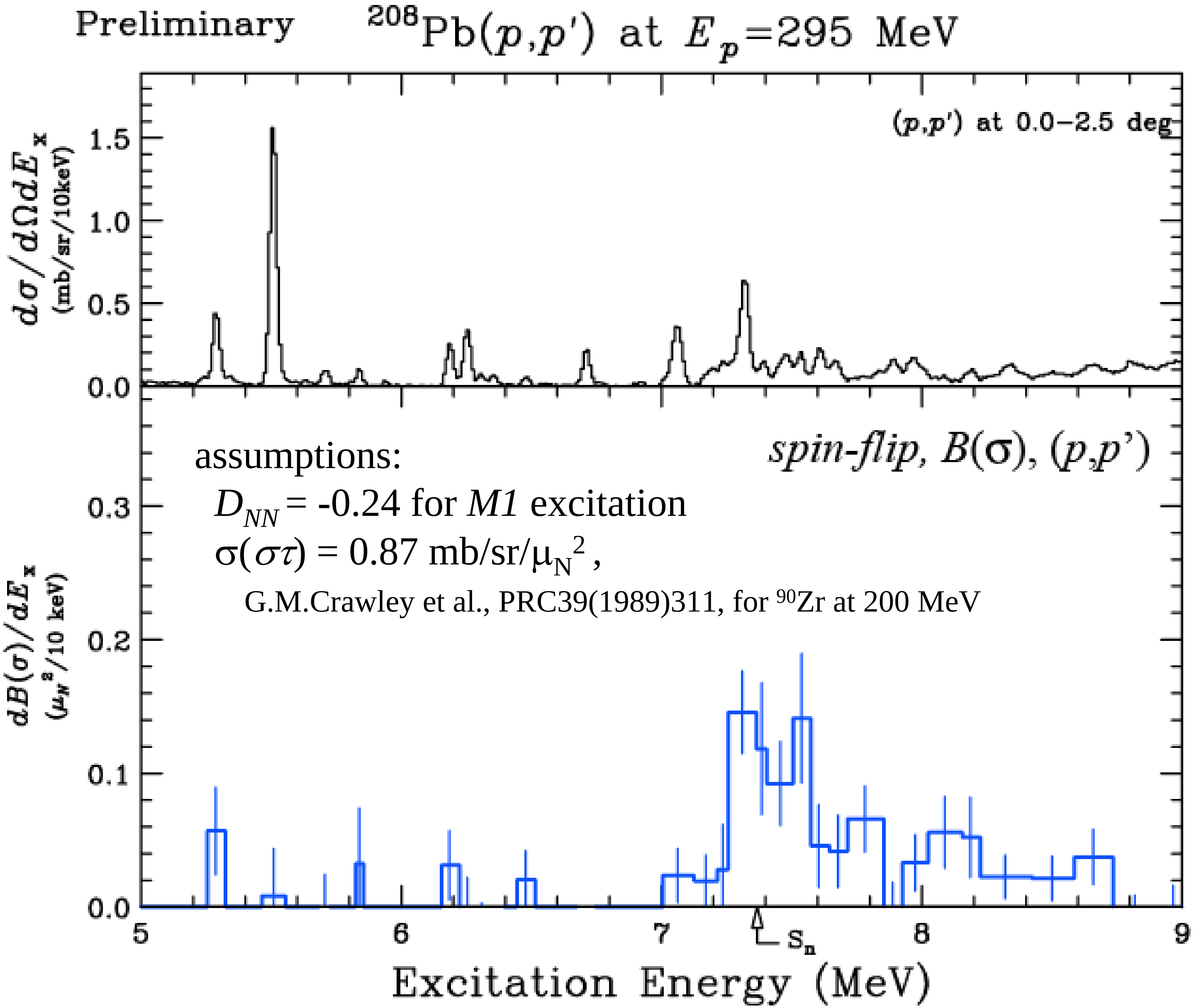


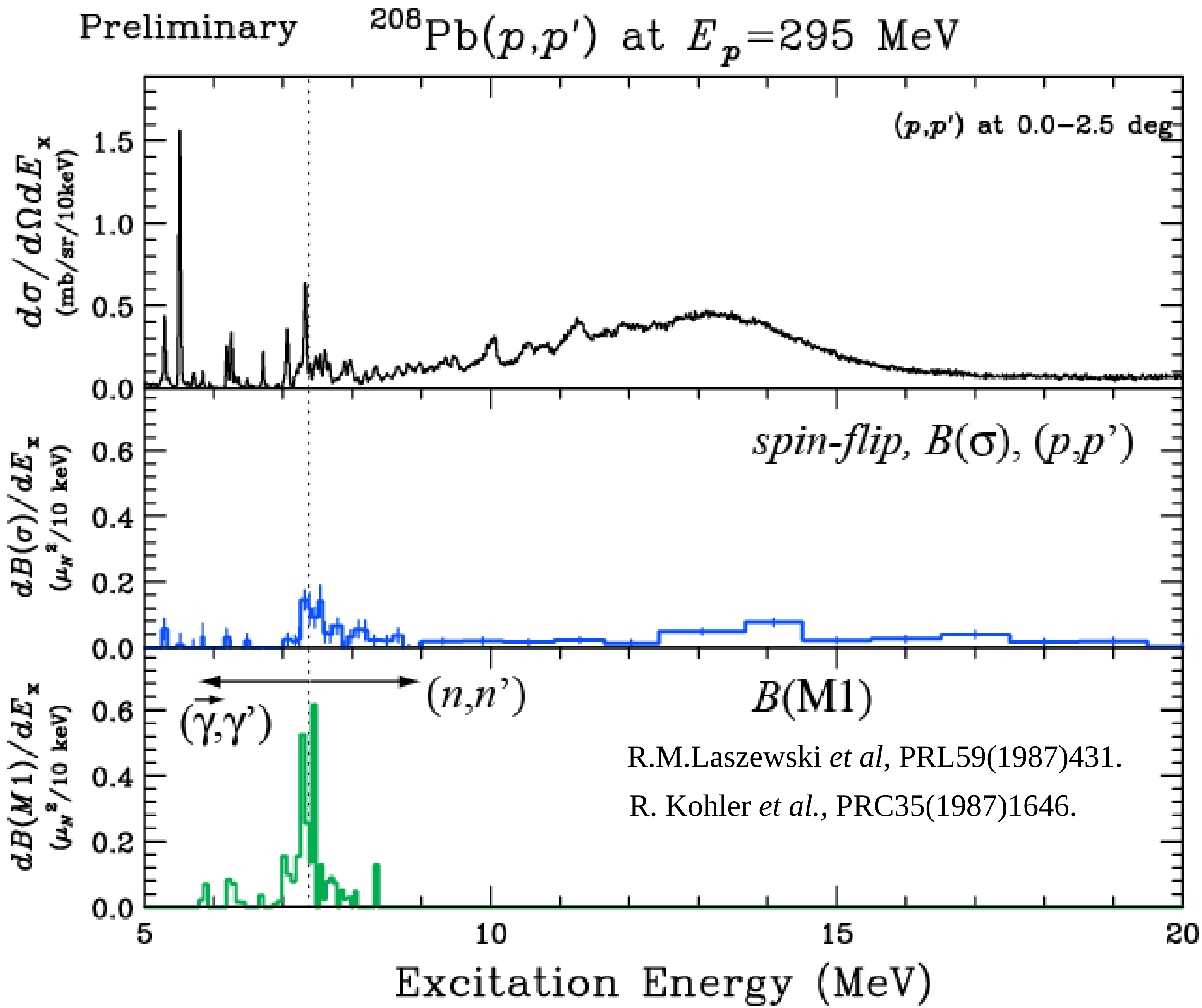
Preliminary
208Pb(p,p') at Ep=295 MeV
(p,p') at 0.0–2.5 deg
(γ,γ') Enders et al.
(γ,γ') Ryezayeva et al.
(γ,n) Laszweski et al.
1⁻; 5.292
1⁻; 5.512
2⁺; 5.716
1⁺; 5.845
1⁻; 5.947
+ 1⁻; 6.264
1⁻; 7.332
+ 1⁻; 7.410 + 1⁻; 7.416
1⁻,(1⁺,2⁺); 9.51
1⁻,(1⁺,2⁺); 9.65
1⁻,(1⁺,2⁺); 9.89
1⁻,(1⁺,2⁺); 10.06
Sn
dσ/dΩdEx (mb/sr/10keV)
Excitation Energy (MeV)
0.0
0.5
1.0
1.5
6
8
10


Preliminary
208Pb(p,p') at Ep=295 MeV
(p,p') at 0.0-2.5 deg
spin-non-flip, (p,p')
E1
J. Enders et al., NPA724(2003)243
N. Ryezayeva et al., ΠRL27(2002)272502
(γ,γ')
(γ,n)
dσ/dΩdEx (mb/sr/10keV)
dσ/dΩdEx (ΔS=0) (mb/sr/10keV)
Sn
Excitation Energy (MeV)



Preliminary
208Pb(p,p') at Ep=295 MeV
(p,p') at 0.0−2.5 deg
spin-non-flip, (p,p')
E1
(γ,γ')
(γ,n)
J. Enders et al., NPA724(2003)243
N. Ryezayeva et al., PRL27(2002)272502
A. Veyssiere et al., NPA159(1970)561
Z.W.Bell et al., PRC25(1982)791
dσ/dΩdEx (mb/sr/10keV)
dσ/dΩdEx (ΔS=0) (mb/sr/10keV)
Sn
Excitation Energy (MeV)


Preliminary
208Pb(p,p') at Ep=295 MeV
(p,p') at 0.0–2.5 deg
dσ/dΩdEx (mb/sr/10keV)
spin-flip, B(σ), (p,p')
assumptions:
DNN = -0.24 for M1 excitation
σ(στ) = 0.87 mb/sr/μN2 ,
G.M.Crawley et al., PRC39(1989)311, for 90Zr at 200 MeV
dB(σ)/dEx (μN2/10 keV)
Sn
Excitation Energy (MeV)


Preliminary
208Pb(p,p') at Ep=295 MeV
(p,p') at 0.0–2.5 deg
dσ/dΩdEx (mb/sr/10keV)
spin-flip, B(σ), (p,p')
dB(σ)/dEx (μN2/10 keV)
(γ,γ')
(n,n')
B(M1)
dB(M1)/dEx (μN2/10 keV)
R.M.Laszewski et al, PRL59(1987)431.
R. Kohler et al., PRC35(1987)1646.
Excitation Energy (MeV)

Summaryに代えて

坂口先生の貢献

RCNP-RINGの物理に関して

- 中性子密度分布(陽子弾性散乱)
- ISGDR, ISGMRの系統的測定と核の非圧縮率
- 12Cの2nd 2^+状態

多くの学生をこの分野に引き込んだ

多くの研究者を輩出

今後も大いに研究を楽しんで下さい！