高分解能(*p*,*p*’)反応による *M1*, *E1* 励起状態の研究

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Contents

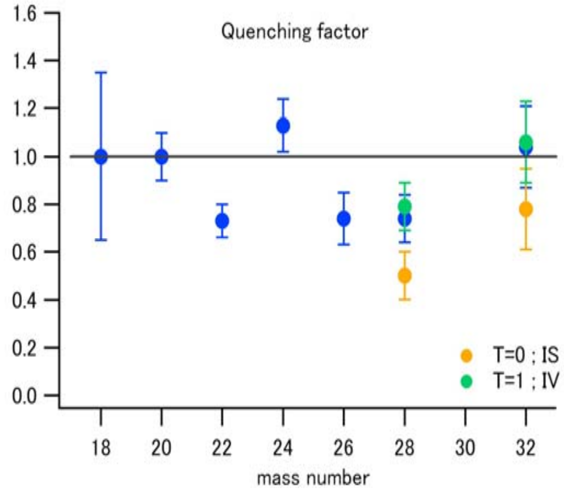
- High-Resolution (*p*,*p*’) scattering experiment at forward angles: motivation
- Experiment and Spectra
- M1 and E1 excitations in ^{208}Pb

(開発・実験はAVF更新をまたいで進められた)

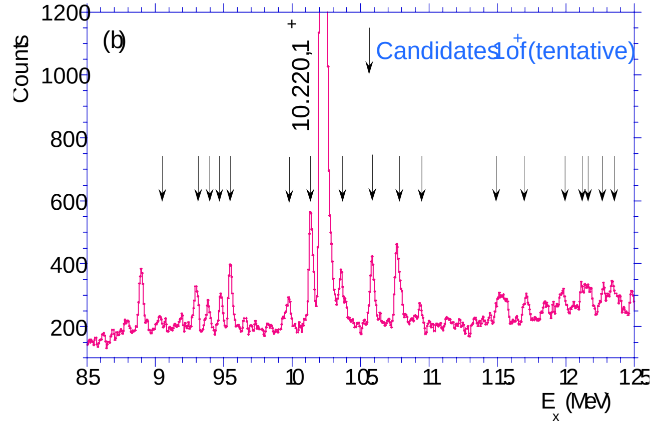
High-resolution (*p*,*p*’) scattering exeperiment at forward angles

Motivation

1. Systematic study of M1 excitation: strength distribution and quenching for each *T*=0 and *T*=1 excitation.
   M1: $0^+ \rightarrow 1^+$, ΔL=0, ΔS=1
   analogous to Gamow-Teller
2. Fragmentation mechanism of M1 Strengths.
3. New or exotic type excitations in nuclei. Toroidal type excitations?
4. Nuclear matrix element of (ν,ν')
   E1 strengths around S_n
   supernovae, nucleosynthesis



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



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

Merit of (*p*,*p*') scattering measurement at 0 deg. (1/2)

- $\Delta L=0$ excitations are favored at 0° (expt. Coulomb excitation of E1)
- ΔL information can be obtained from angular distribution of $d\sigma/d\Omega$ at forward angles.
- $d\sigma/d\Omega$ at 0° is approximately proportional to the relevant reduced matrix elements.

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

- ΔS is model-independently identified by measuring polarization transfer coefficients at 0° (ΔS decomposition of the strengths)

$$D_{SS} + D_{NN} + D_{LL} = \begin{cases} -1 \text{ for } \Delta S = 1 & \text{e.g. M1} \\ 3 \text{ for } \Delta S = 0 & \text{e.g. E1} \end{cases}$$

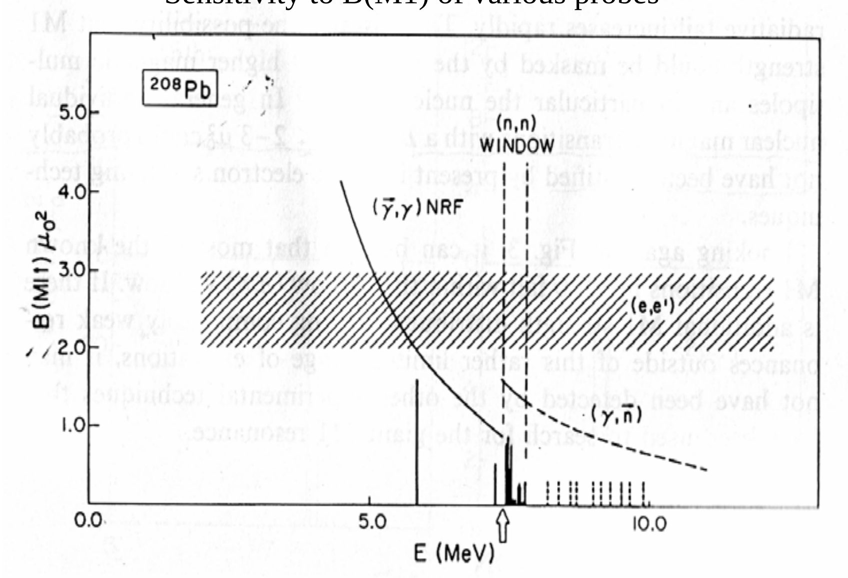
T.Suzuki, PTP103(2000)859

- High-resolution measurement (20 keV) is possible.
- Other reaction data, *e.g.* (*d*,*d*'), (α,α'), (^{3}He, *t*), (γ,γ') and (*e*,*e*'), provide complementary information

Merit of (*p,p'*) scattering measurement at 0 deg. (2/2)

- Excitation strengths can be measured in a wide E_x range ($5<E_x<25$ MeV) by a "single-shot" measurement (missing-mass spectroscopy)
  - independent of the decay channel
  - flat and high detection efficiency
  - total width (or total excitation strength)

Sensitivity to B(M1) of various probes



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

- Comparison with (*e,e'*)
  - complimentary:
    B(σ) by (*p,p'*) ⇔ *B*(*M1*) by (*e,e'*)
  - no radiative tail
  - large cross-section
  - reaction mechanism is not "very well-known"

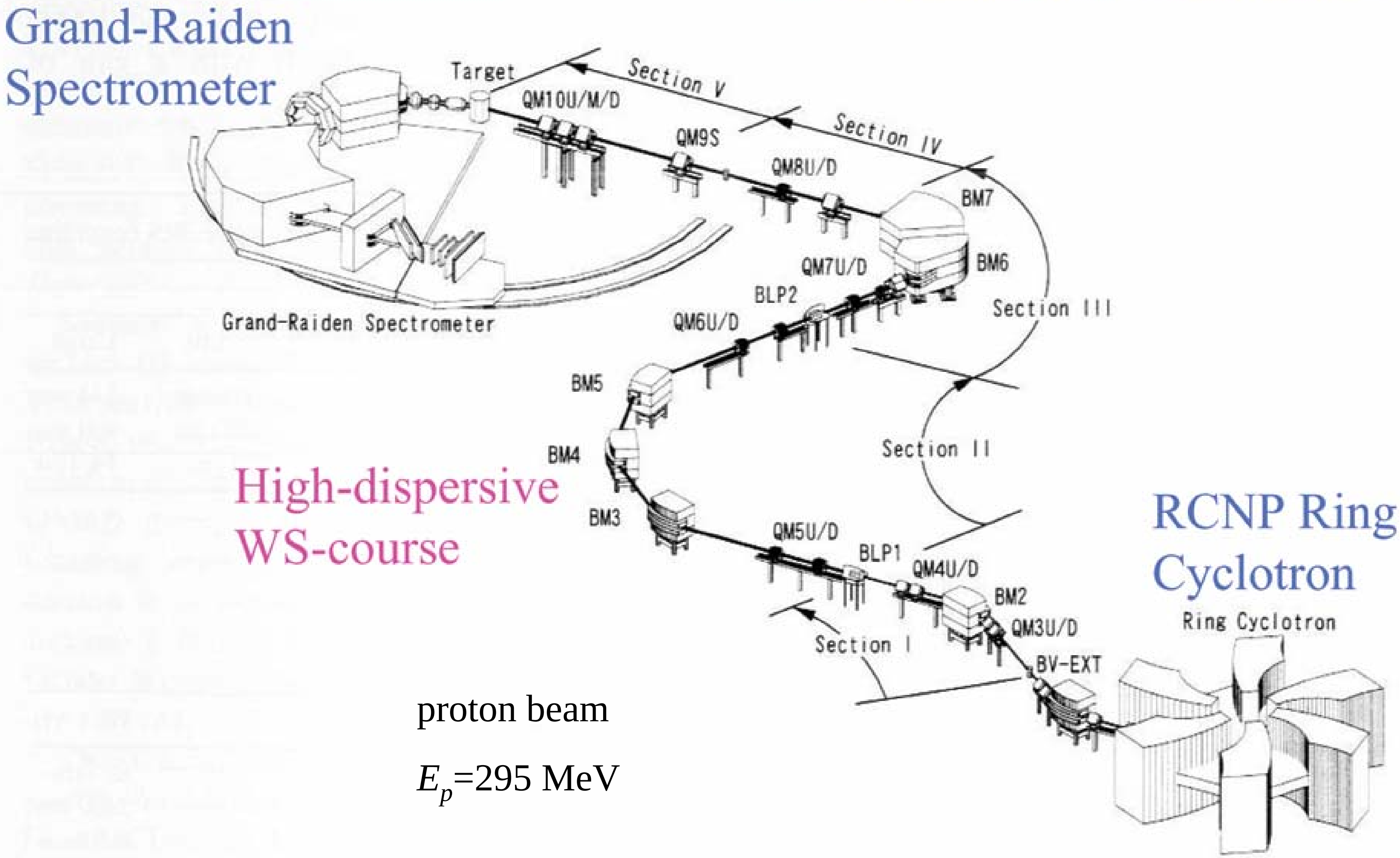
Demerits

- Reduction of instrumental B.G. is essential
  ... requires a high-quality halo-free beam and beam stability
- Absolute normalization of the strength is not very straightforward

Experiment

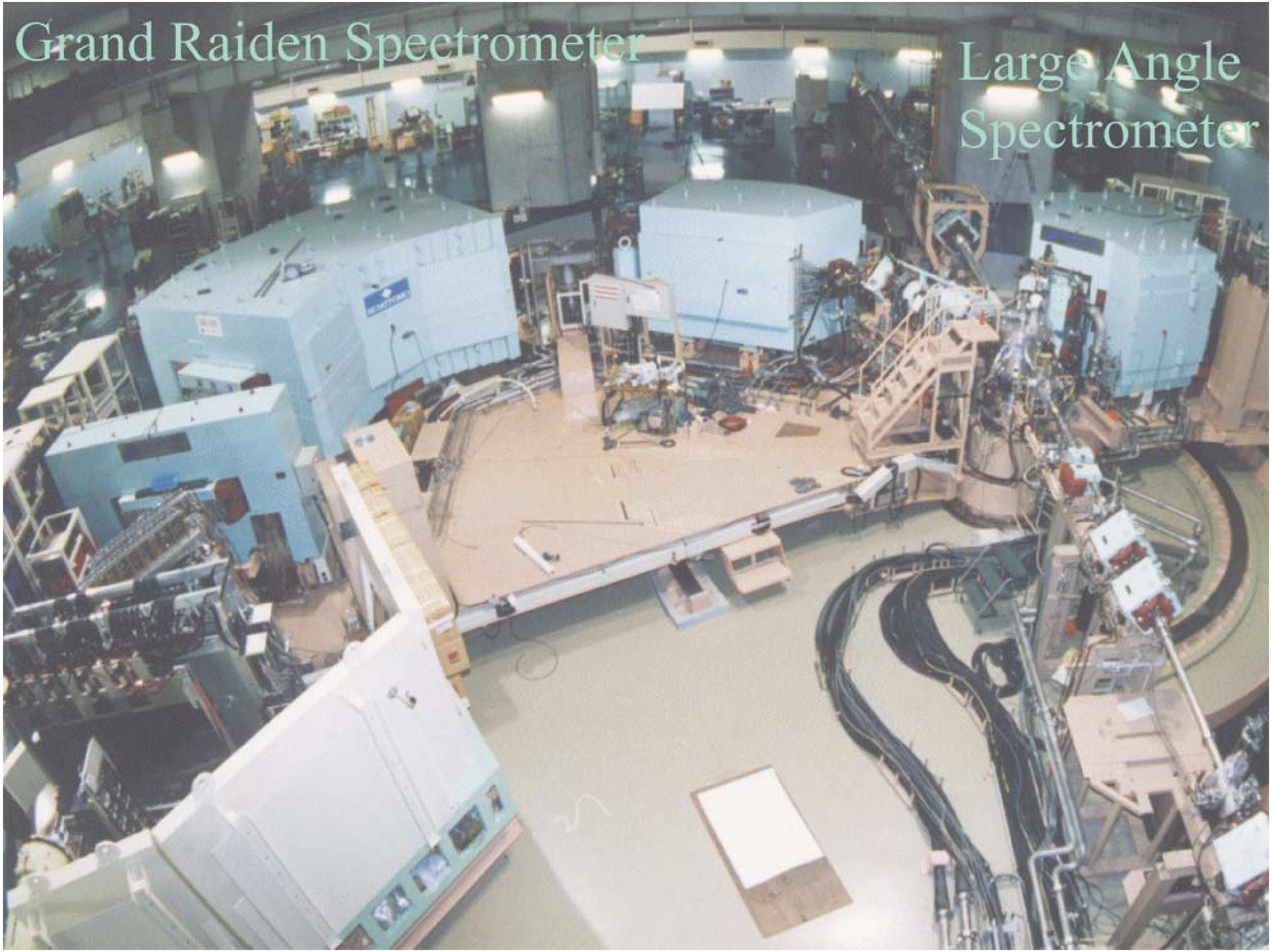
Beam line WS-course

T. Wakasa et al., NIM A482 ('02) 79.



proton beam

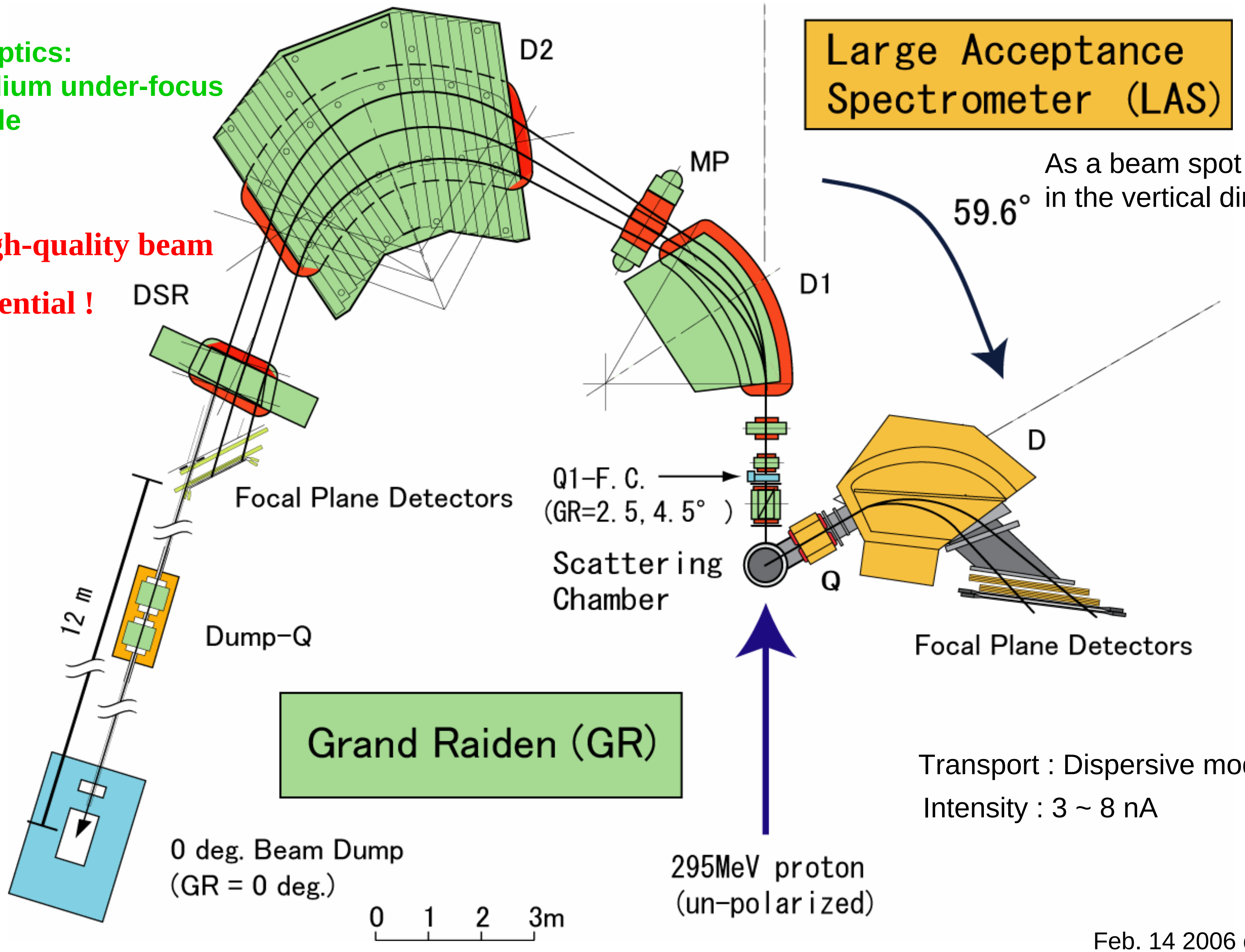
E_p=295 MeV


Grand Raiden Spectrometer
Large Angle
Spectrometer

Spectrometers in the 0-deg. experiment setup

Ion optics:
Medium under-focus mode

A high-quality beam is essential !



As a beam spot monitor in the vertical direction

Transport : Dispersive mode

Intensity : 3 ~ 8 nA

Beam Tuning

- Beam energy spread was checked by $^{197}Au(p,p_0)$ elastic scattering in the achromatic transport mode

  40-60 keV (FWHM) at E_p=295 MeV

  It corresponds to a beam spot size of
  3~5 mm on target
  in the dispersive transport mode.

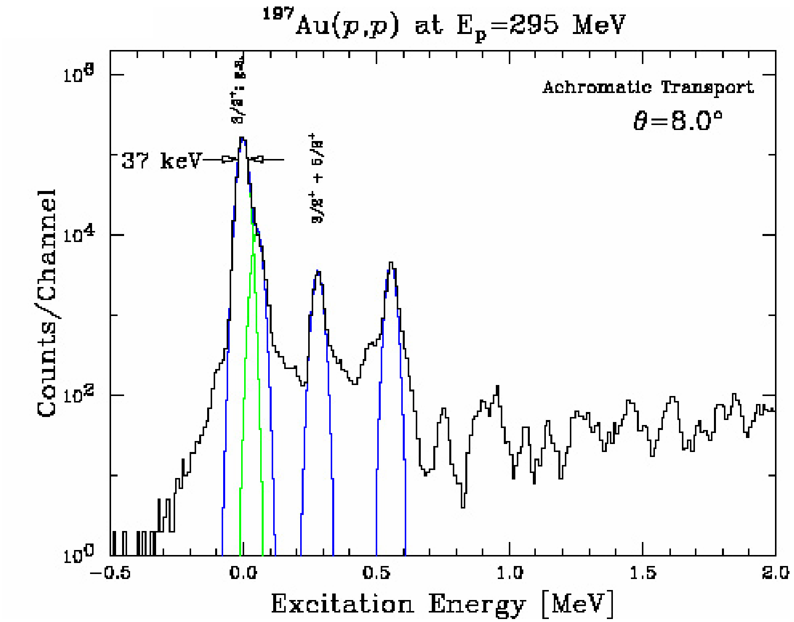
- Halo free beam tuning at 0 deg. (achro. beam)
  Single turn extraction of the AVF cyclotron

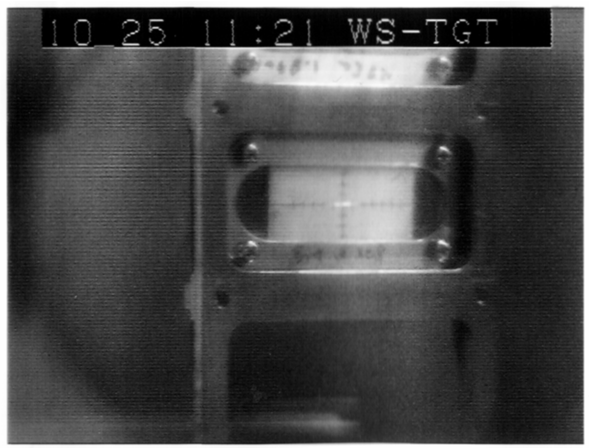
- Tuning of dispersion matching

  20 keV (FWHM) at E_p=295 MeV

It takes ~2 days for the beam tuning.

Comment: Combination of high-res. measurement and decay measurement is now becoming feasible.





Beam spot in the dispersive mode

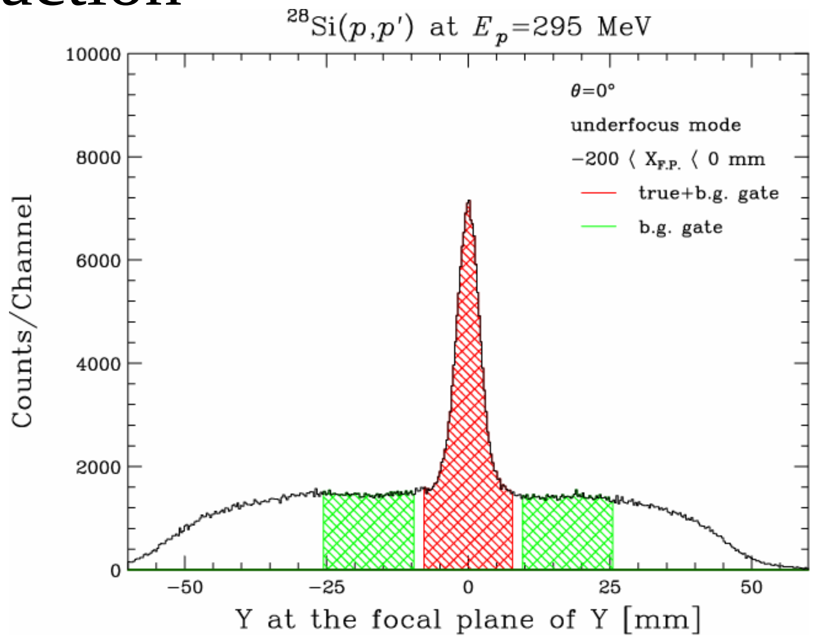
Background Subtraction

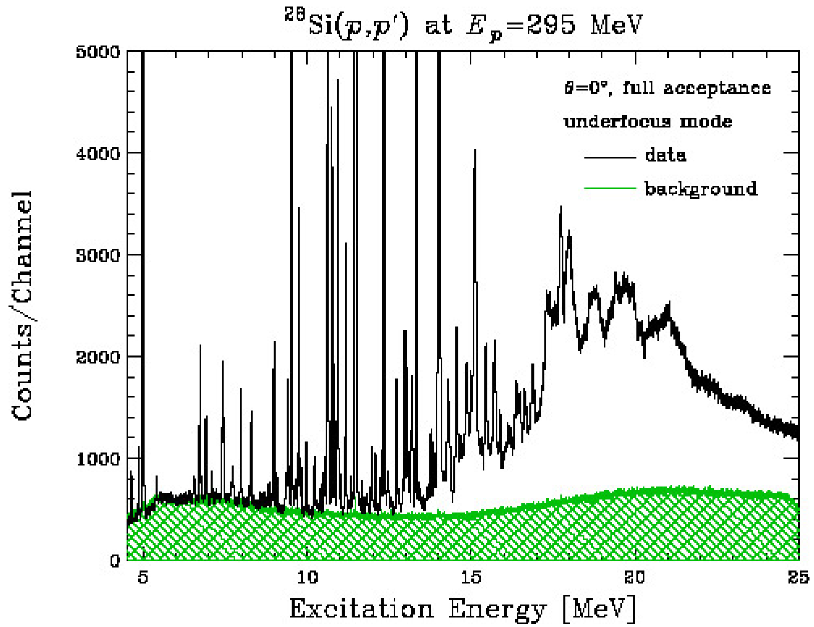
Vertical positions projected at the vertical focal plane were calculated.

Background subtraction was applied by gating the Y position with true+b.g. and b.g. gates.

Linear shape of the background in the Y position spectrum is assumed.

The background spectrum seems reasonable.





Targets and Angles

	0°	2.5°	4.5°	6°	9,12,15,18°	achrom. 0°	elastic	thickness (mg/cm^2)
^{nat}C	◎	◎	◎	◎	◎	◎	◎	30 (partly 1.1)
mylar	◎	◎	◎	−	−	−	−	10
$^{13}CH_2$	○	−	−	−	−	−	−	0.7
^{24}Mg	○	−	−	−	−	−	−	1.8
^{25}Mg	○	○	○	−	−	−	−	4.00
^{26}Mg	◎	◎	◎	◎	−	−	−	1.55
^{27}Al	○	−	−	−	−	−	−	1.8
^{28}Si	◎	◎	◎	◎	◎	◎	◎	1.86 (58.5 a part of elastic)
^{40}Ca	○	−	−	−	−	−	−	13
^{48}Ca	◎	◎	◎	−	−	−	−	1.9
^{58}Ni	◎	◎	◎	−	−	−	−	4
^{64}Ni	◎	◎	◎	−	−	−	−	4.7
^{90}Zr	△	−	−	−	−	−	−	1.0
^{120}Sn	△	−	−	−	−	−	−	2.6
^{208}Pb	◎	◎	◎	◎	−	−	−	5.2

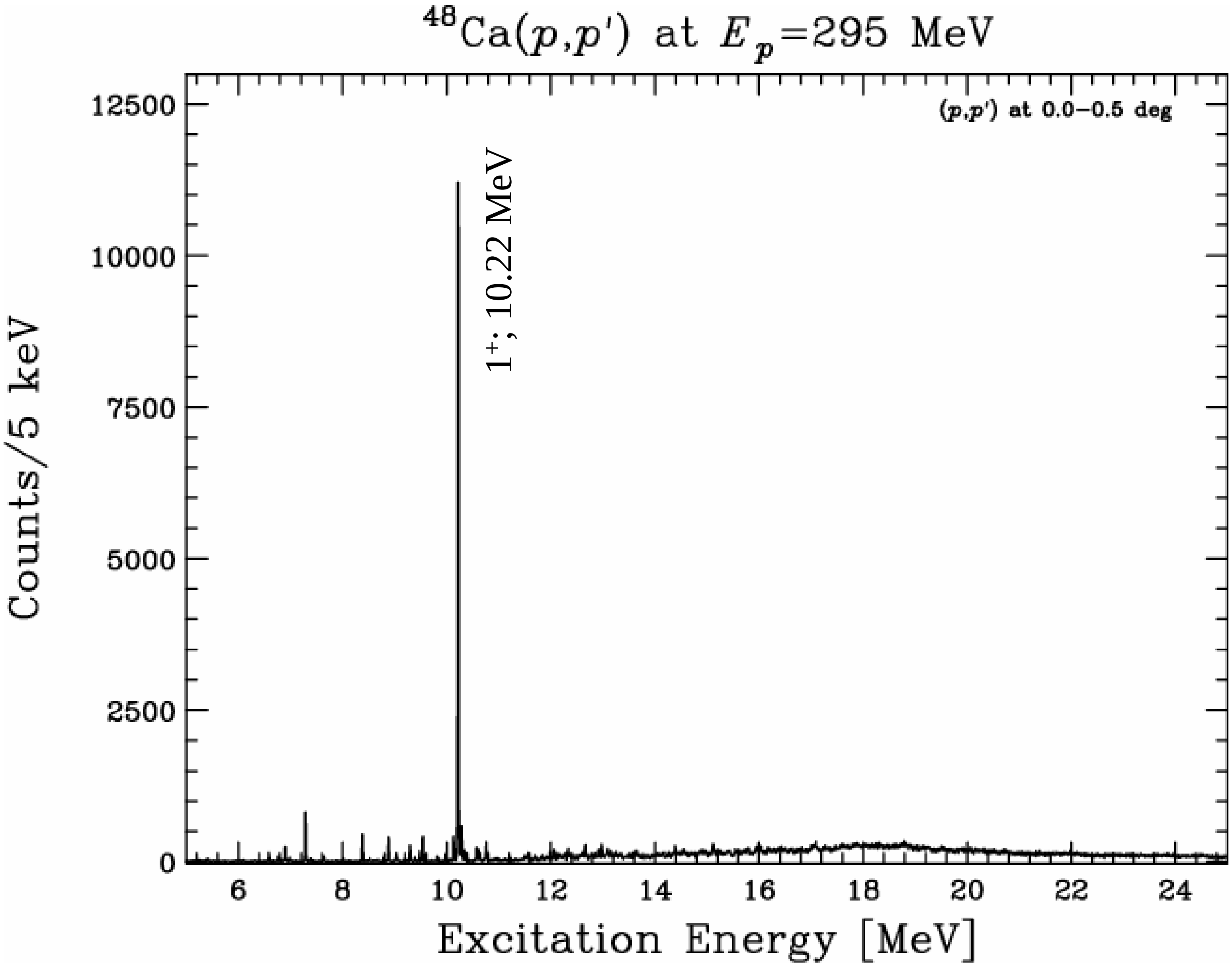
○... measured, ◎... good statistics, △... poor statistics, −... not measured

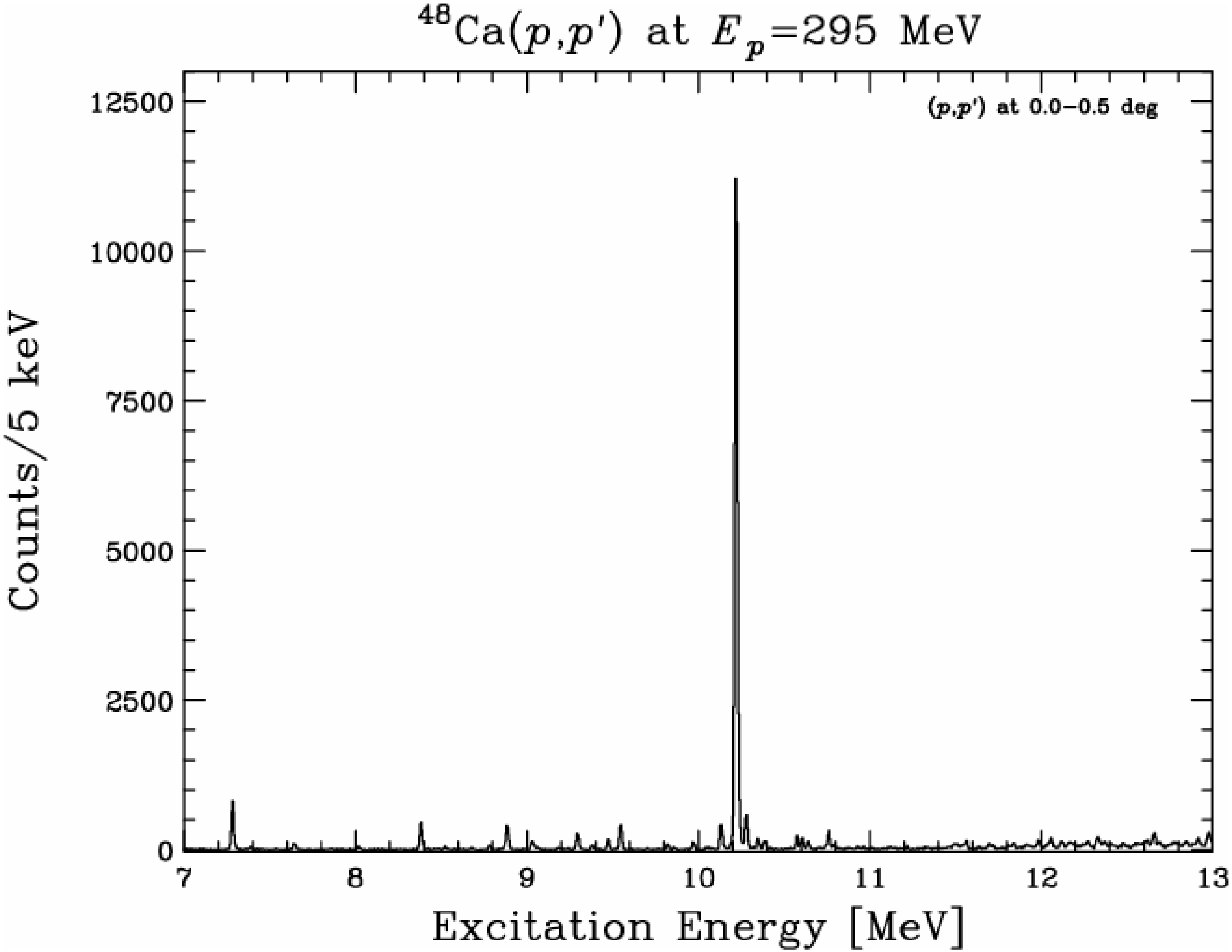
Analysis

Detailed calibrations have mostly been finished.

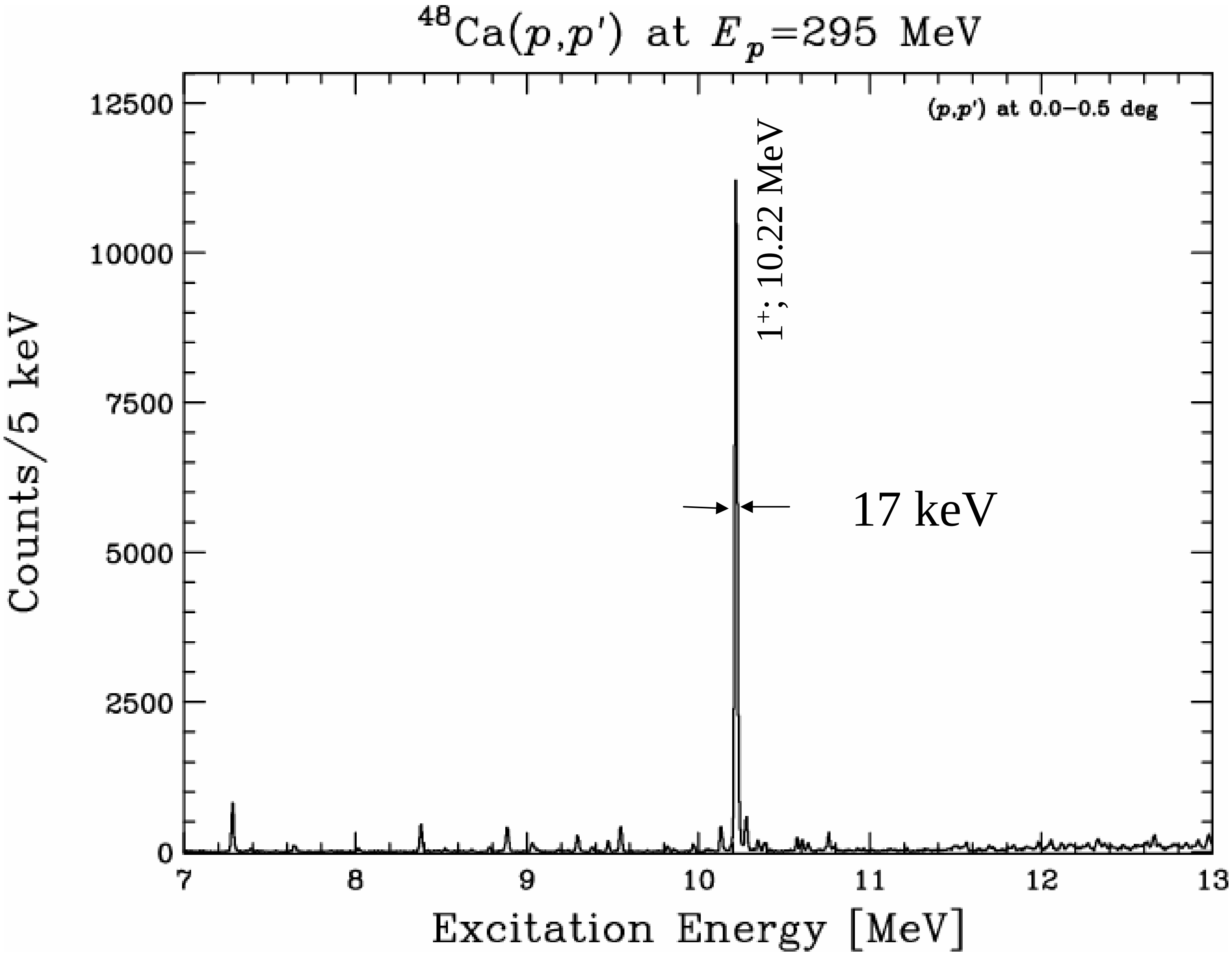
- Calibration of the scattering angle, solid angle.
  $\Delta\theta \sim 0.6^\circ$
- Calibration for high energy-resolution data.
  $\Delta E \sim 20$ keV
- Background subtraction
  works well
- Absolute cross sections and continuous angular distribution
  from 0 deg to large angles

Spectra

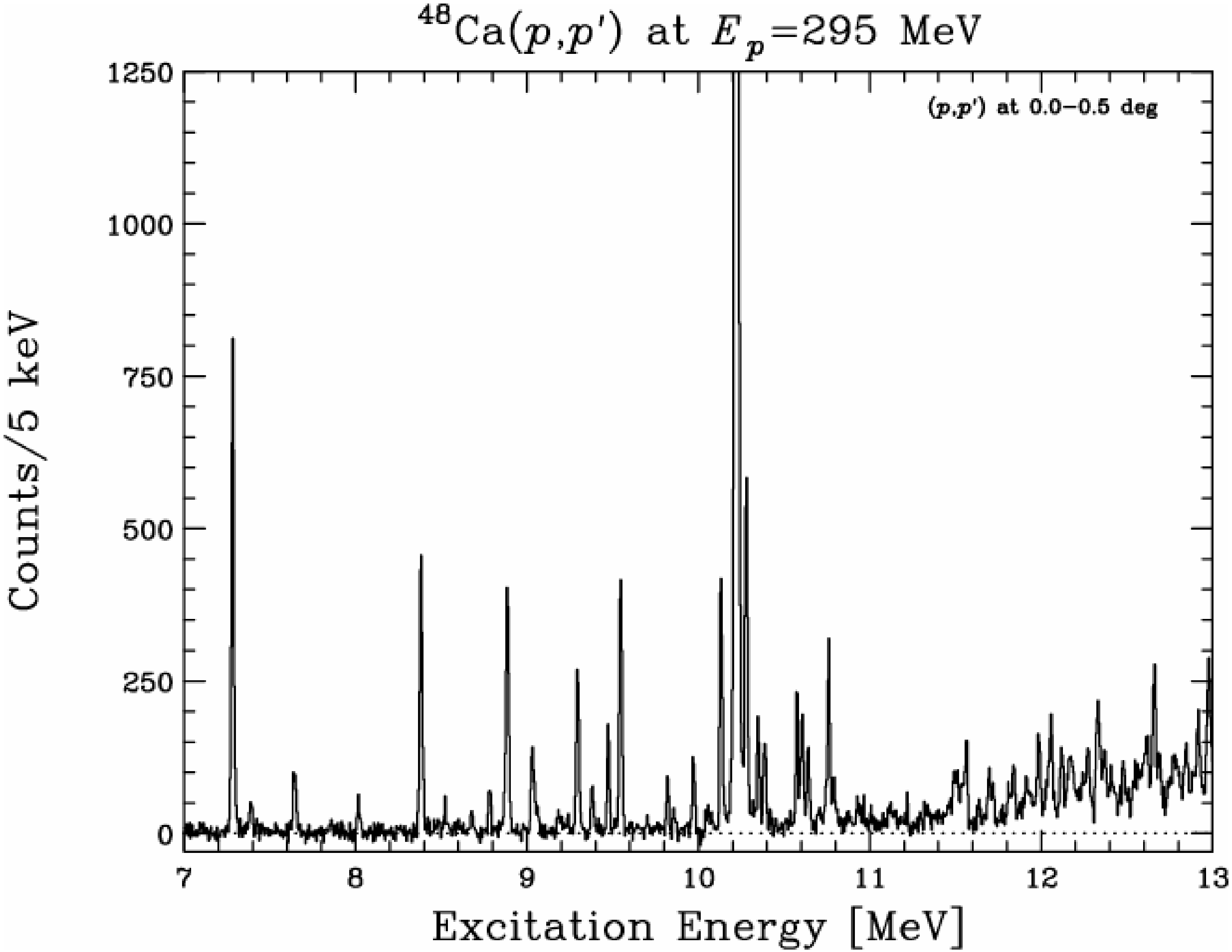

^{48}Ca(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
1^+; 10.22 MeV
Counts/5 keV
Excitation Energy [MeV]
12500
10000
7500
5000
2500
0
6
8
10
12
14
16
18
20
22
24



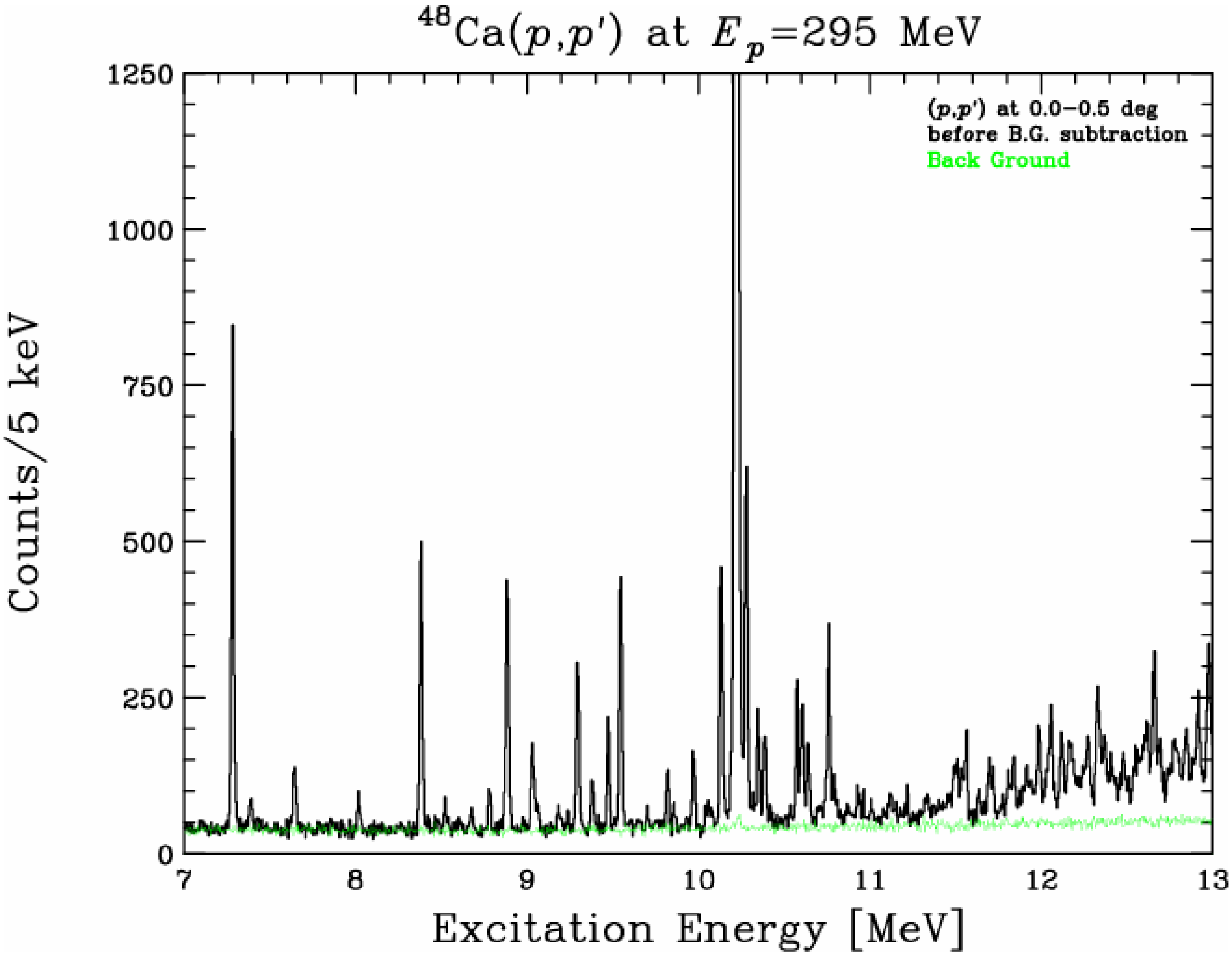
^{48}Ca(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
Counts/5 keV
12500
10000
7500
5000
2500
0
7
8
9
10
11
12
13
Excitation Energy [MeV]



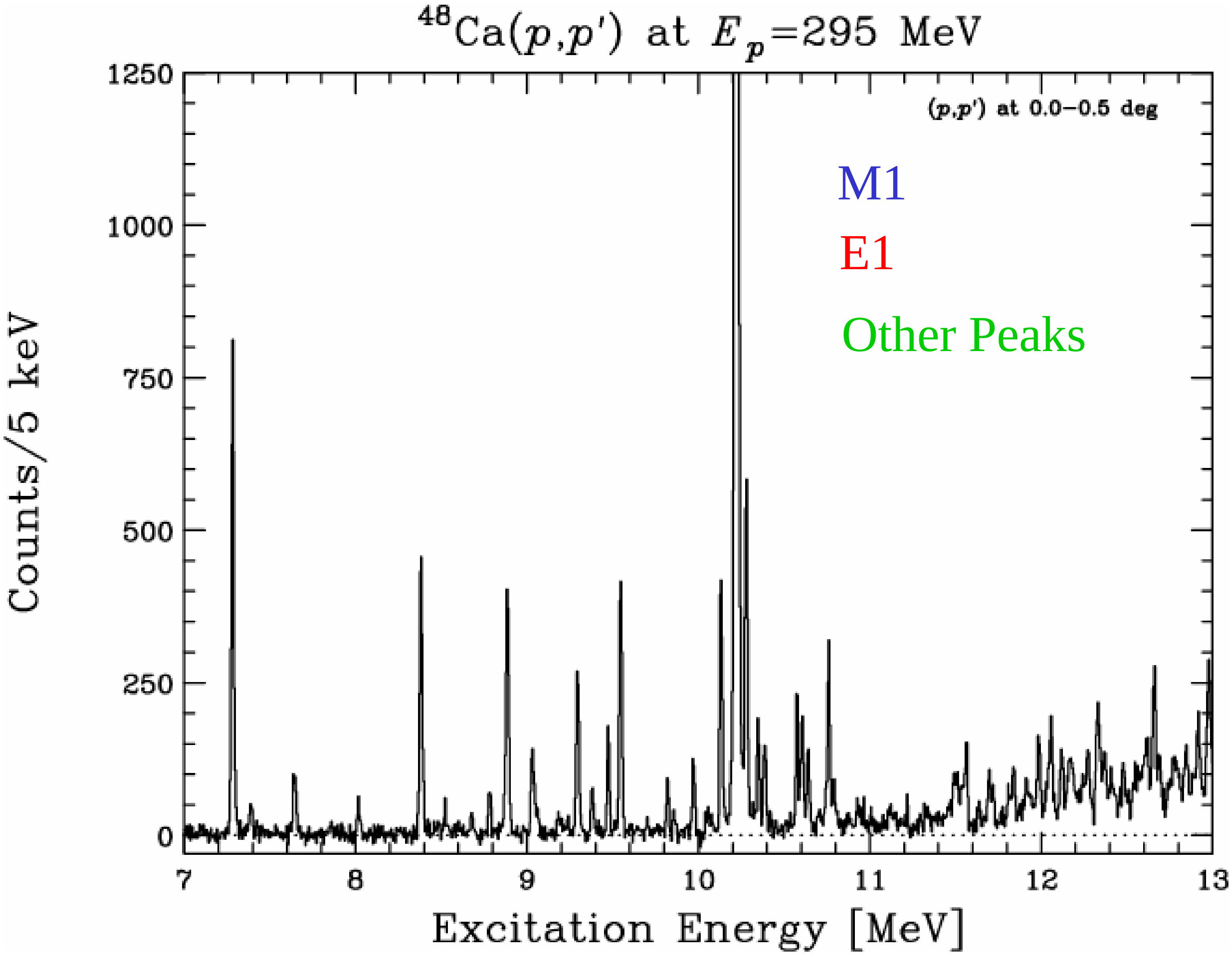
$^{48}Ca(p,p')$ at E_p=295 MeV
(p,p') at 0.0–0.5 deg
1^+; 10.22 MeV
17 keV
Counts/5 keV
12500
10000
7500
5000
2500
0
7
8
9
10
11
12
13
Excitation Energy [MeV]



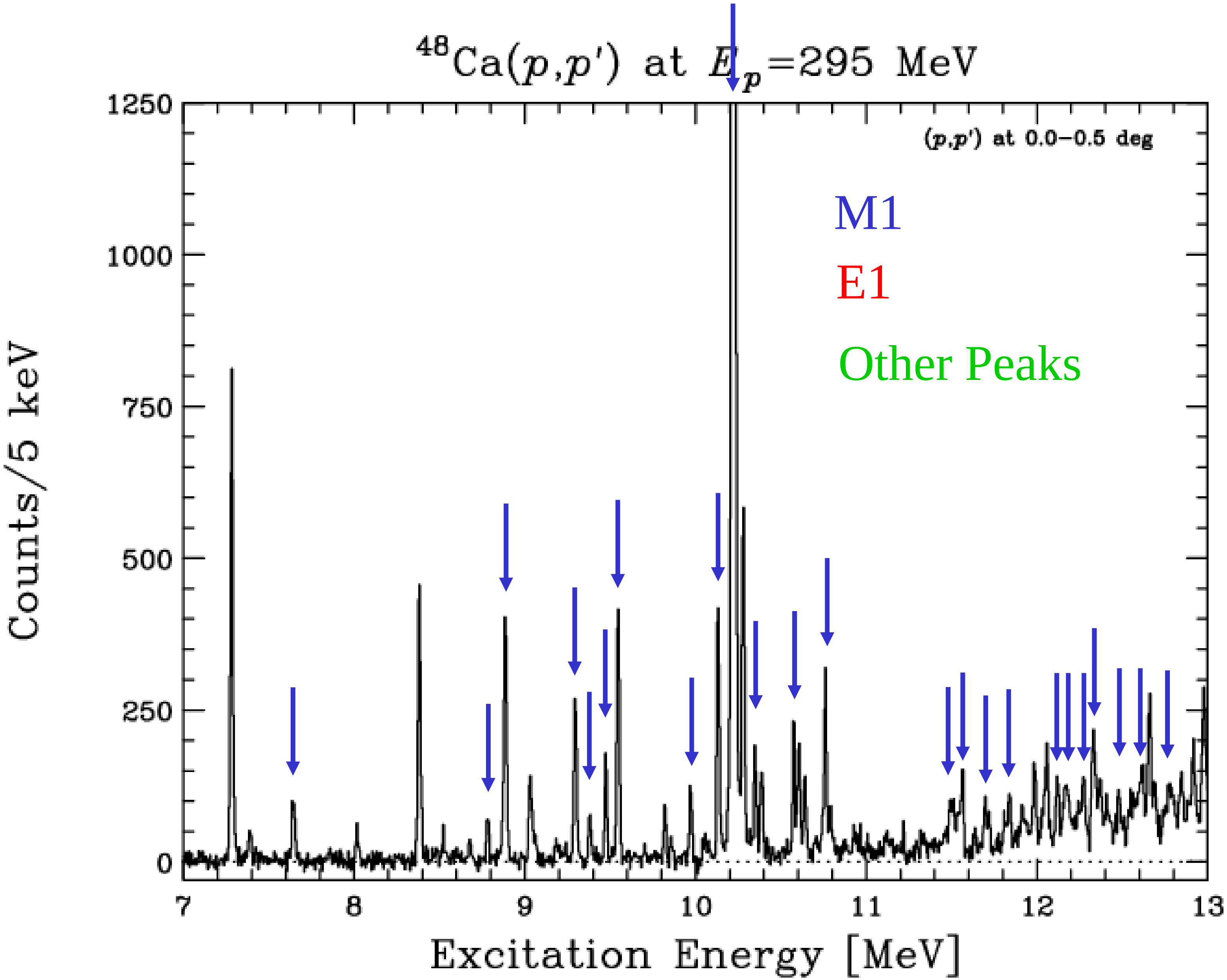
^{48}Ca(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
Counts/5 keV
1250
1000
750
500
250
0
7
8
9
10
11
12
13
Excitation Energy [MeV]

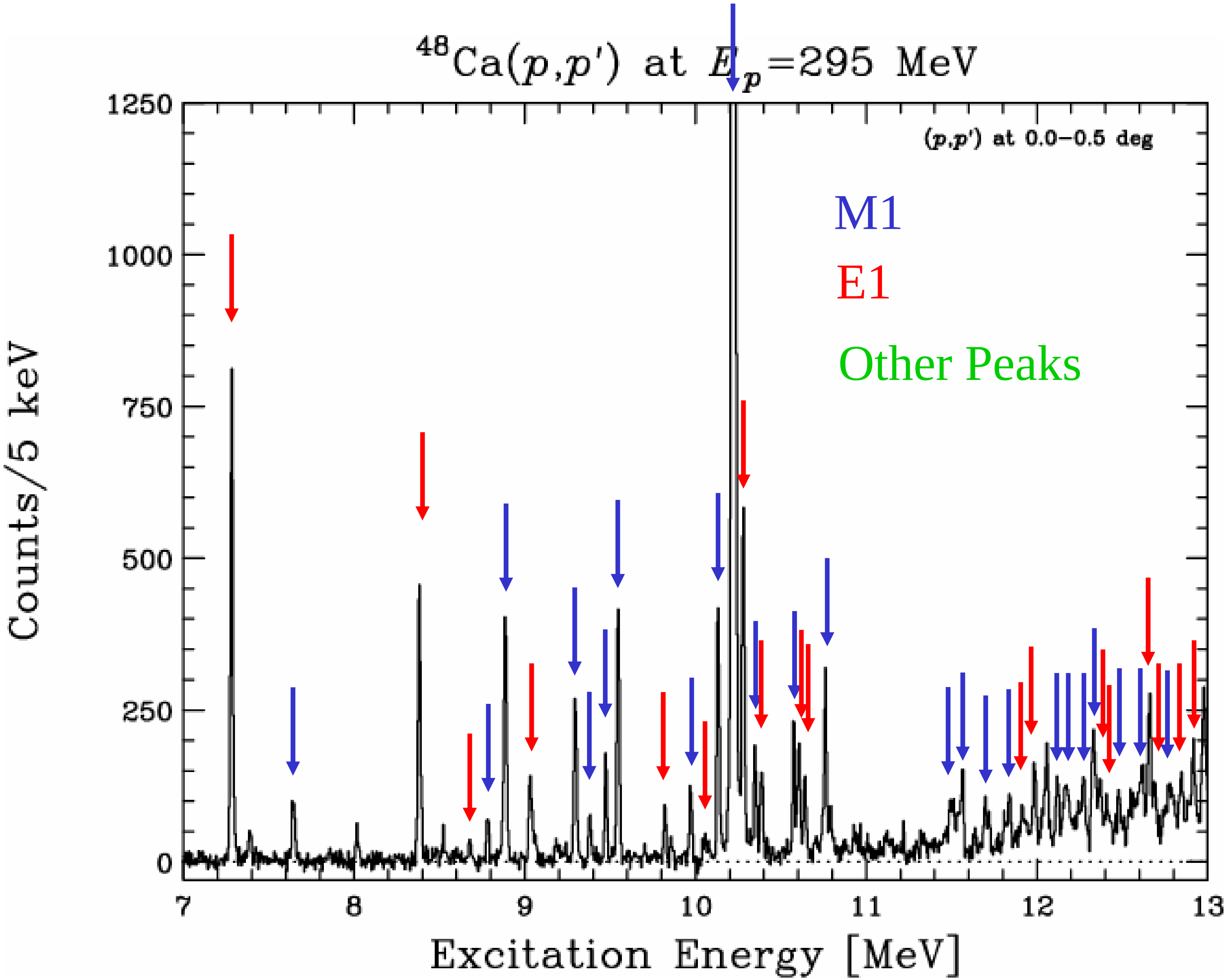


48Ca(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
before B.G. subtraction
Back Ground
Counts/5 keV
Excitation Energy [MeV]
0
250
500
750
1000
1250
7
8
9
10
11
12
13

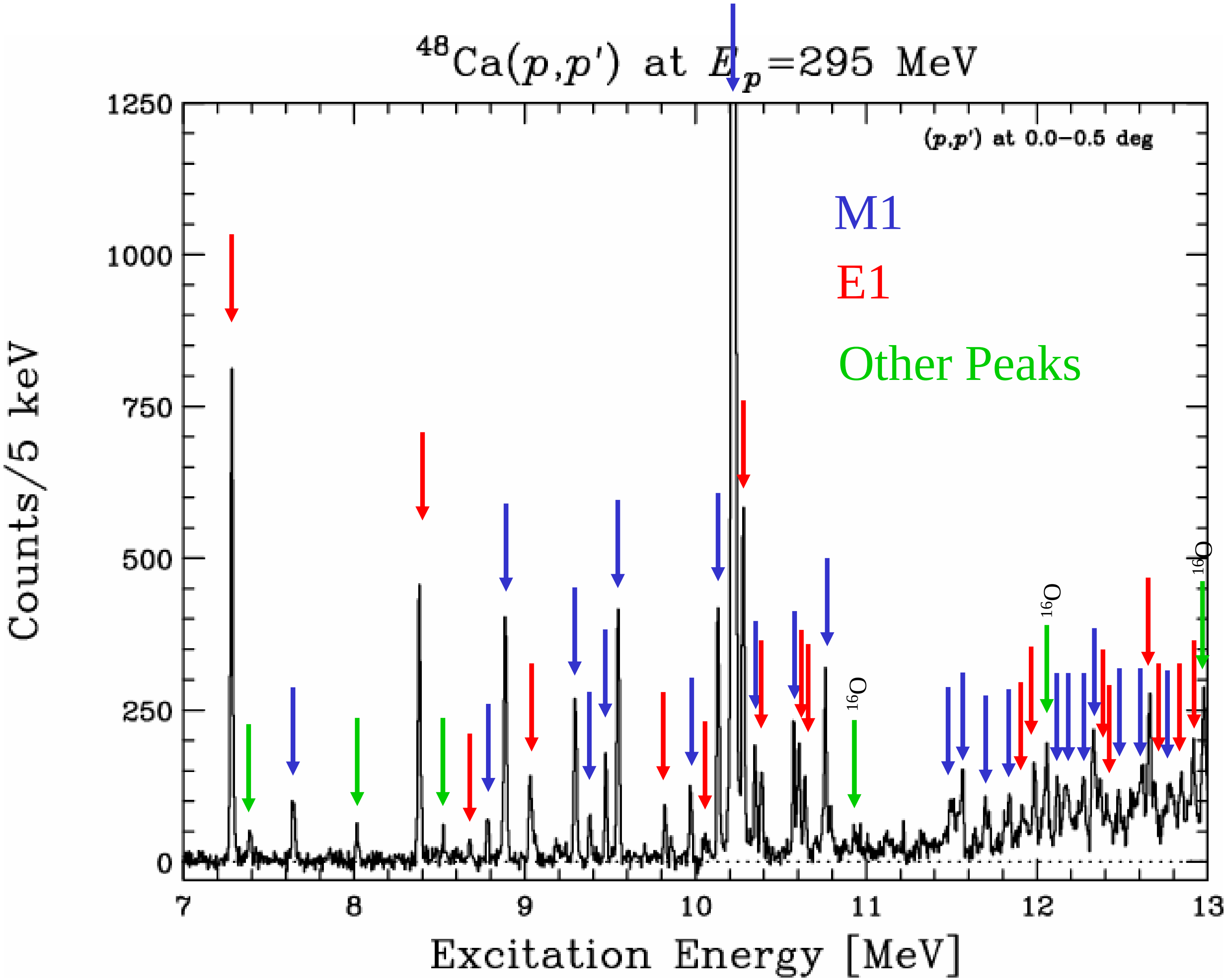


^{48}Ca(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
M1
E1
Other Peaks
Counts/5 keV
Excitation Energy [MeV]
1250
1000
750
500
250
0
7
8
9
10
11
12
13

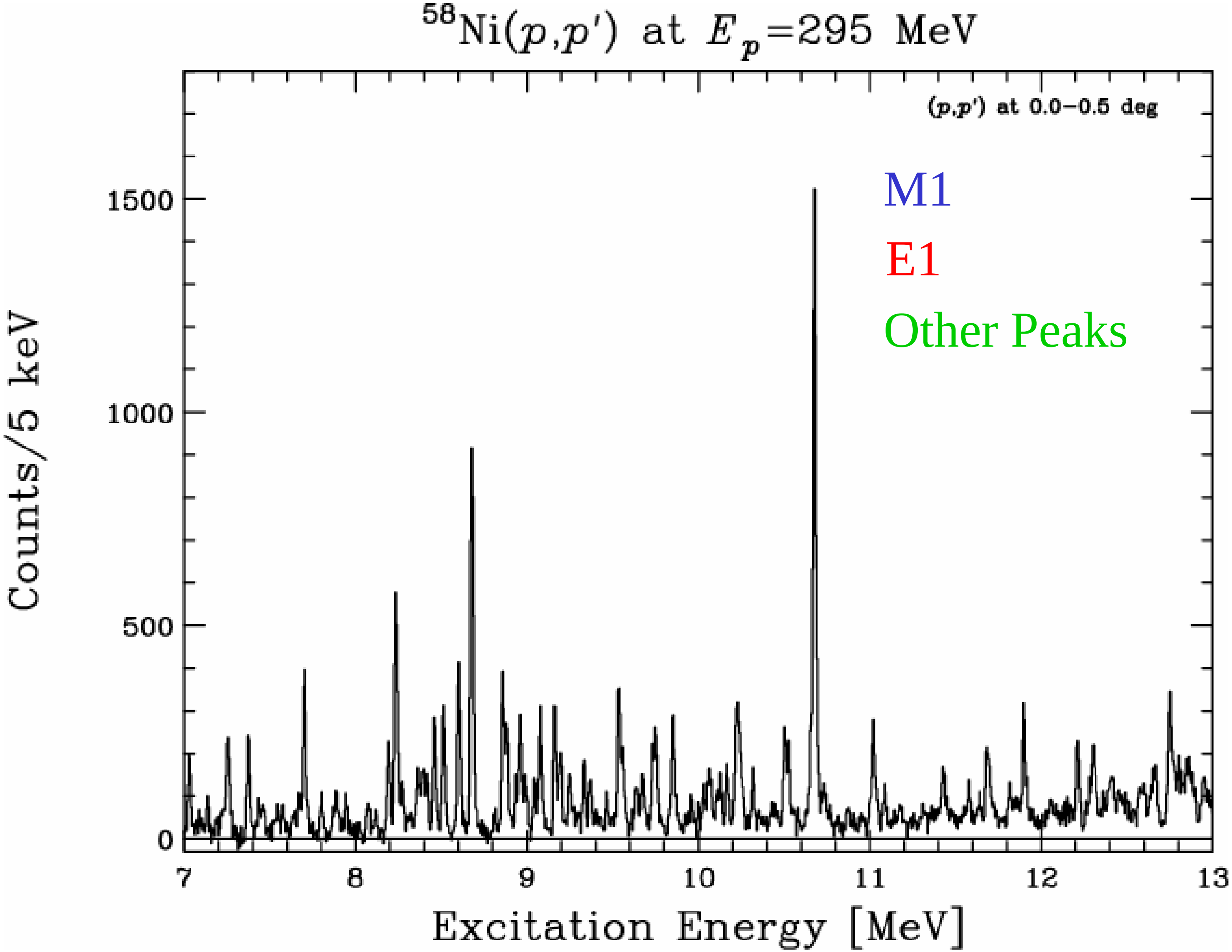

^{48}Ca(p,p') at E_p=295 MeV
(p,p') at 0.0−0.5 deg
M1
E1
Other Peaks
Counts/5 keV
Excitation Energy [MeV]
1250
1000
750
500
250
0
7
8
9
10
11
12
13



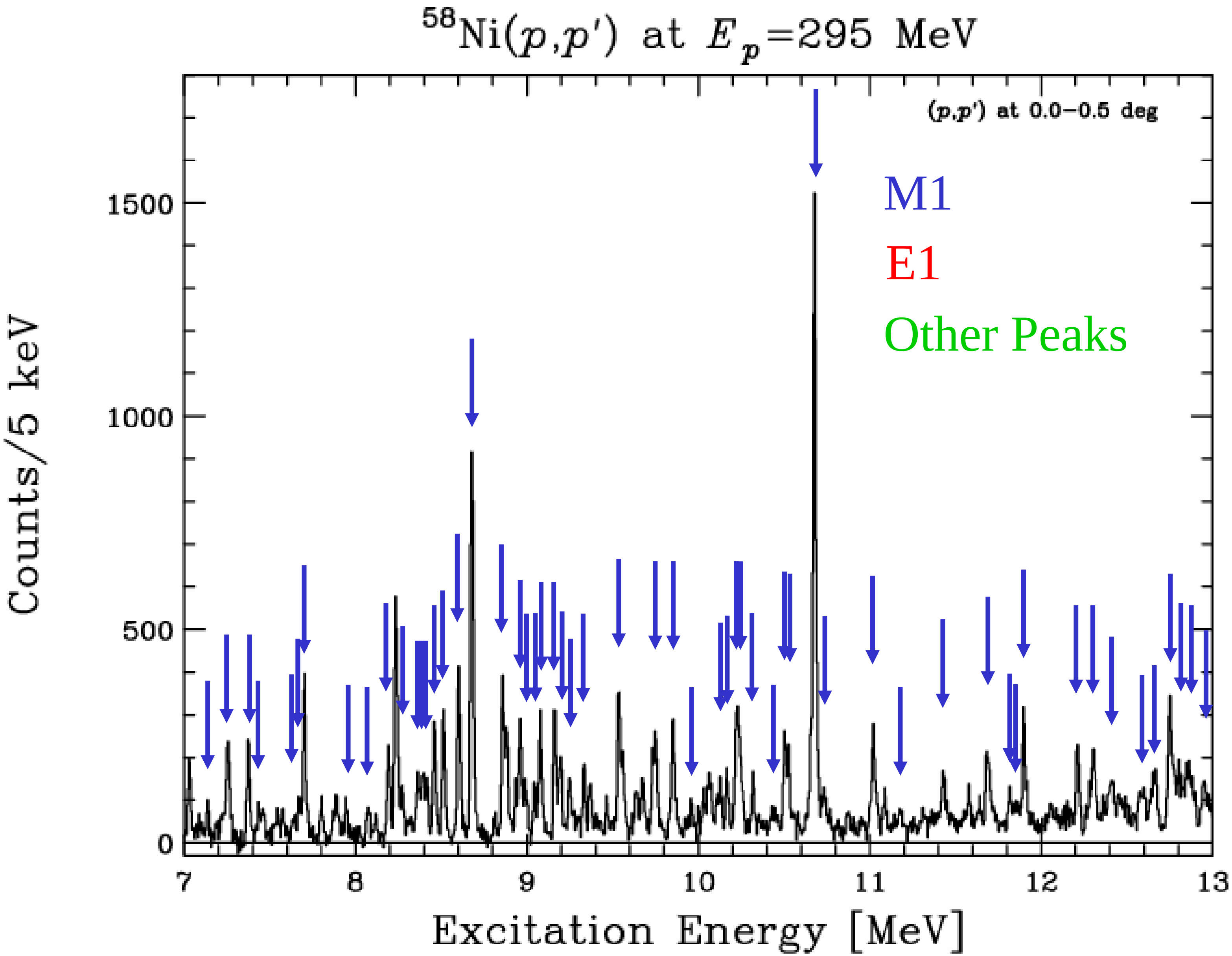
^{48}Ca(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
M1
E1
Other Peaks
Counts/5 keV
Excitation Energy [MeV]
1250
1000
750
500
250
0
7
8
9
10
11
12
13



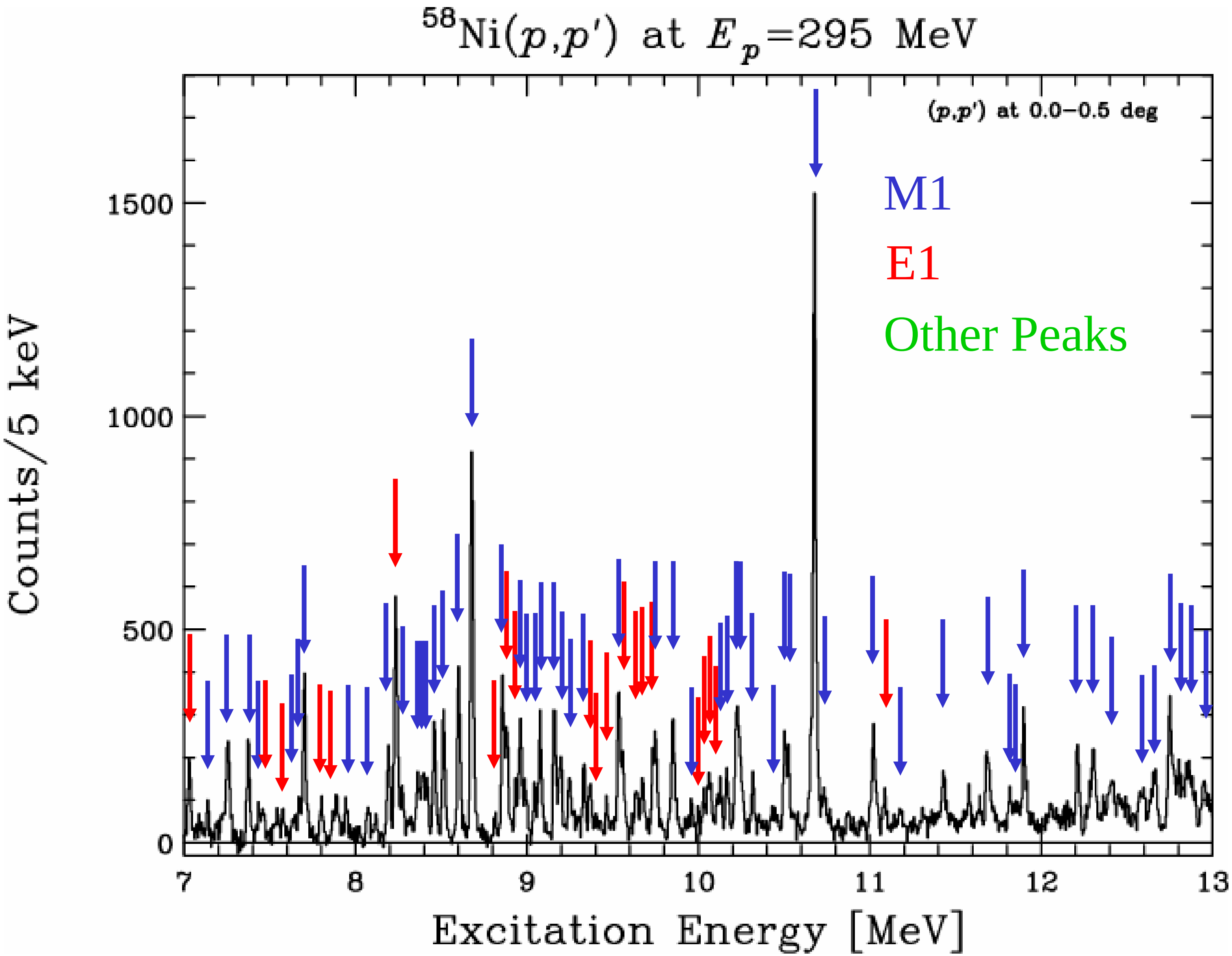
^{48}Ca(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
M1
E1
Other Peaks
^{16}O
^{16}O
^{16}O
Counts/5 keV
Excitation Energy [MeV]
1250
1000
750
500
250
0
7
8
9
10
11
12
13



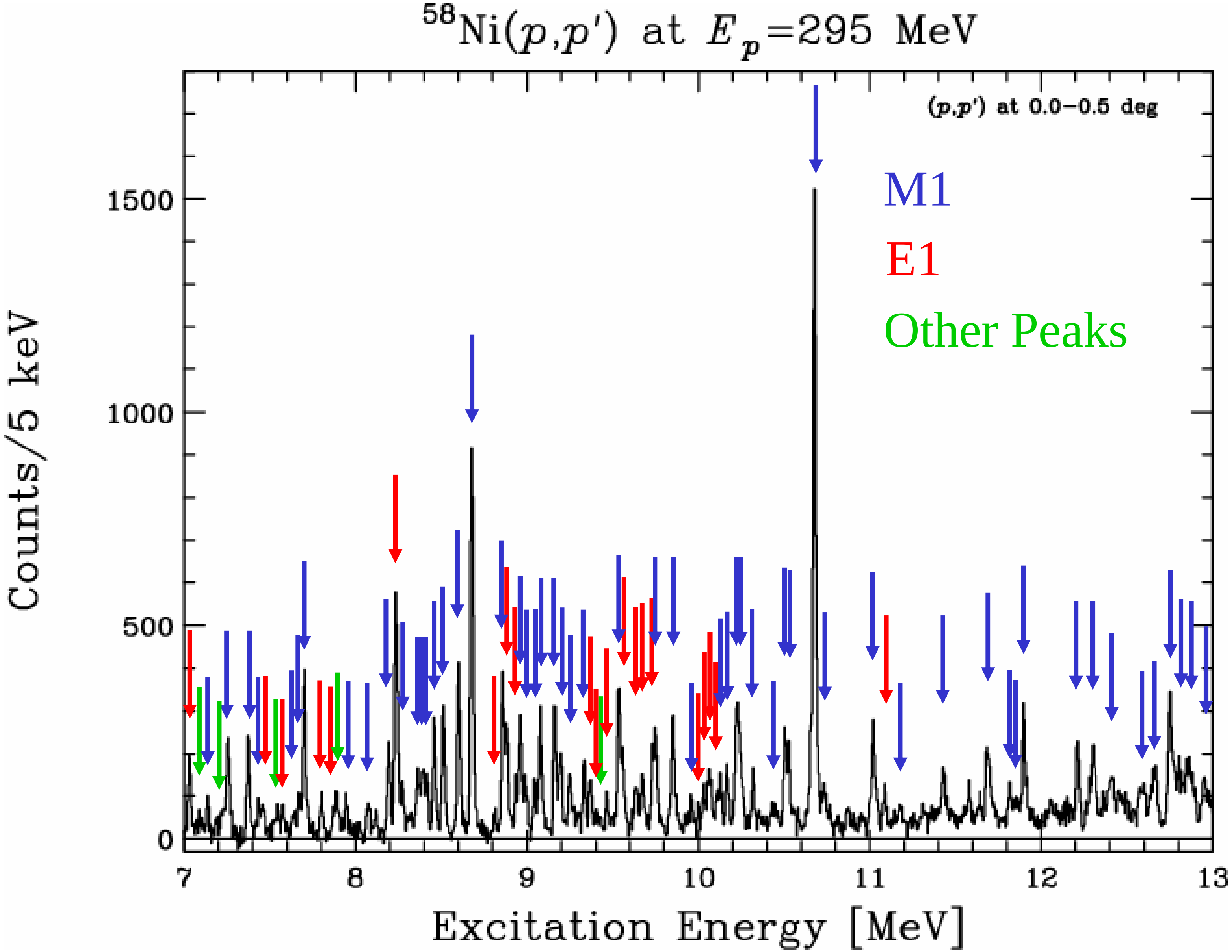
^{58}Ni(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
M1
E1
Other Peaks
Counts/5 keV
1500
1000
500
0
7
8
9
10
11
12
13
Excitation Energy [MeV]

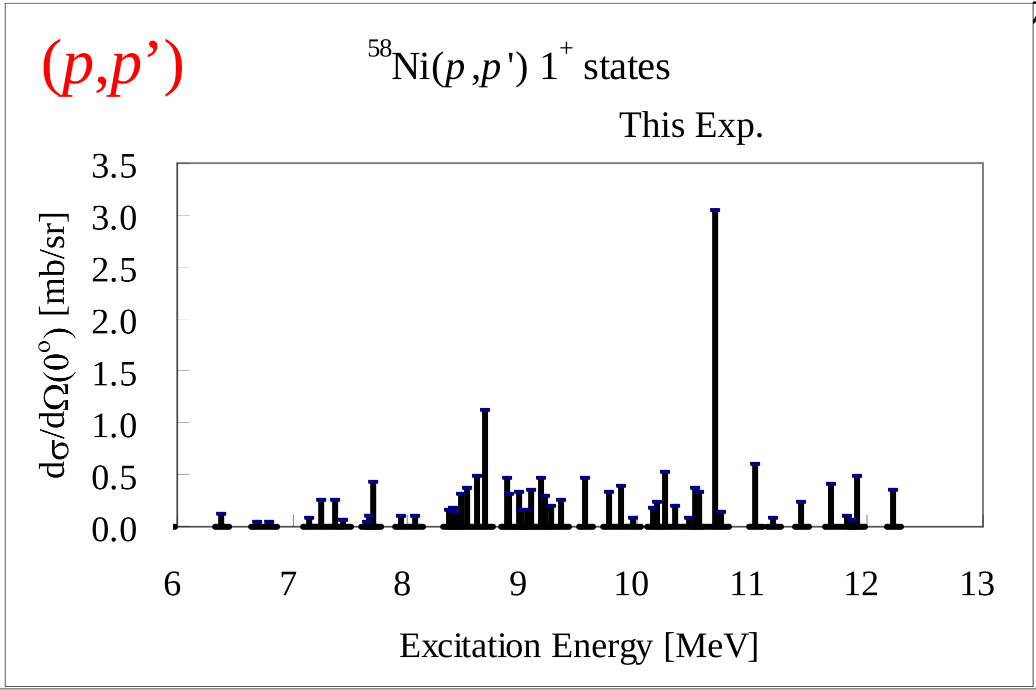


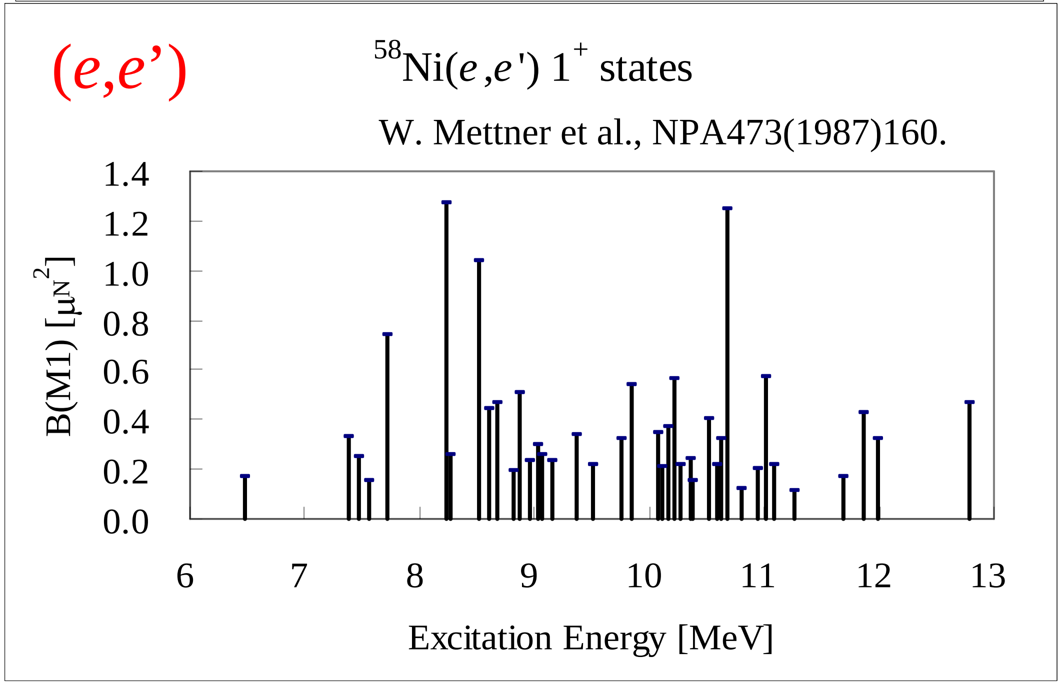
^{58}Ni(p,p') at E_p=295 MeV
(p,p') at 0.0–0.5 deg
M1
E1
Other Peaks
Counts/5 keV
Excitation Energy [MeV]
0
500
1000
1500
7
8
9
10
11
12
13



^{58}Ni(p,p′) at E_p=295 MeV
(p,p′) at 0.0–0.5 deg
M1
E1
Other Peaks
Counts/5 keV
1500
1000
500
0
7
8
9
10
11
12
13
Excitation Energy [MeV]


^{58}Ni(p,p′) at E_p=295 MeV
(p,p′) at 0.0–0.5 deg
M1
E1
Other Peaks
Counts/5 keV
1500
1000
500
0
7
8
9
10
11
12
13
Excitation Energy [MeV]





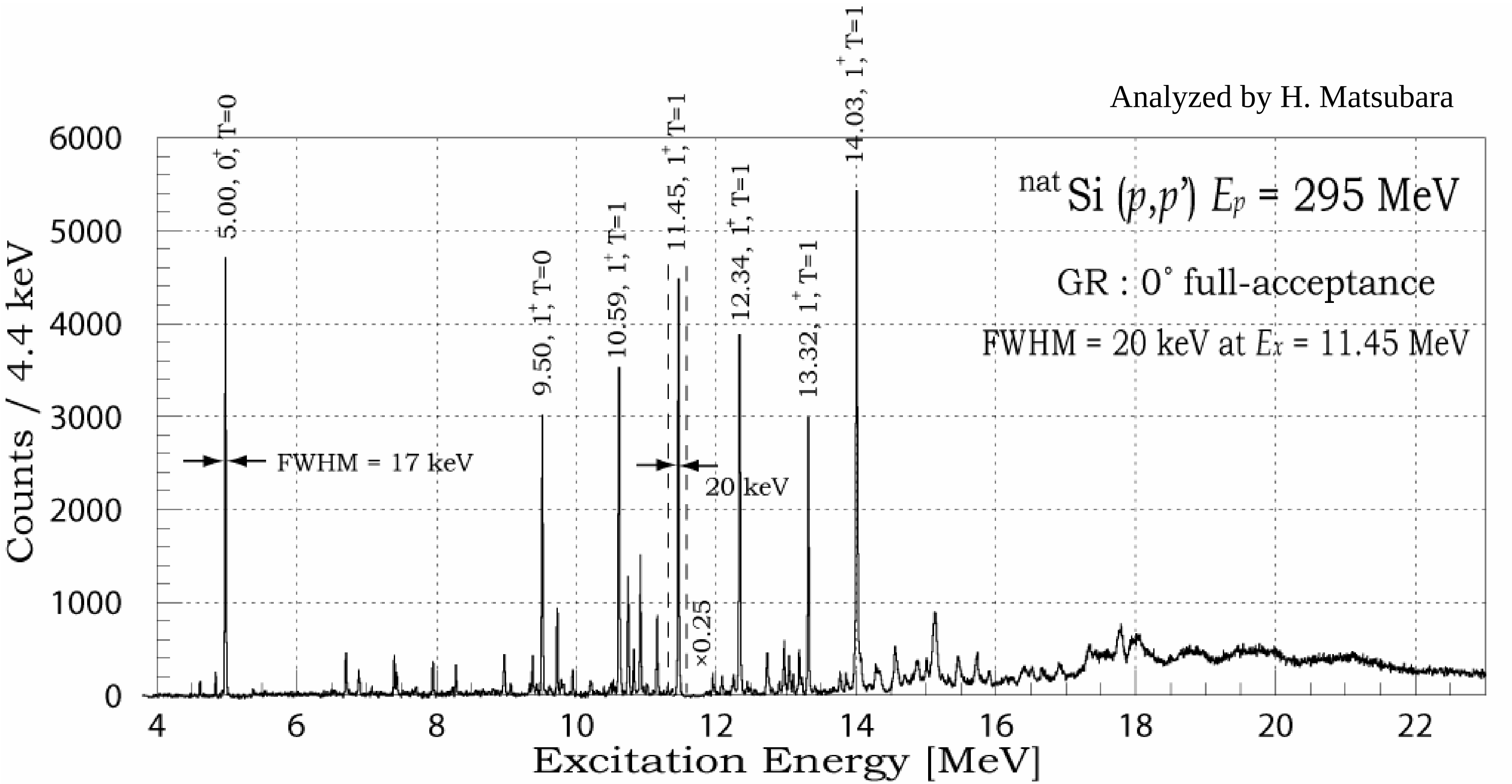
Differences come from:
orbital par of the M1 operator

↓

Extraction of general trend by checking the orbital contribution in each state.

B(σ): (p,p')
B(M1): EM probes
orbital part: combination

Inelastic Scattering from ^{28}Si at 0 degrees



Angular Distribution of IS and IV 1^+ excitations

DWBA calculation

Trans. density : A. Willis et al., PRC 43(1991)5 (by OXBASH in sd shell only)

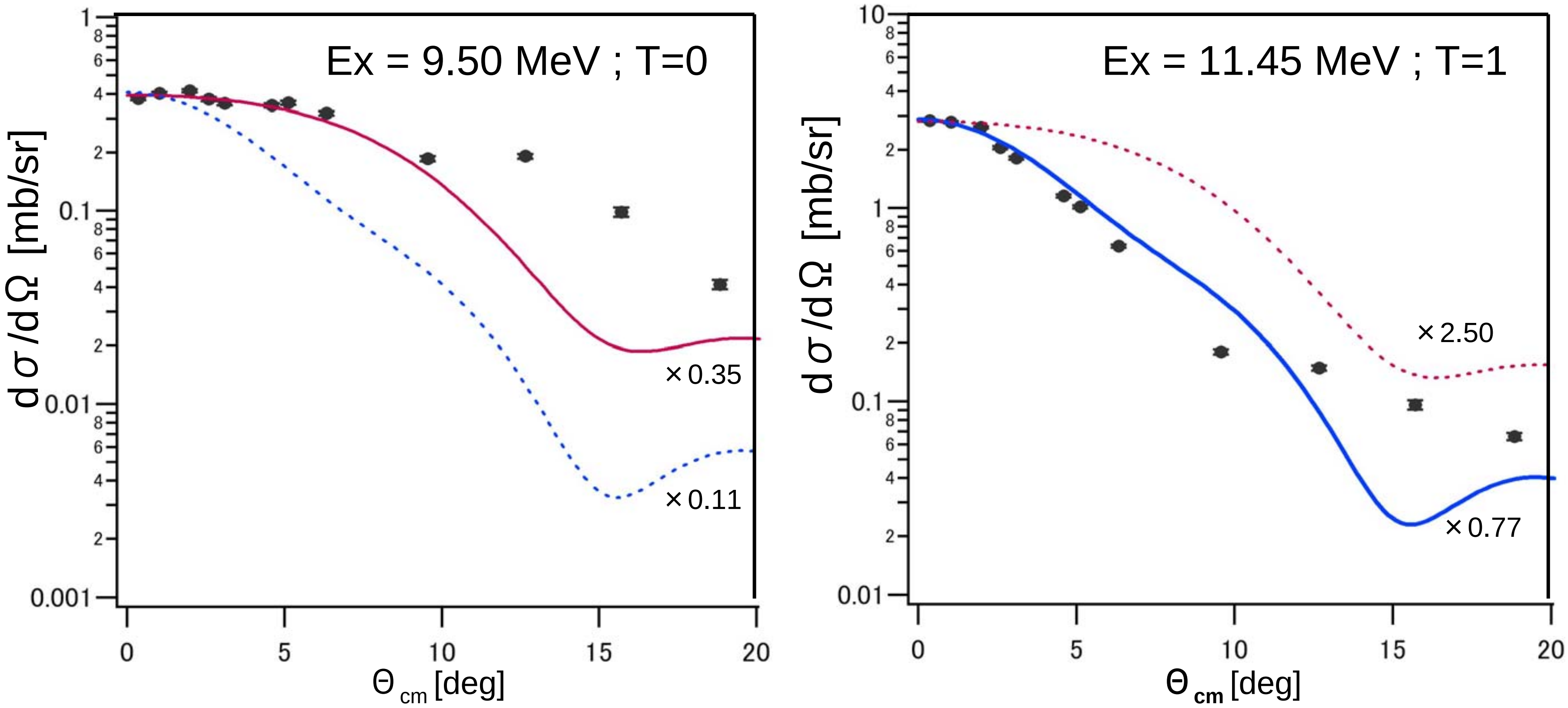
NN interaction. : Franey and Love, PRC31(1985)488. (325 MeV data)

Optical potential : K. Lin, M.Sc. thesis., Simon Fraser U. 1986.

DWBA, T=0 ; IS

DWBA, T=1 ; IV

Analyzed by H. Matsubara



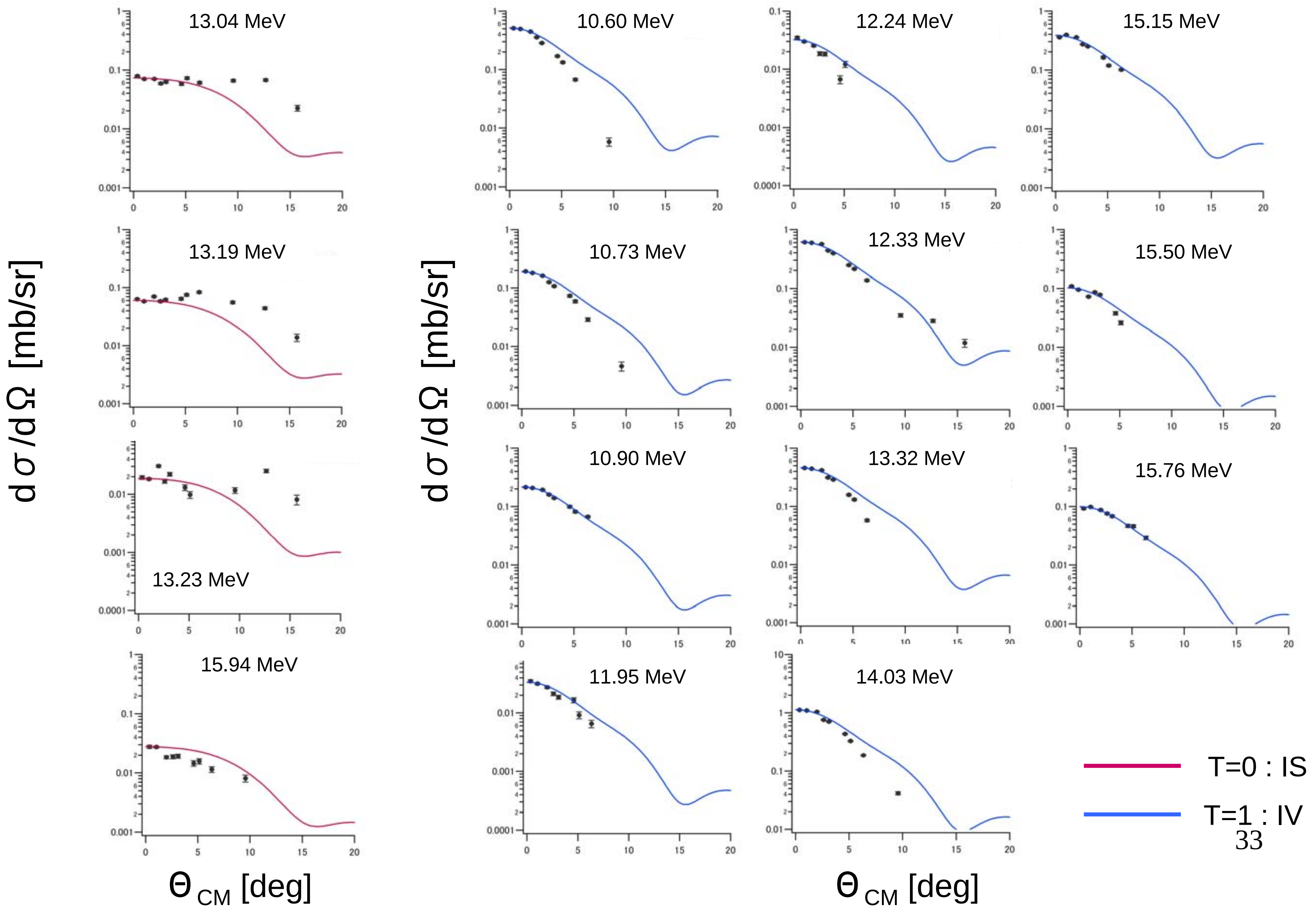
From angular distribution, isospin value is identified.

Other states identified as 1^+

1^+, T=0 states

1^+, T=1 states

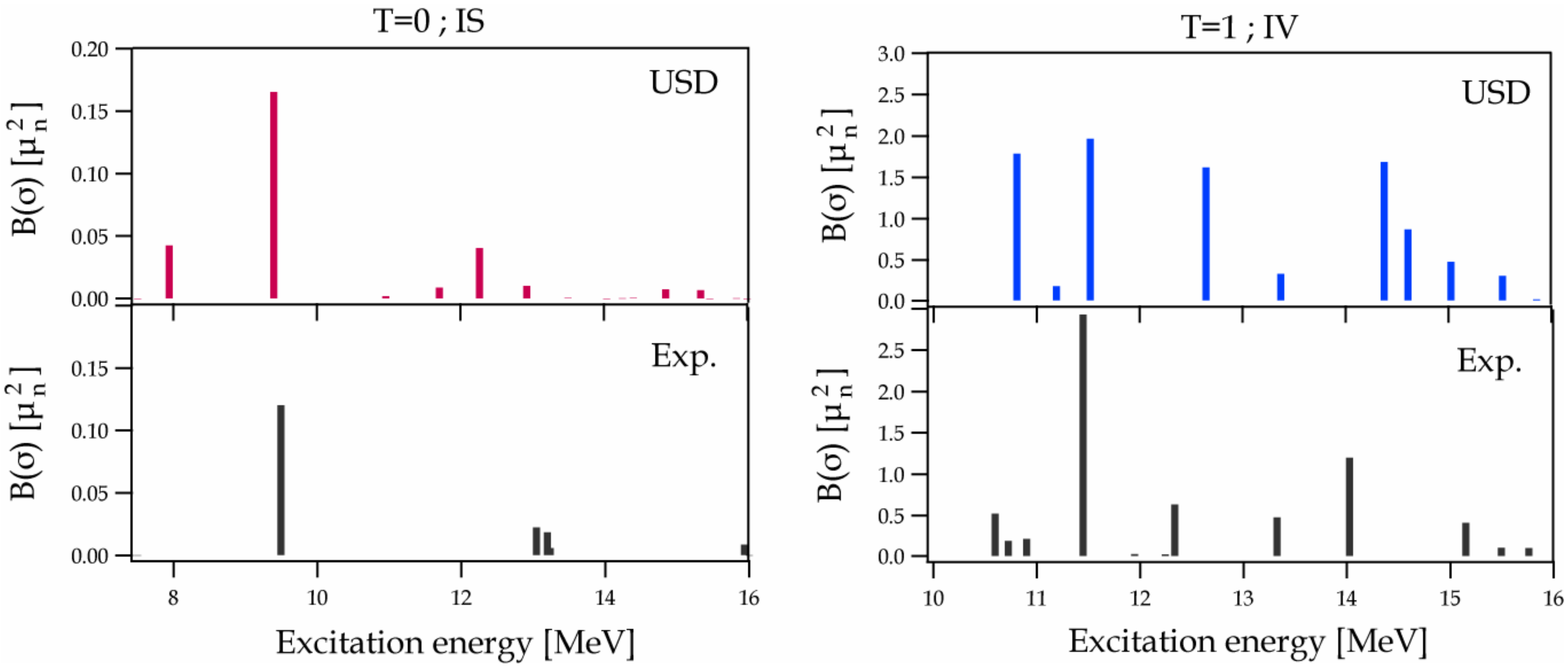
Analyzed by H. Matsubara



Strength distribution

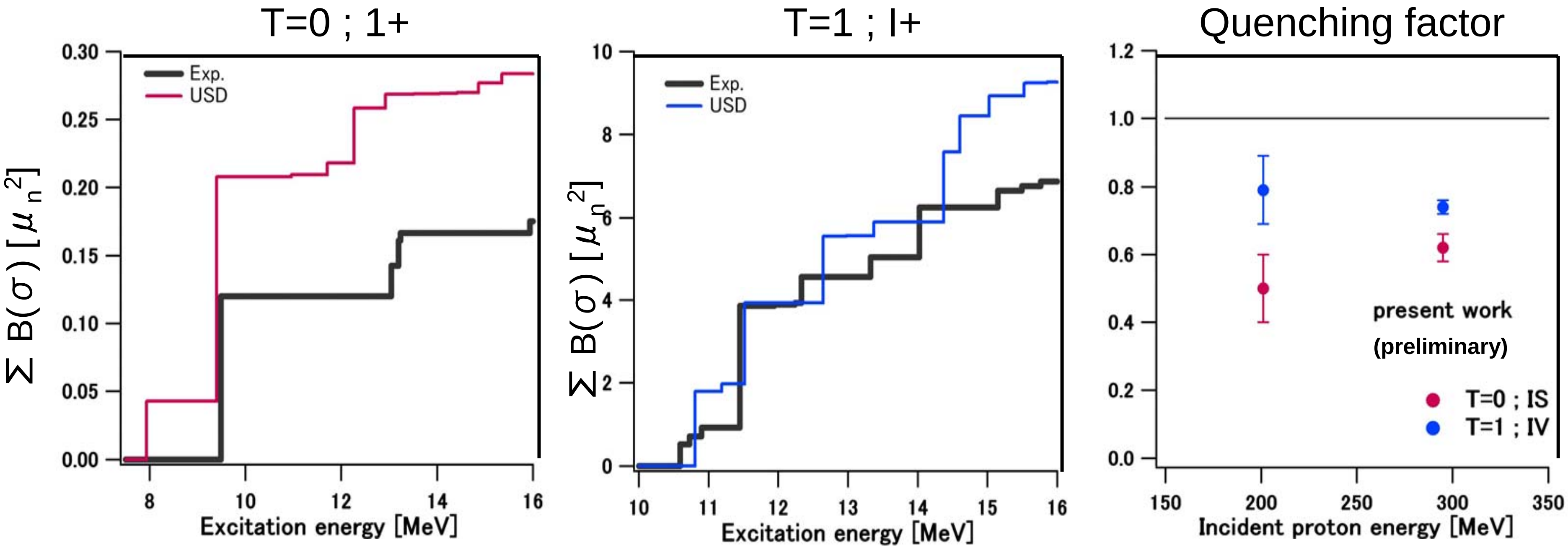
preliminary

shell model calculation:
OXBASH + USD interaction



Total sum of the strengths preliminary

Cumulative Sum



Followings should be checked more carefully.

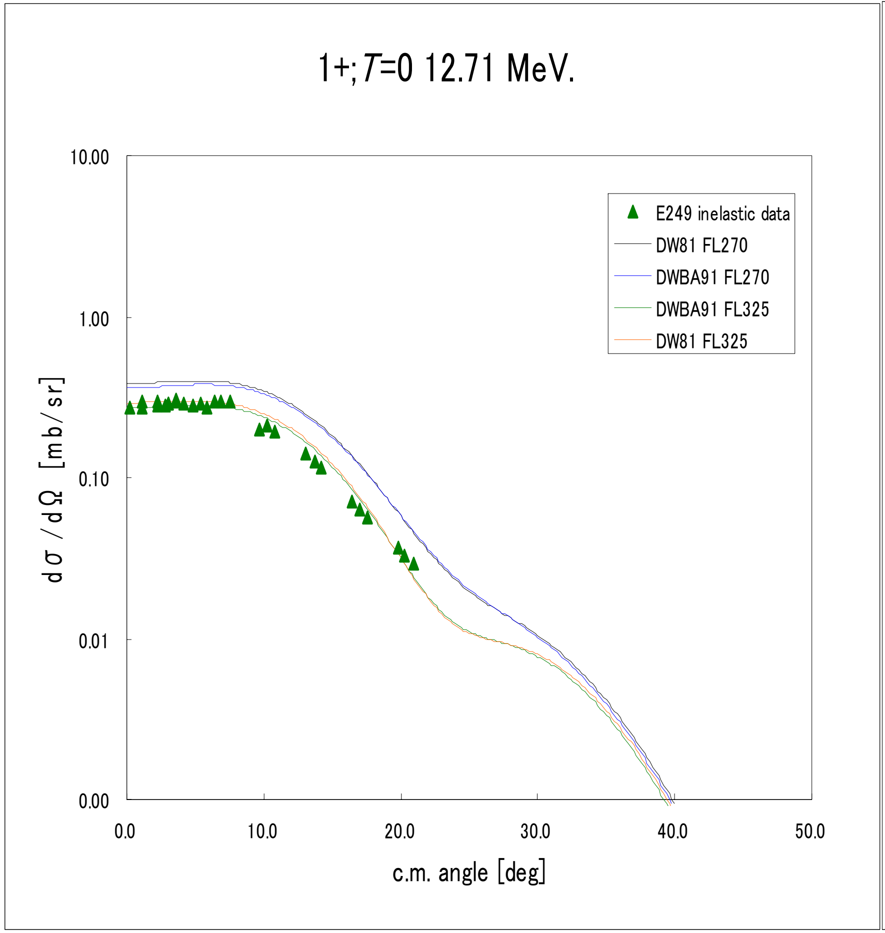
- B(σ) is determined from dσ/dΩ(q=0) relying on the eff. interaction and DWIA calculation.

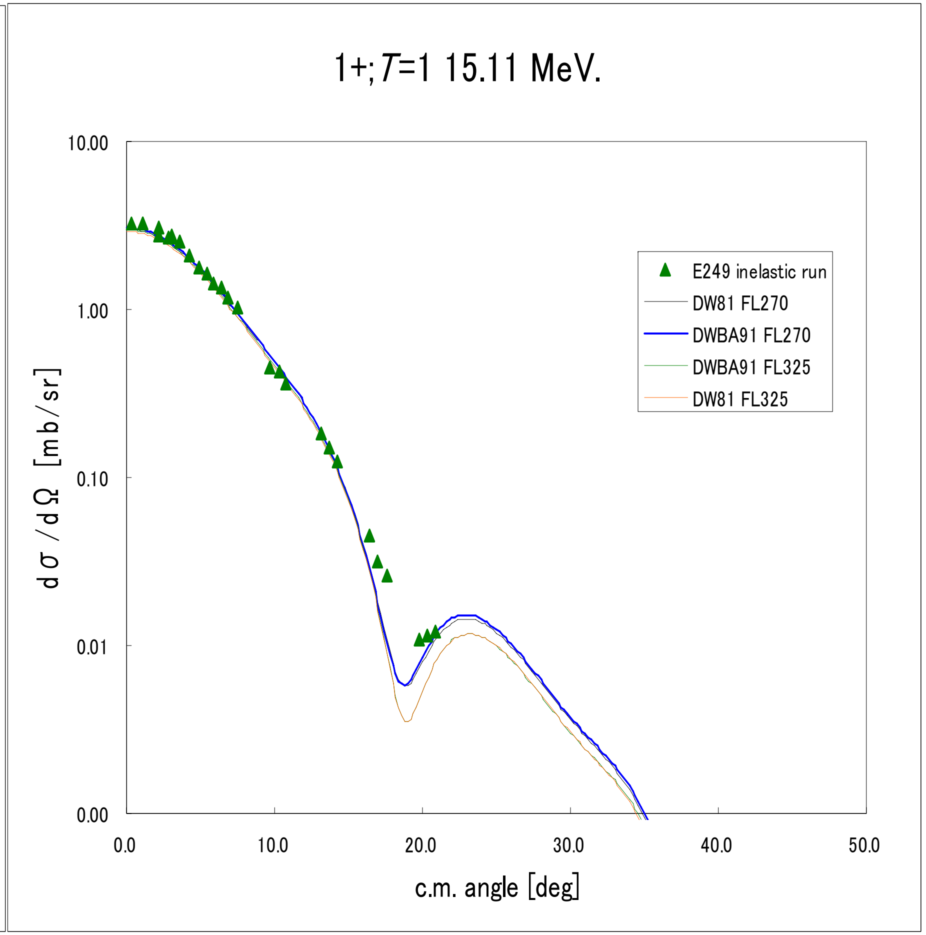
•Bare g-factor is used in the S.M. calculation.

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

Inelastic Scattering from ^{12}C

DWBA calc.
Cohen Kurath Wave Function
Franey Love Effective Interaction





DWBA calculations using Cohen Kurath W.F. and Franey-Love effective interaction (parameter set at 325 MeV, red line) well reproduce the data without any normalization.

M1 and *E1* excitations in ^{208}Pb

高品質·高分解能ビームラインで展開する物理
RCNP, Osaka, 28–29 March 2000

Study of M1 excitations via the ^{208}Pb(p, p') reaction at 0° and very forward angles

Department of Physics, University of Tokyo

A. Tamii

Prediction of the M1 strengths in ^{208}Pb with 1*p*-1*h* basis

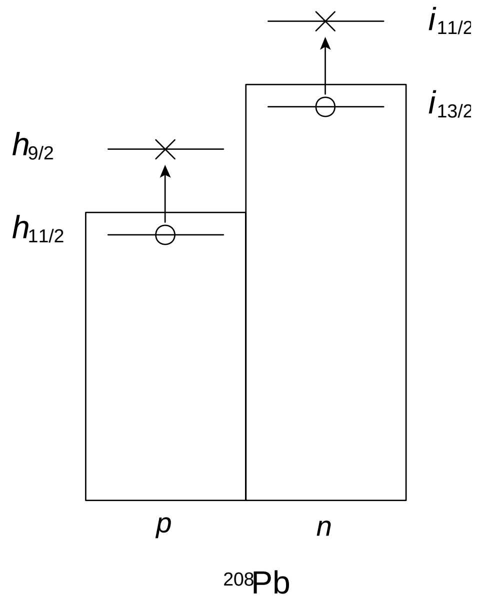
1*p*-1*h* excited states of protons $|\pi\{h_{9/2}\text{-}h_{11/2}^{-1}\}>$ and neutrons $|\nu\{i_{11/2}\text{-}i_{13/2}^{-1}\}>$ strongly couples to each other due to

- spin-orbit splittings of *p* and *n* orbits are similar
- orbital angular momentum l's are similar

and yield

- a lower-lying state at ~ 5.4 MeV with B(M1) ~ 1 μ_N^2
- a higher-lying state at ~ 7.5 MeV with B(M1) ~ 50 μ_N^2

in Tamm-Dancoff approximation.



see *e.g.*
J.D. Vergados, Phys. Lett. 36B (1971) 12.
Bohr and Mottelson, Nuclear Structure vol II (1975)636.

Fragmentation of the M1 strengths in ^{208}Pb

The low-lying strength is considered to be exhausted by a state located at 5.846 MeV.

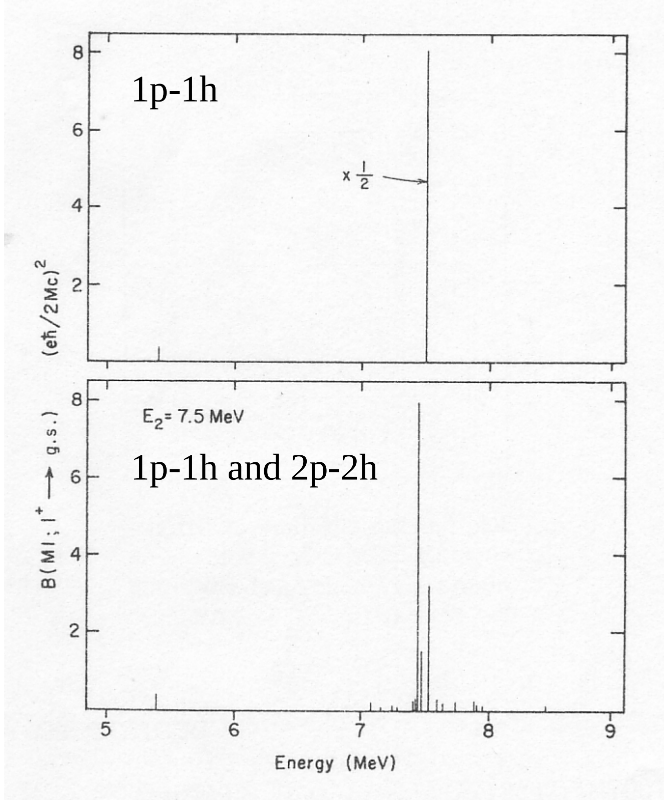
observed by (*p*,*p*') S.I. Hayakawa *et al*., PRL49(1982)1624, (e,e'), and (d,d').

The higher-lying strength is fragmented into many tiny states by mechanisms:

- core-polarization or g.s. correlation
- coupling to 2p-2h states
- coupling to Δ-h states
- meson exchange current

Experimentally, only a strength of ~10 μ_N^2 has been observed (until 1988) comparing with theoretical predictions of ~10 μ_N^2 .

→ "Missing M1 strength in ^{208}Pb"



calc. by Lee and Pittel PRC11(1975)607.

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 the meachanisms additively contribute,
"the best that be expected from theoretical predictions is 20 μ_N^2"
I.S. Towner, Phys. Rep 155 (1987) 263.

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’)

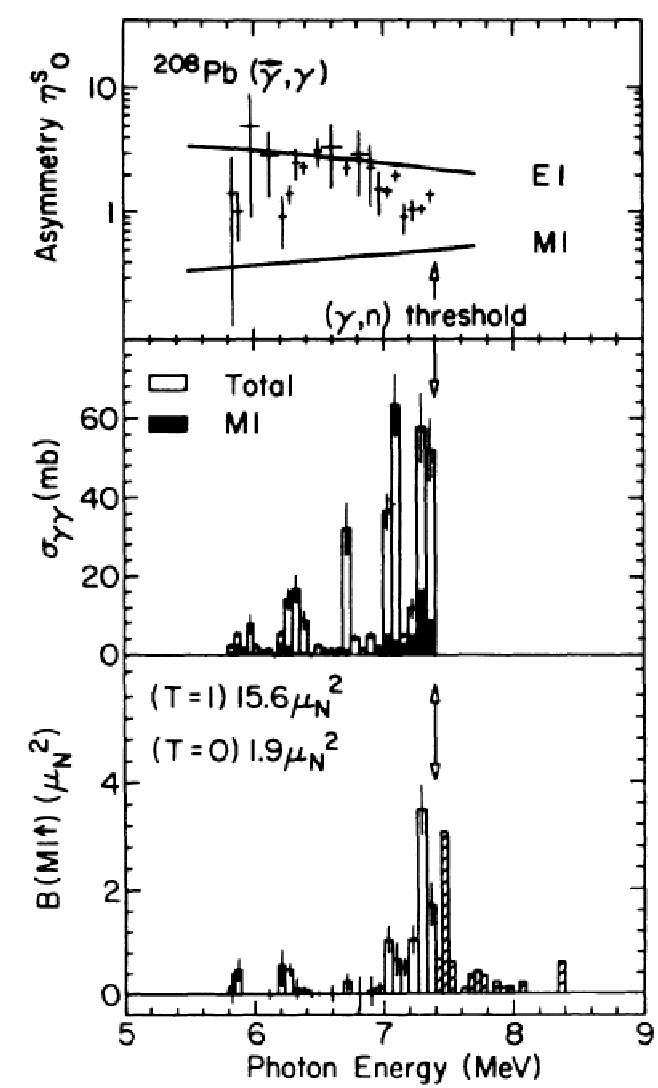
In 1988, R.M. Laszewsky et al. have identified

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

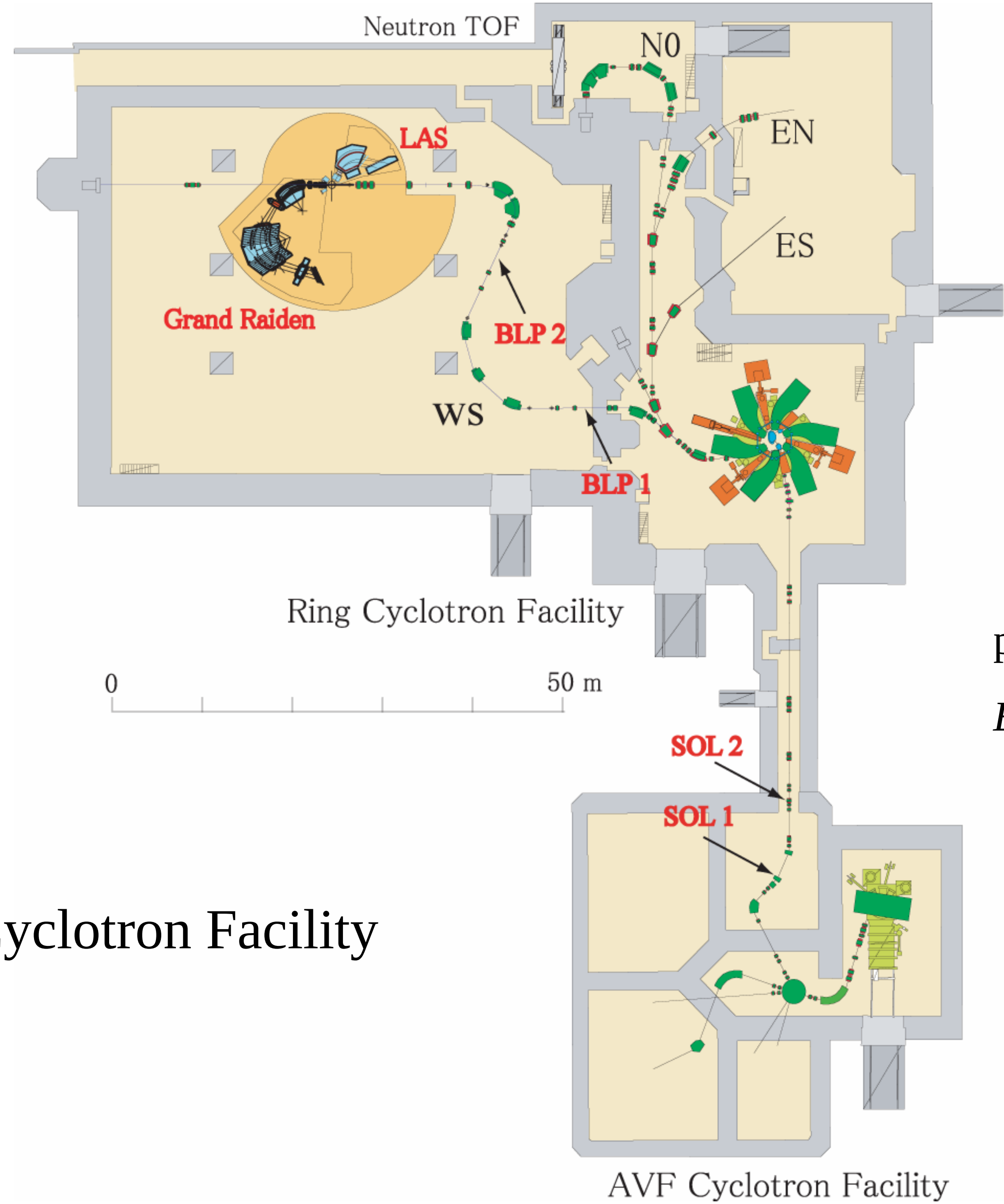
In total the higher-lying strength became $15.6\mu_N^2$

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

Still the search for M1 strengths in ^{208}Pb is an important job to experimentally determine the M1 strengths and their E_x distribution.



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



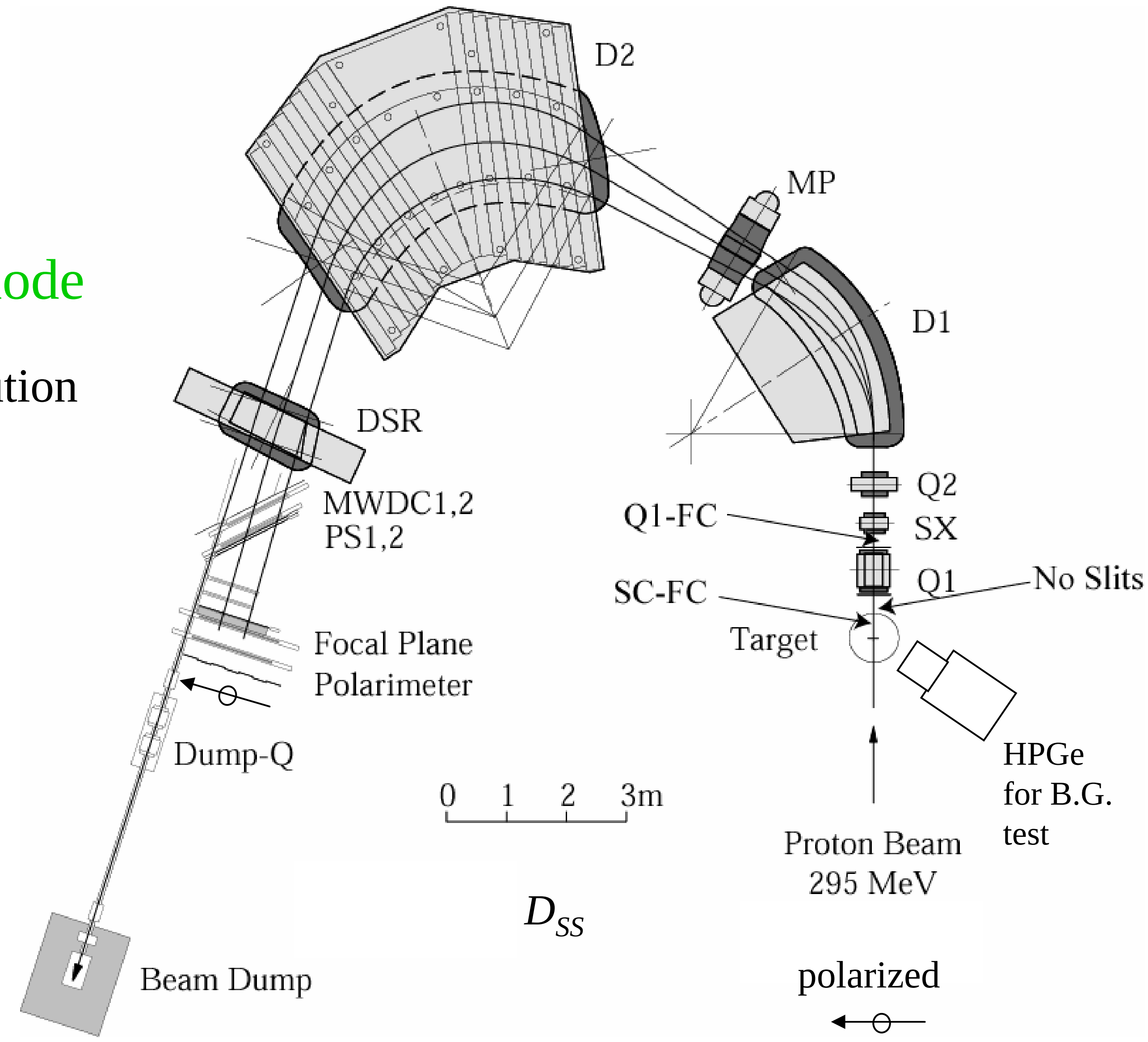
proton beam

E_p=295 MeV

RCNP Cyclotron Facility

medium under focus mode

- vertical scatt. angle resolution
- background subtraction



Preliminary Spectra

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将来計画

- AVF-FT への期待
  - ビームのさらなる安定化
  - (偏極ビームを含めた)High-Quality ビームの高輝度化
    (当面必要なのは~ 5nA)

- 実験計画
  - ^{208}Pb DLL データの取得 (approved)
  - *sd*-shell のN=Z核のデータ取得 (H. Matsubara, proposal is submited)
  - γ-decay のコインシデンス実験 (proposal in preparation)
  - Zr データ(偏極移行量)の取得

ビーム起因の HPGe Trigger

0.8 kcps at 1nA on 208Pb, at 560 mm from the target, threshold ~500 keV

Summary

- Experimental method of high-resolution (*p*,*p*') measurements at forward angles is successfully developed.

  ΔE~20 keV, Δθ~0.6 deg, up to ^{208}Pb

- (*p*,*p*') at forward angles is a very power probe for studying M1, E1 and other excitations.

  M1 and E1 excited states can be identified from their

  - angular distribution, energy dependence, and/or spin transfer.

  B(σ) : (p,p')

  B(M1) by EM probes (e,e') (γ,γ')

  orbital part: combination