In-beam Spectroscopy of Exotic Nuclei Using Intermediate Energy RI Beams

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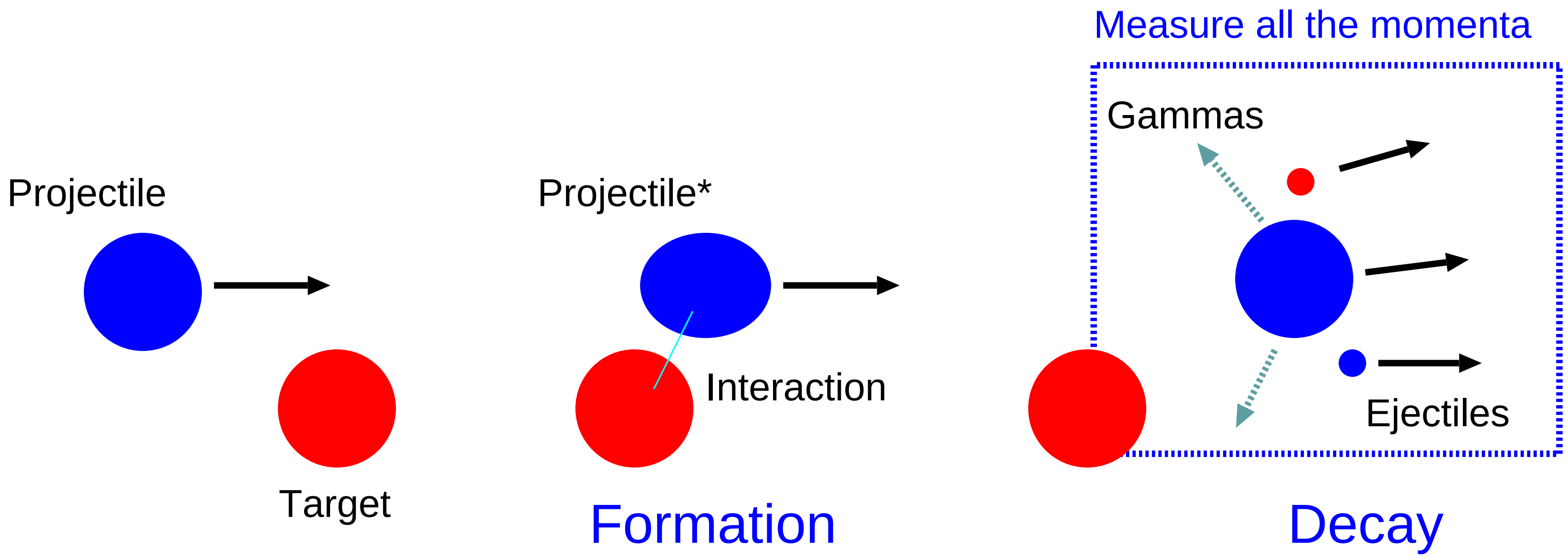
Introduction

- Variety of Nuclei
  - Two kinds of constituents: Proton & Neutron
  - Numbers of Protons & Neutron => Properties of Nuclei
    - Independence / Coherence
  - c.f. Number of electrons => Properties of Atoms

- Nuclear Structure as functions of Z and N
  - Ground State Properties (mass, size, lifetime, moments...)
  - Spectroscopy of Excited States
  - Nuclear Response

Inverse Kinematics

■ Formation of Excited States and Their Decays



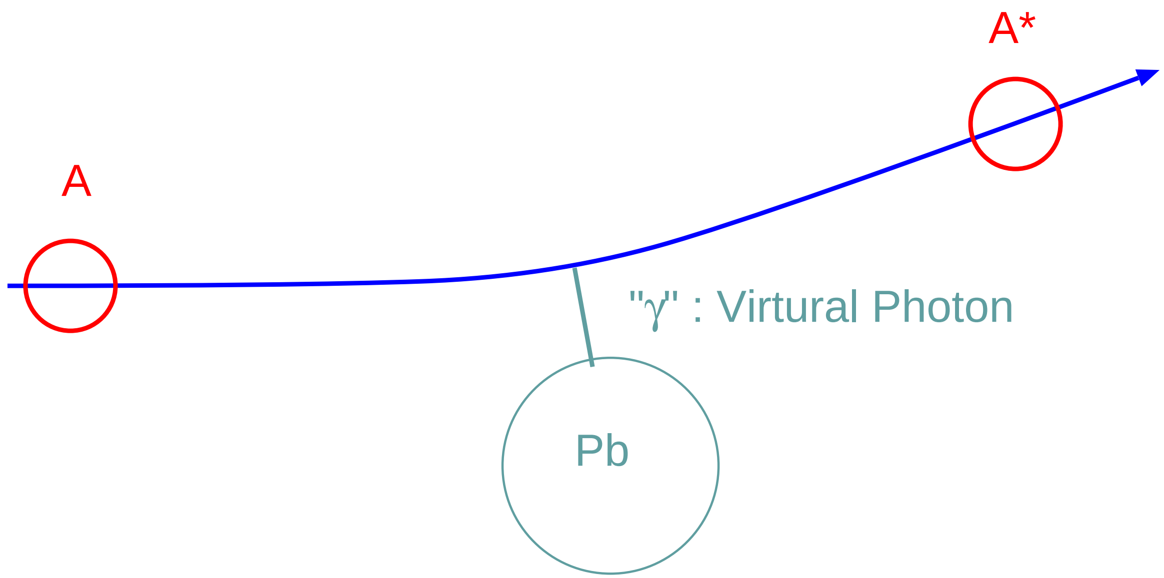
- Target is a Probe= Projectile* is Physical Target to be studied
  - Simple interaction = Direct reaction
- Velocities of Ejectiles are almost same as that of projectile
- Gamma-rays are Doppler-Shifted

Excitation of Beam-Like nuclei with Targets as Probes

- Heavy Nuclei: Strong Coulomb Field
  - Coulomb Excitation, Coulomb Dissociation
- Hydrogen, Deuterium
  - Inelastic Scattering
  - Charge Exchange Reaction
  - Knockout
- Herium-4
  - Inelastic Scattering
  - Nucleon Transfer
- Other light elements
  - Inelastic Scattering
  - Knockout
  - Fragmentation

Selectivities

- **Coulomb Excitation, Coulomb Dissociation**
  - Number of virtual photons
    - E1 > E2 > E3 ...
    - M1 > M2 ...
  - Interaction with Protons only
    - Isovector Excitation



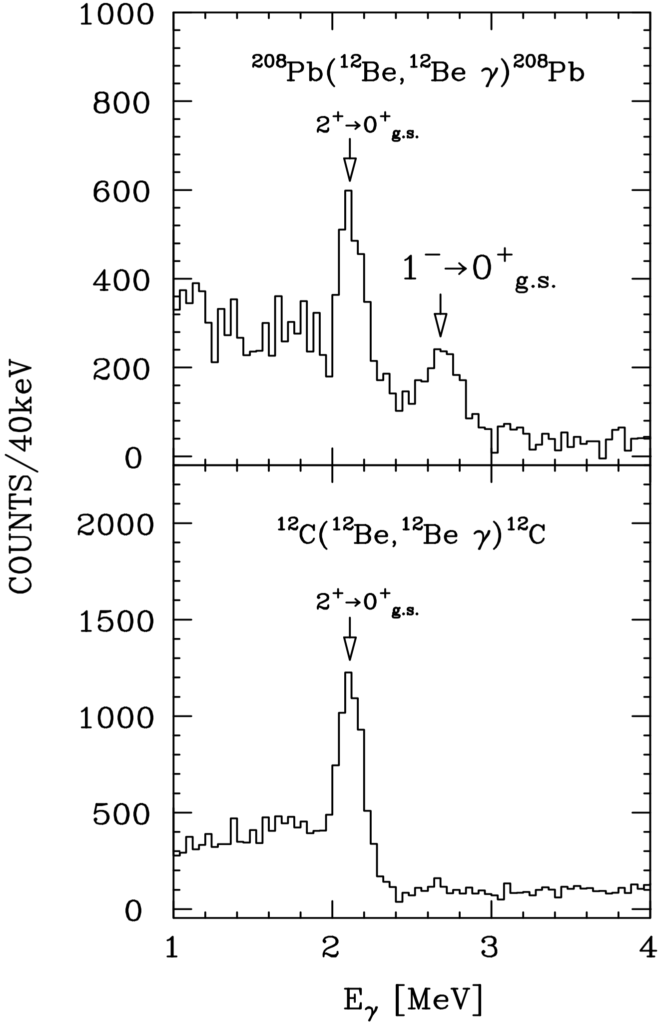
Nuclear Excitation

- Interaction with Protons and Neutrons
  - Isovector/Isoscalar Excitaion
  - E1 << E2

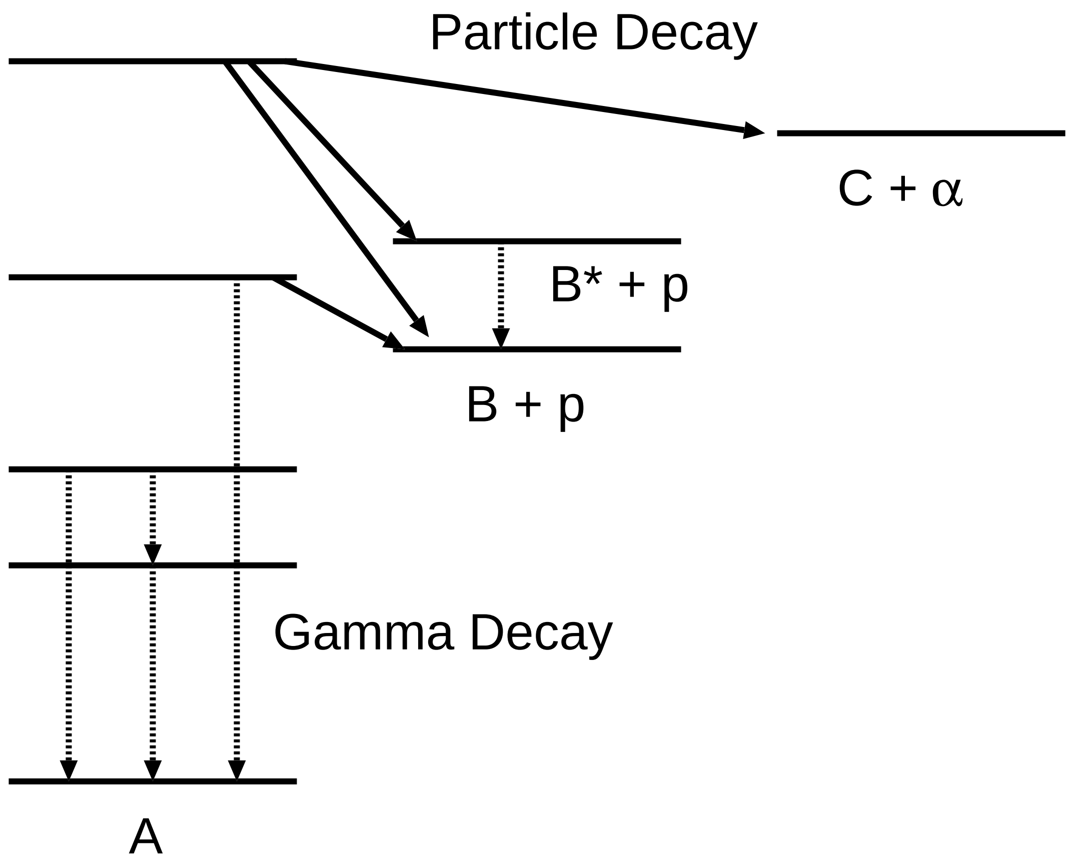
  note: Isoscalar E1 Excitation is Higher order
- Higher angular momentum may be transferred
- Proton/Deuteron can make spin-excitation
  - (p,n): dS = 0, 1; (d,2n),(d,2p): dS=1
  - IAS, GT, SFD, ...
- Helium-4 cannot make both the spin and isospin excitation
  - Natural parity states for even-even nuclei
  - ISGMR, ISGDR, ...

Example of E1/E2 by Coulomb/Nuclear excitation

- 12Be (Iwasaki et al., Phys. Lett. B481 (2000) 7)



Decays of Excited States



- Momenta of all the decay particles including gamma rays ->
- Excitation energy (from invariant mass)
- Selectivities, Particle-particle, particle-gamma, ..., correlation ->
- Spins and Parities

Invariant Mass Spectroscopy

$$M_{inv}^2 = (\Sigma_i E_i)^2 - (\Sigma_i \vec{p_i})^2$$
$$E_{decay} = M_{inv} - \Sigma_i m_i$$

- Decay energy is independent of incident energy
- For small decay energy, Resolution is relatively good
  - Example:
    - 70 MeV/nucleon
    - E(decay)=1 MeV
    - Resolution of Momentum = 1 %
    - Resolution of Decay energy = 250 keV

    - Tips: http://www.cns.s.u-tokyo.ac.jp/~shimoura/releq/

Transition Probabilities

- Cross section of Coulomb Excitation -> B(EL)...
- Cross section of Nuclear Excitation -> Deformation Length -> B(EL)...
  - Adequate reaction model required (DWBA ...)
- Lifetime and Branching Ratio -> B(EL)...

Doppler Shift of Gamma-Ray

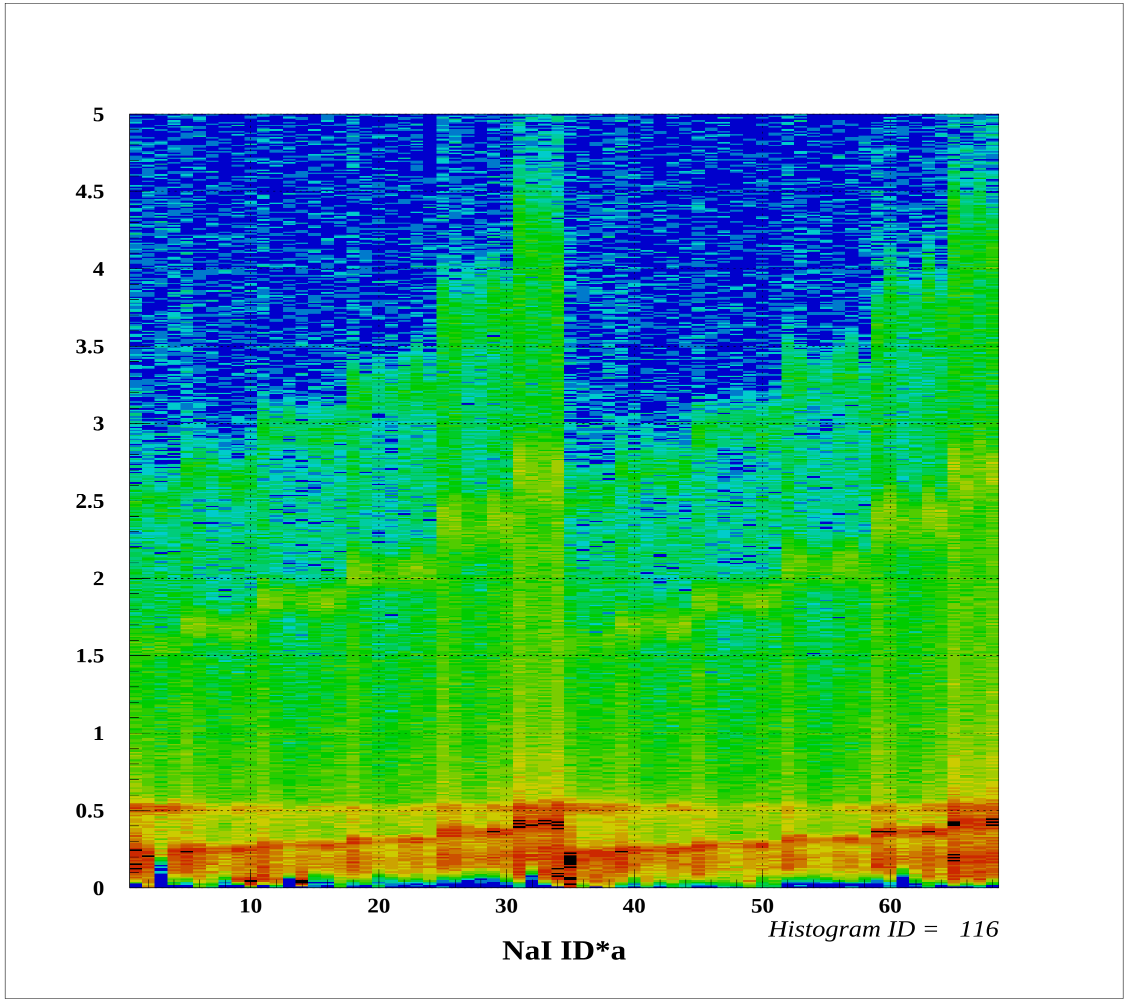
- Transformation between CM and Lab system:

$$E_\gamma^L = E_\gamma^C \gamma(1 + \beta \cos \theta^C)$$
$$E_\gamma^C = E_\gamma^L \gamma(1 - \beta \cos \theta^L)$$
$$\cos \theta^L = (\beta + \cos \theta^C)/(1 + \beta \cos \theta^C)$$

$$\left| dE_\gamma^C / d\theta^L \right| = E_\gamma^L \gamma\beta \sin \theta^L \simeq E_\gamma^L \gamma\beta \text{ around 90 degree}$$

- Good angular resolution of gamma detectors
    - Granuality corresponds to intrinsic resolution of detectors

- Example: Scattering angle vs. Energy of Gamma (data)
  - 2.1 MeV gamma-rays from in-flight 12Be* are shifted
  - 0.5 MeV gamma-rays from positron annihilation are not shifted



Experimental Equipments

Spectroscopy of Neutron-Rich Be isotopes

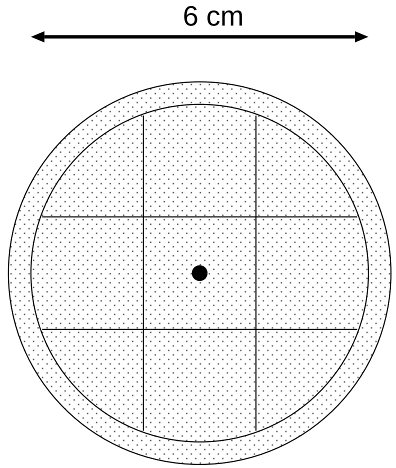
- Low-lying 12Be states
  - 1- intruder state (Coulex)
  - collectivity of 2+ state (p,p')
  - isomeric 0+ state (isomeric "beam" from fragmentation)
  - proton/neutron matrix elements using different probes
    - (p,p'), (alpha,alpha'), Coulex
- Cluster states in 12Be and 14Be
  - Inelastic excitation to resonances
  - Resonant fragments in fragmentation reaction
- Halo structure of 14Be derived from its IAS by (p,n) reaction
  - Coulomb displacement energy, decay properties

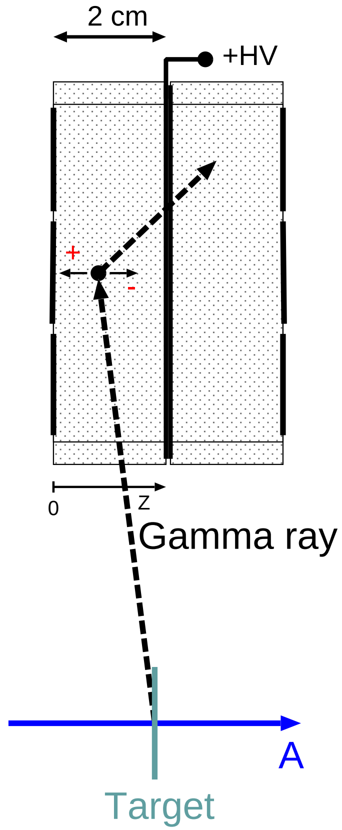
CNS Ge Array

- Requirement:
  - Detectors should be located as close to the target as possible
    - Detectors around 90 degree with respect to beam axis
    - -> Largest Doppler-shift broadening
  - Good angular resolution (1-2 degree) corresponding to intrinsic resolution of Ge detectors (a few keV)
    - Planar-type
    - Pulse-shape analysis

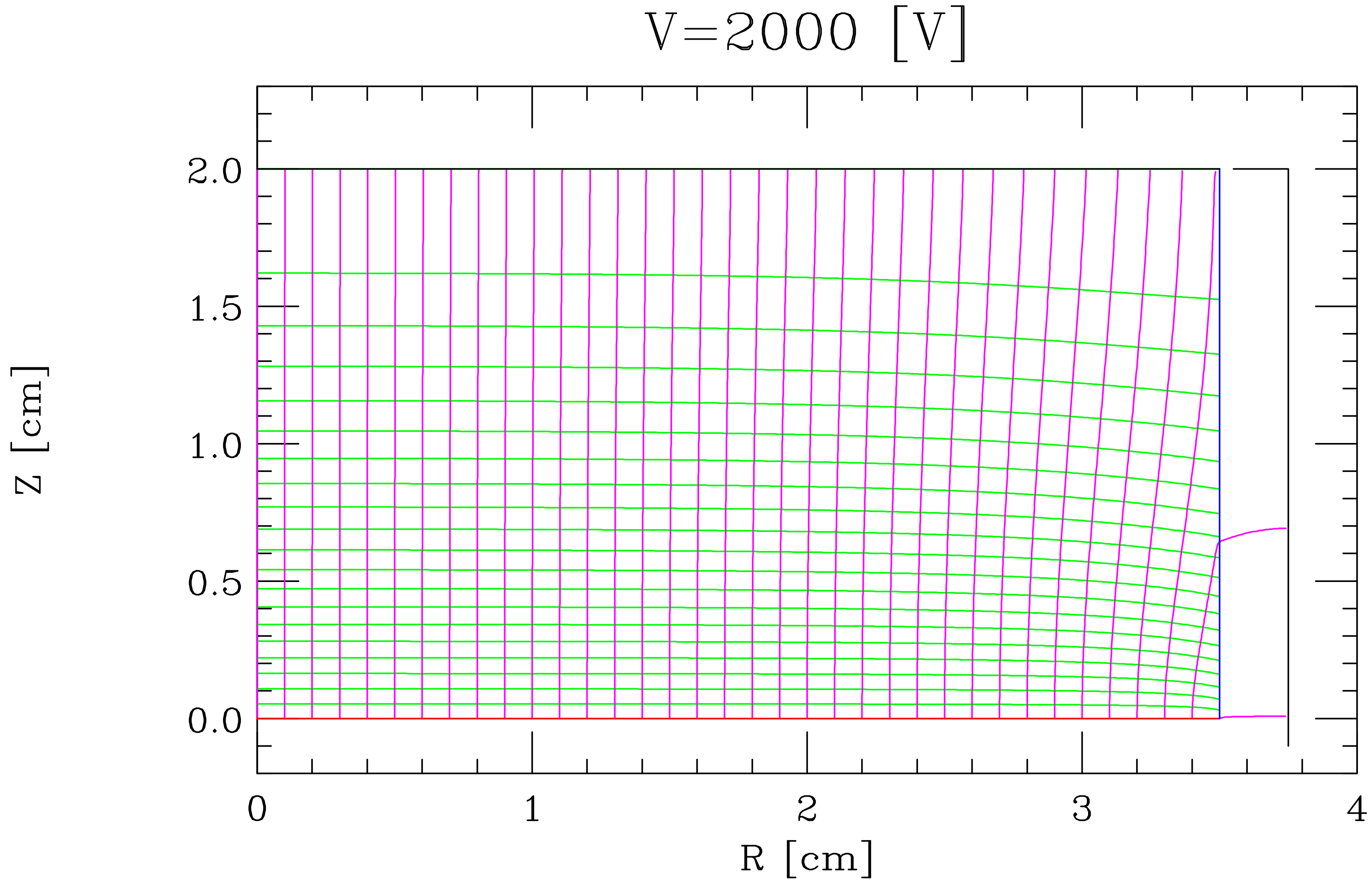
    position along the electric field

- 6cm-dia x 2cm-thick x 2 Ge-crystals
- Each crystal is segmented to 3 x 3
- Locates around 90 degree with respect to beam



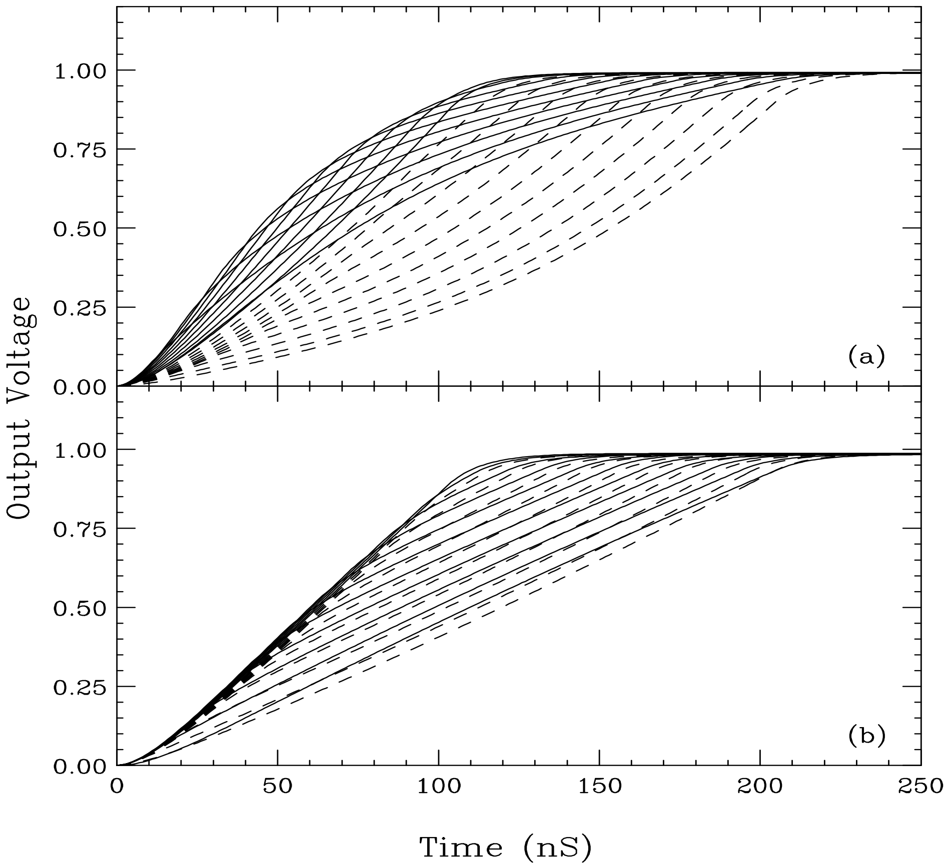


Electric field of planar detector

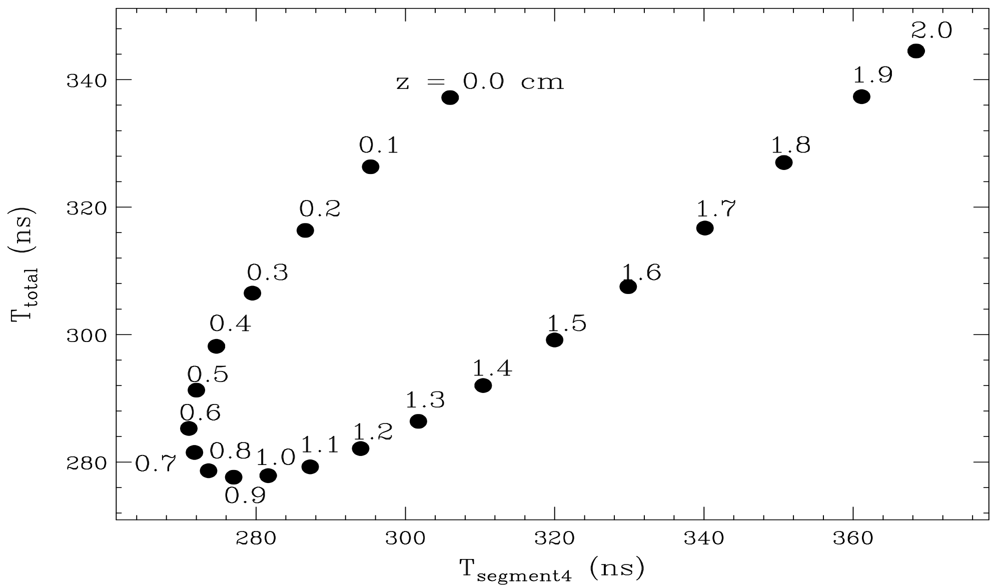


Pulse-shape analysis of segmented Ge

- Good resolution for ONE direction

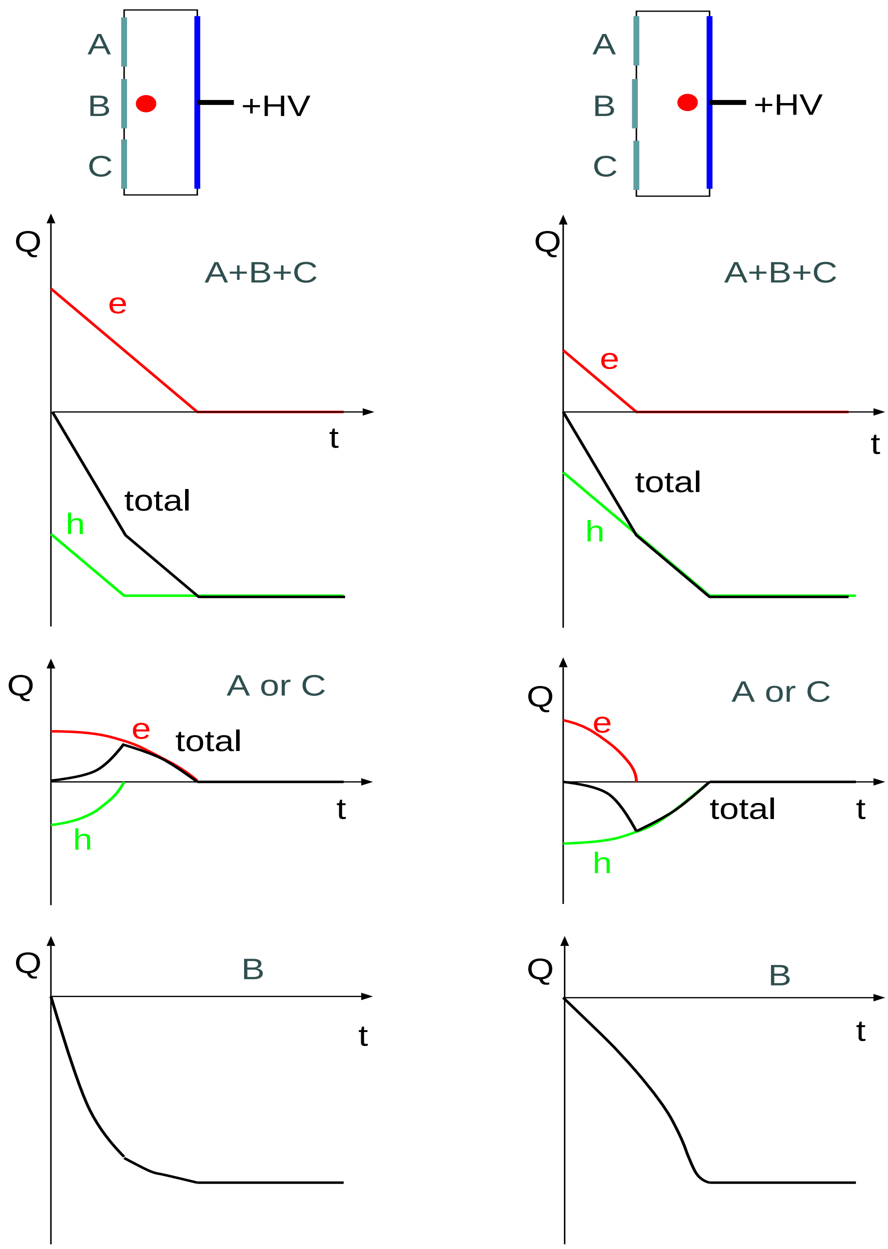


Pulse shapes as a function of depth for
Planer Detector (a) hit segment (b) total

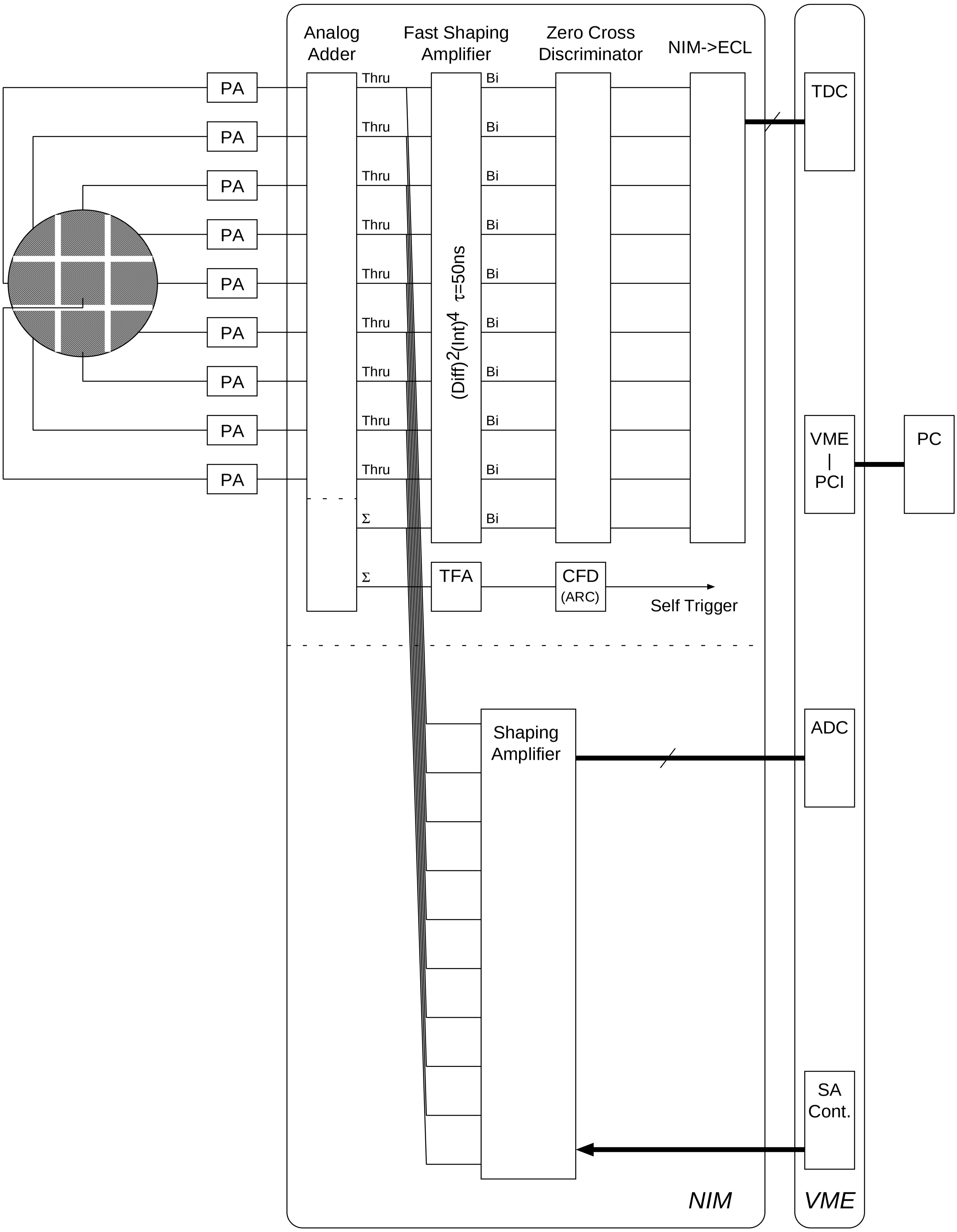


Zero cross timings of
2nd derivative signals
for "hit segment" and "total"

Pulse Shape (saturated drift velocity)

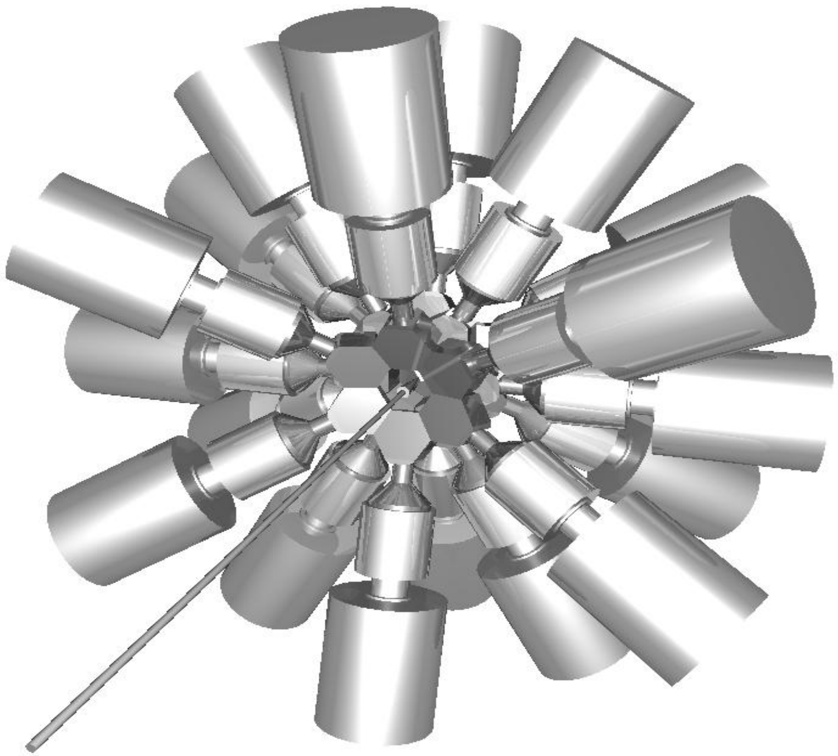


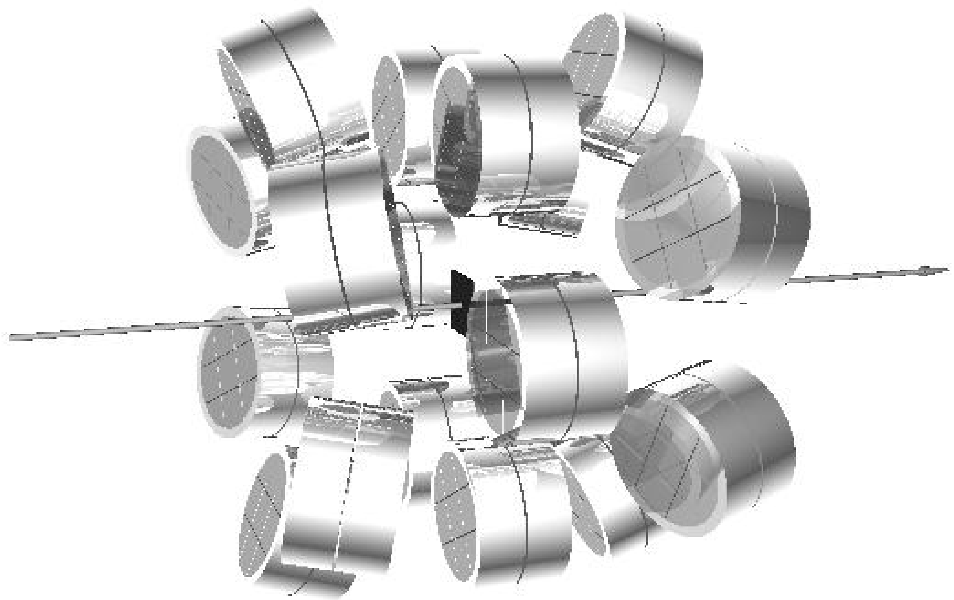
Signal processing of segmented Ge detector



Array Configuration

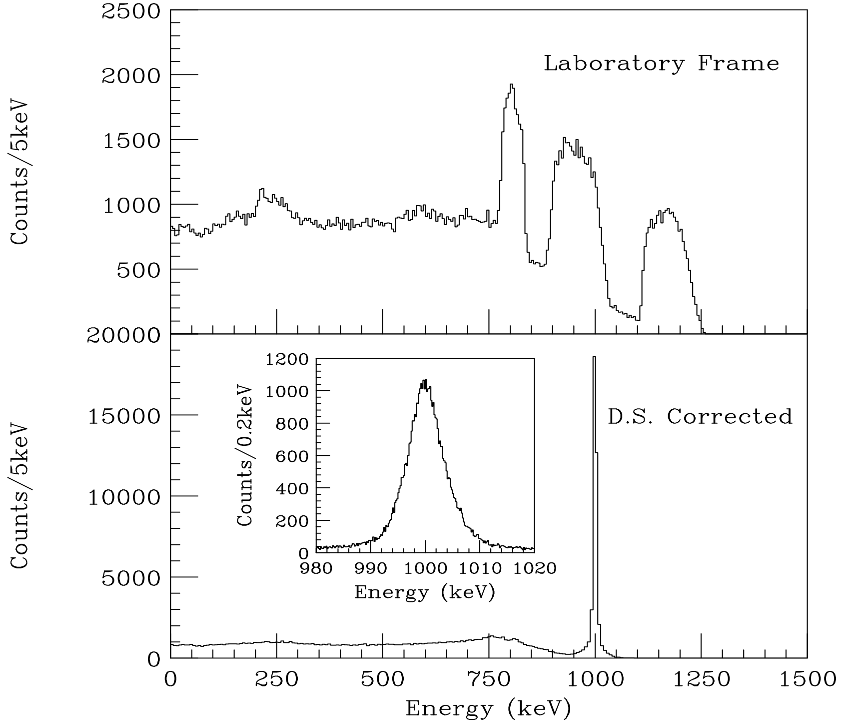
- Locates 18 detectors around 90 degree with respect to beam



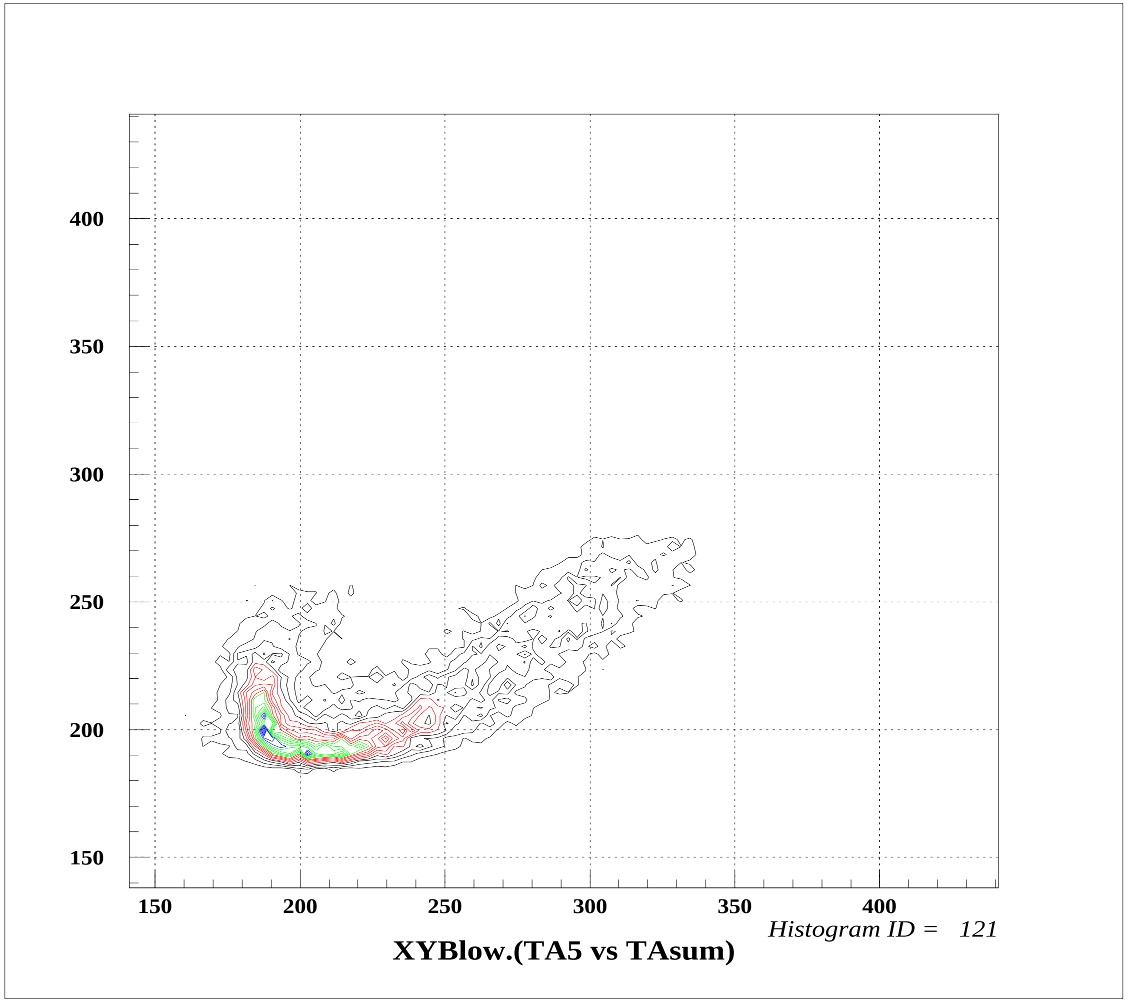


Performance (Simulation)

- Energy Resolution after Doppler-Shift Corrected (v/c = 0.3)
  - 8 keV (FWHM) 17 keV (FWTM) for 1-MeV gamma
- Total Detection Efficiency (epsilon x Omega)
  - 5 % (All) 3.4 % (more than single hit)
- Peak-to-Total Ratio
  - 23 % (All) 42 % (more than single hit)

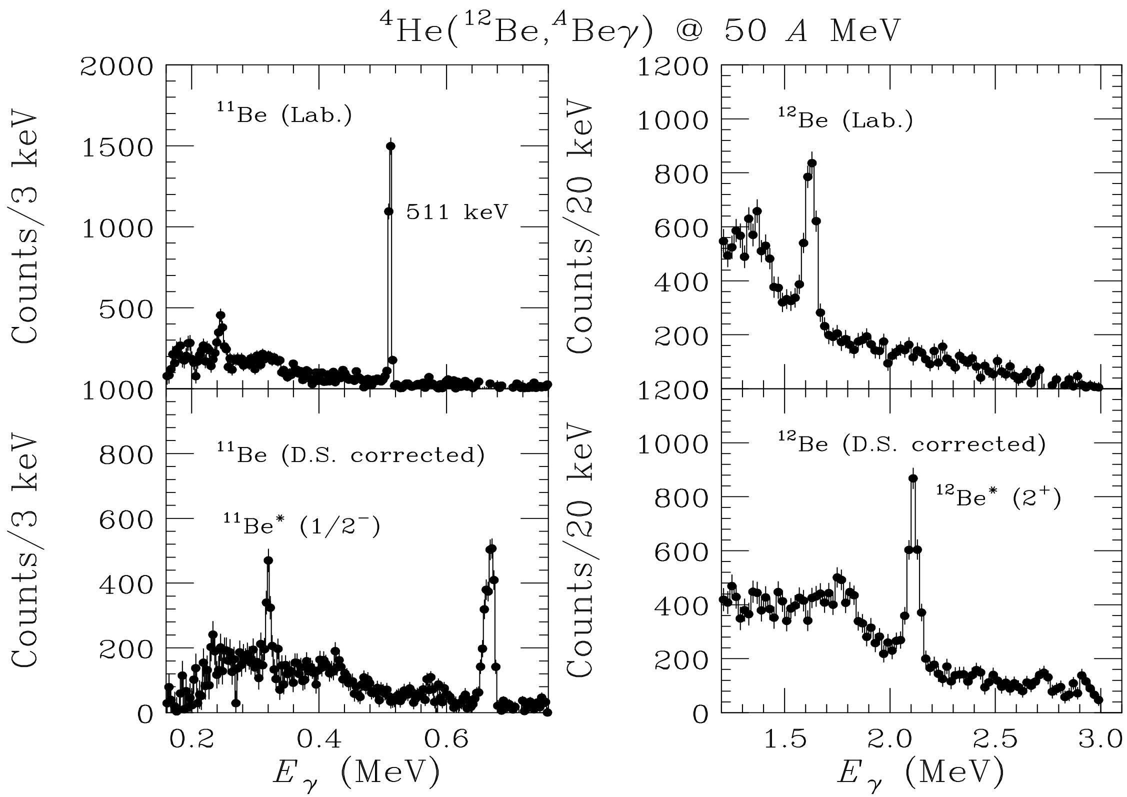


Performance (Experiment)



- T(total) vs T(hit segment) [Sourse Test]

Performance (Experiment)



- Not yet applying Pulse Shape analysis

Coulomb Excitation of Unstable Nuclei

Motivation:

Excitation Spectra

Transition Probabilities [B(Oλ)]

of Unstable Nuclei

↓

Structure change as a function of

N with same Z

Z with same N

T_Z with same T

S_n / S_{2n} / S_p / S_{2p} ..

Volume 296, number 3,4 PHYSICS LETTERS B 17 December 1992

Example

N=20

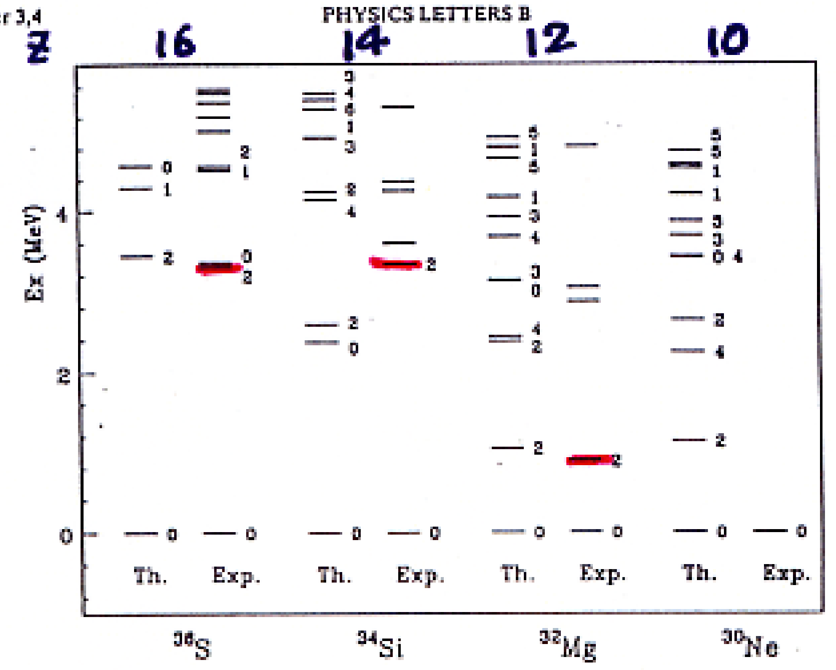
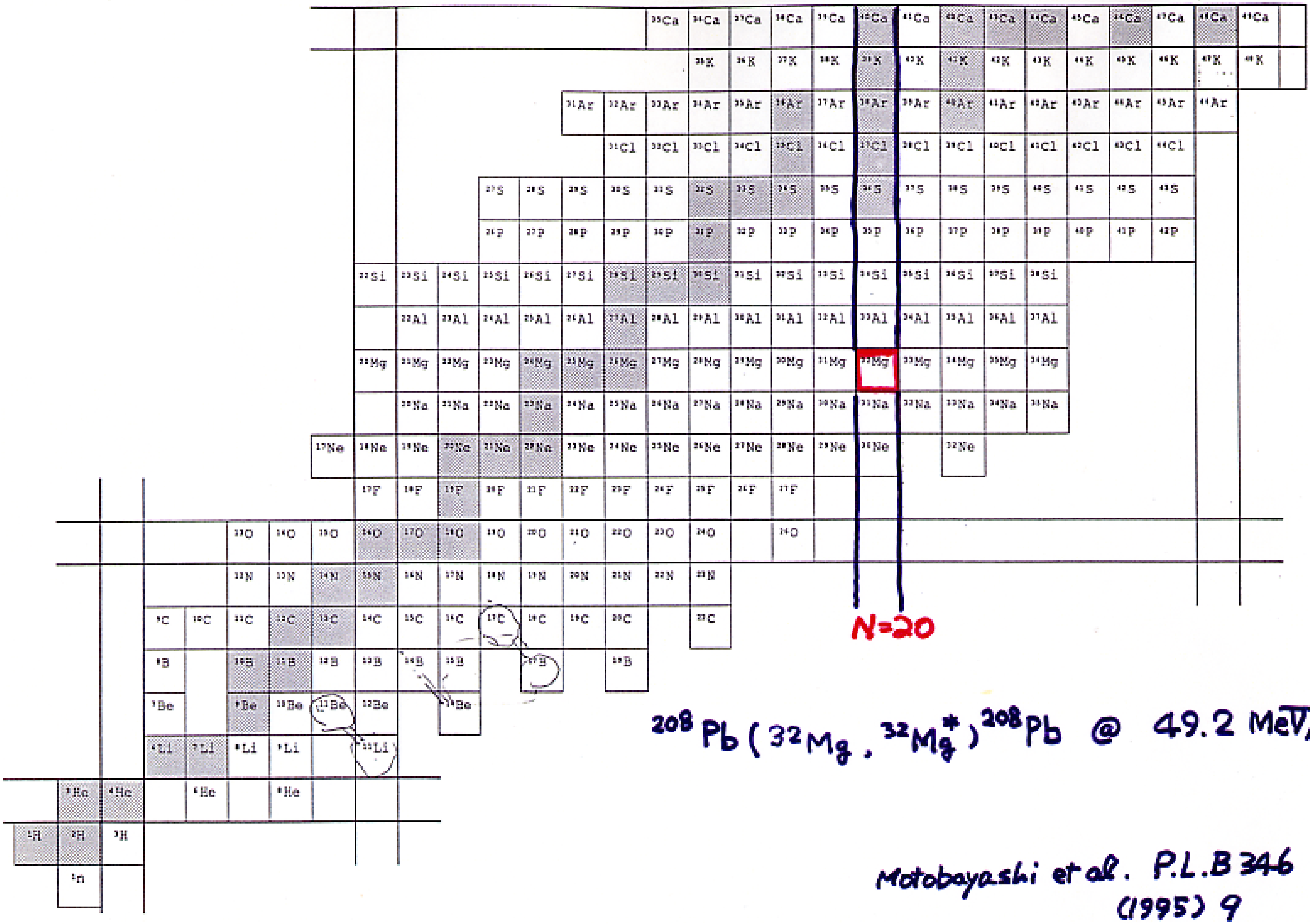


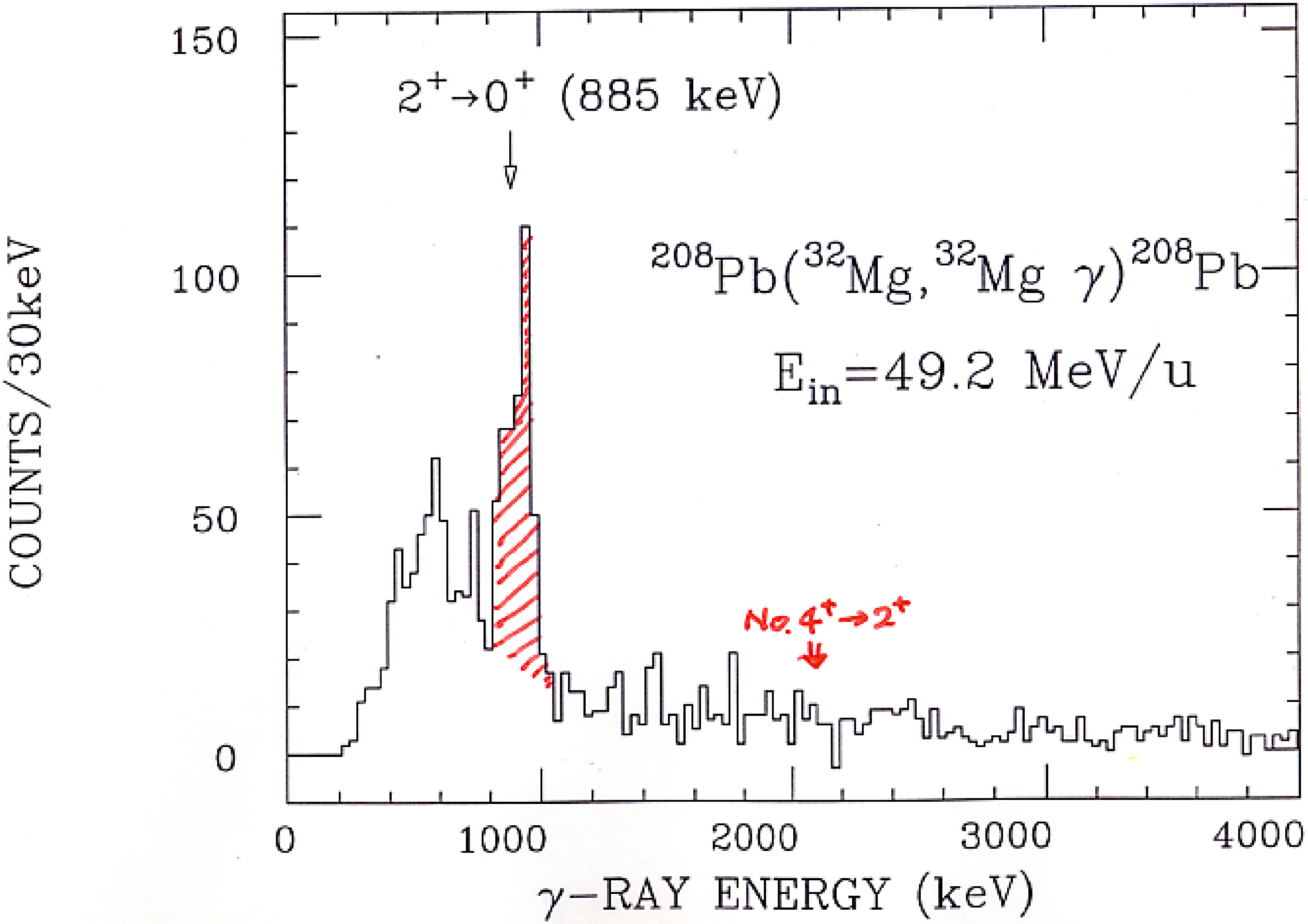
Fig. 1. Experimental (Exp.) and calculated (Th.) energy levels of the positive-parity states of even-Z N=20 isotones.

Fukunishi
Otsuka
Sebe

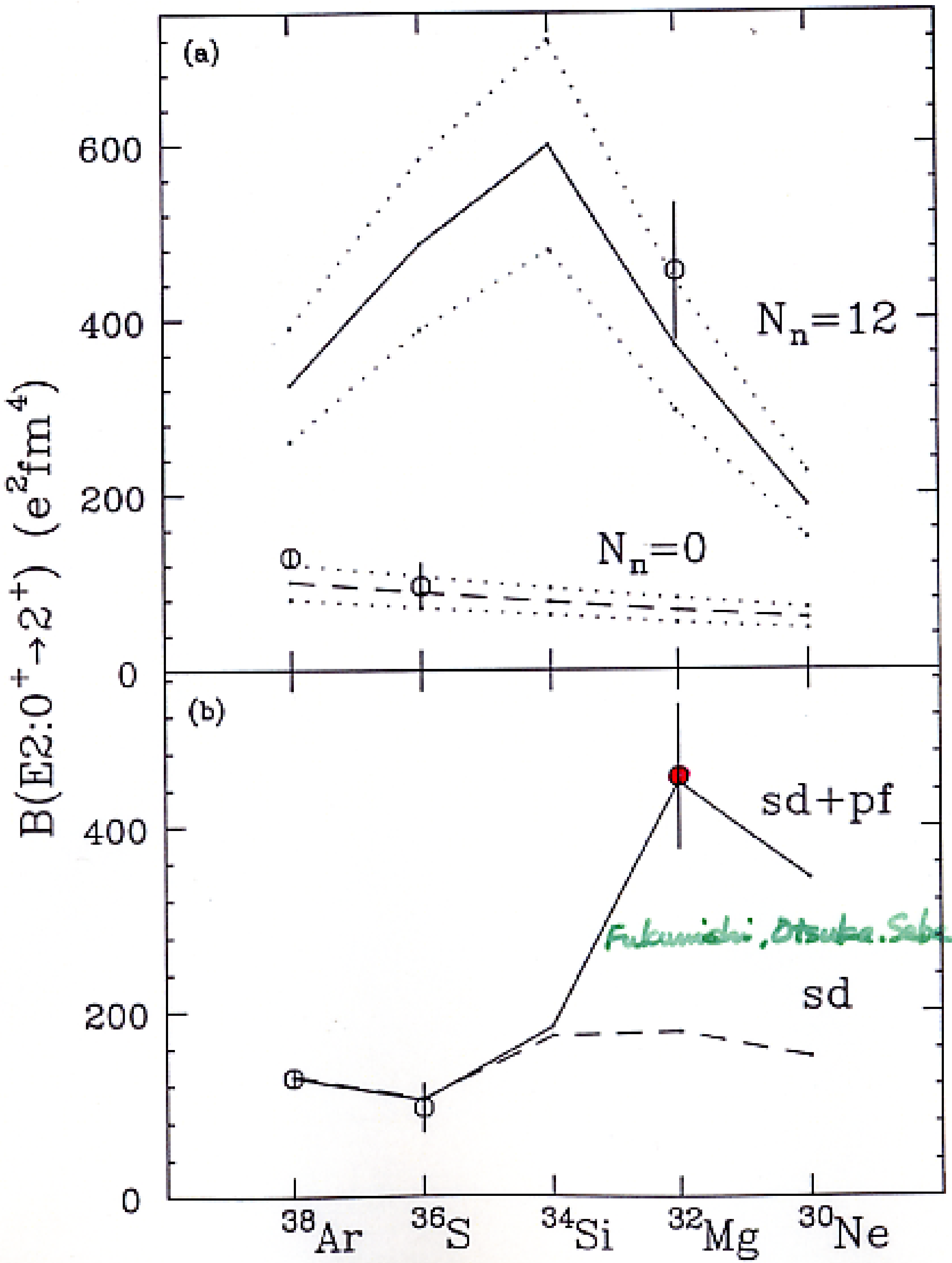


$^{208}Pb(^{32}Mg, ^{32}Mg^{*})^{208}Pb$ @ 49.2 MeV/u

Motobayashi et al. P.L.B 346 (1995) 9



$2^+ \rightarrow 0^+$ (885 keV)
^{208}Pb(^{32}Mg, ^{32}Mg γ)^{208}Pb
E_{in}=49.2 MeV/u
No. $4^+ \rightarrow 2^+$
COUNTS/30keV
γ–RAY ENERGY (keV)
150
100
50
0
0
1000
2000
3000
4000

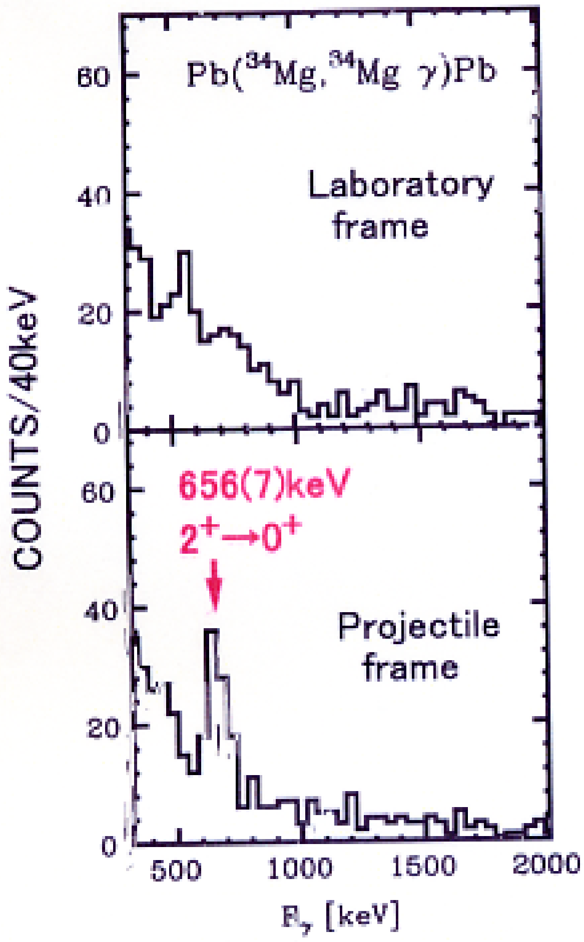


NpNn-model

$B(E2) = 454 \pm 78$ $(e^2fm^4$

Coulomb excitation of ^{34}Mg

Physics Letters B522(2001)227

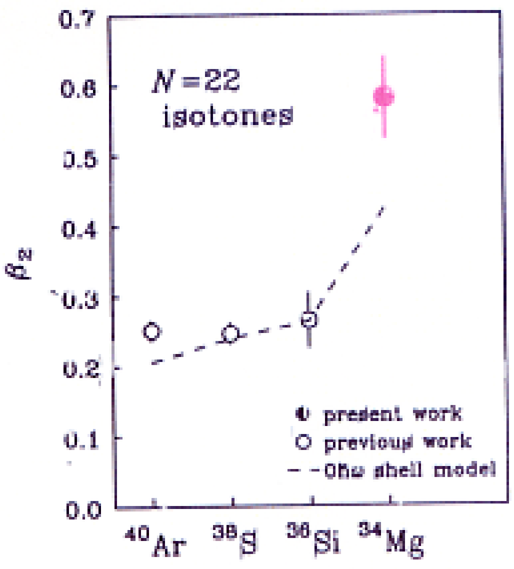


A large excitation cross section of 286(52)mb was obtained from the γ-ray yields.

↓

$B(E2;0^+ \rightarrow 2^+) = 631(126)\ e^2fm^4$

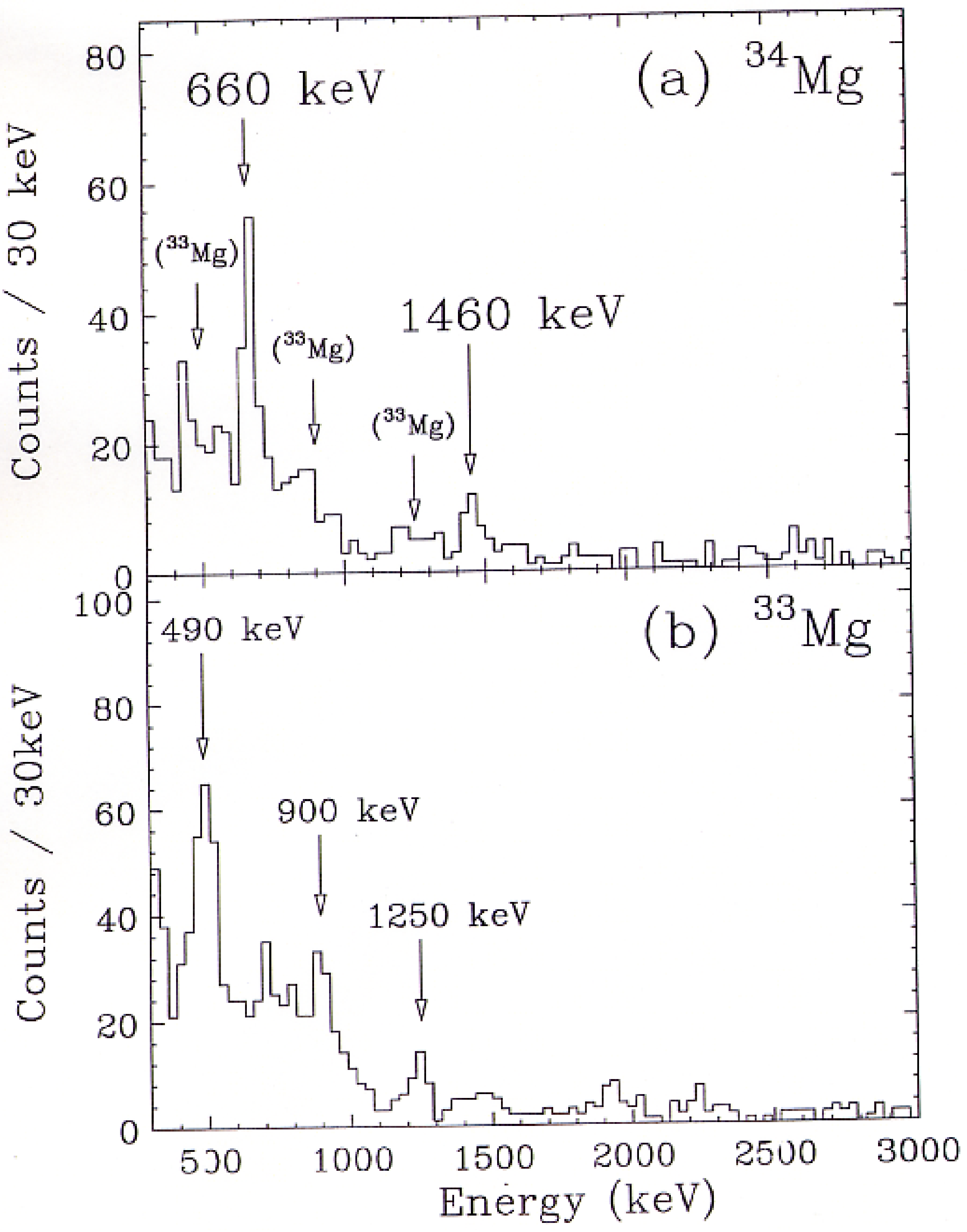
$\beta_2 \sim 0.58$!!



large deformation of ^{34}Mg

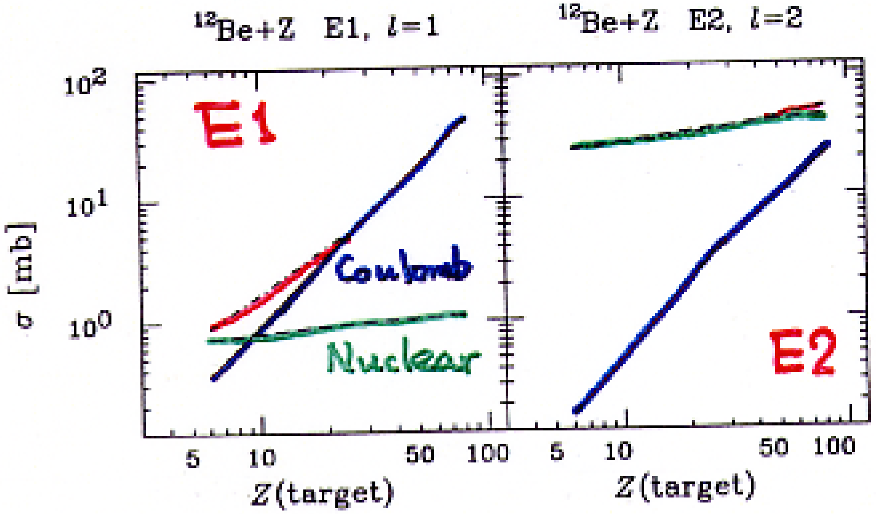
Yoneda et al.

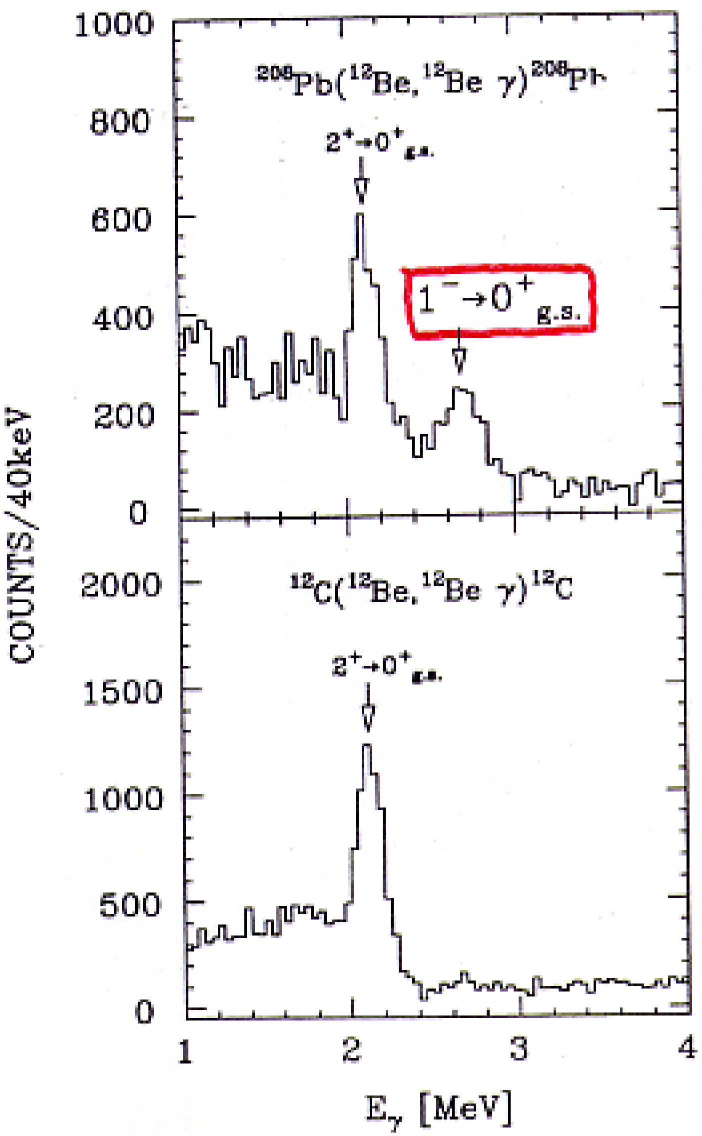
$^{36}Si\ (38A\,MeV) + {}^{9}Be \rightarrow {}^{A}Mg$



Low-lying intruder 1^- state in ^{12}Be

Iwasaki et al., Phys. Lett. 491B (2000)8

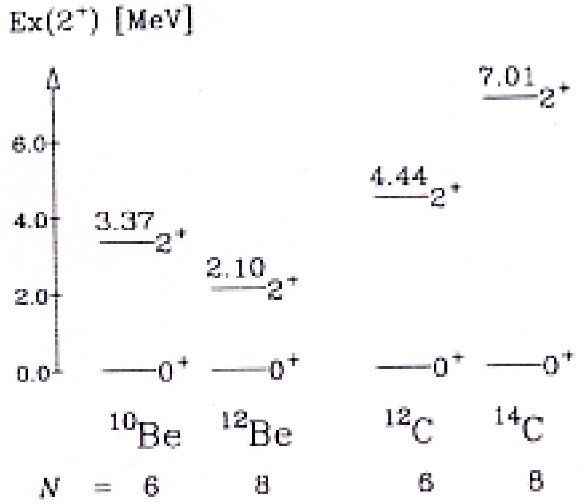


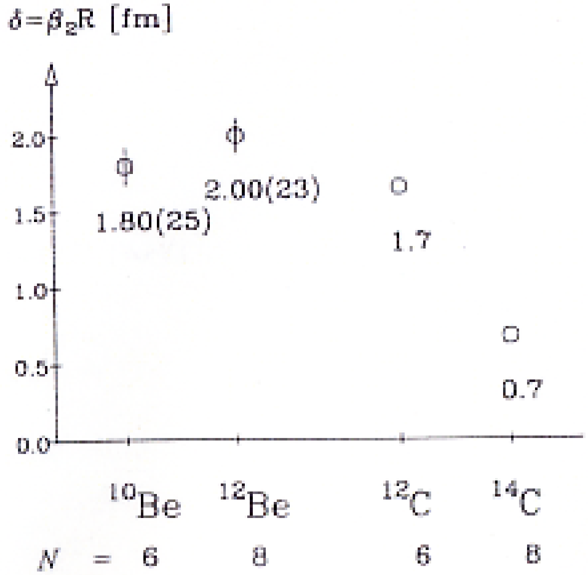


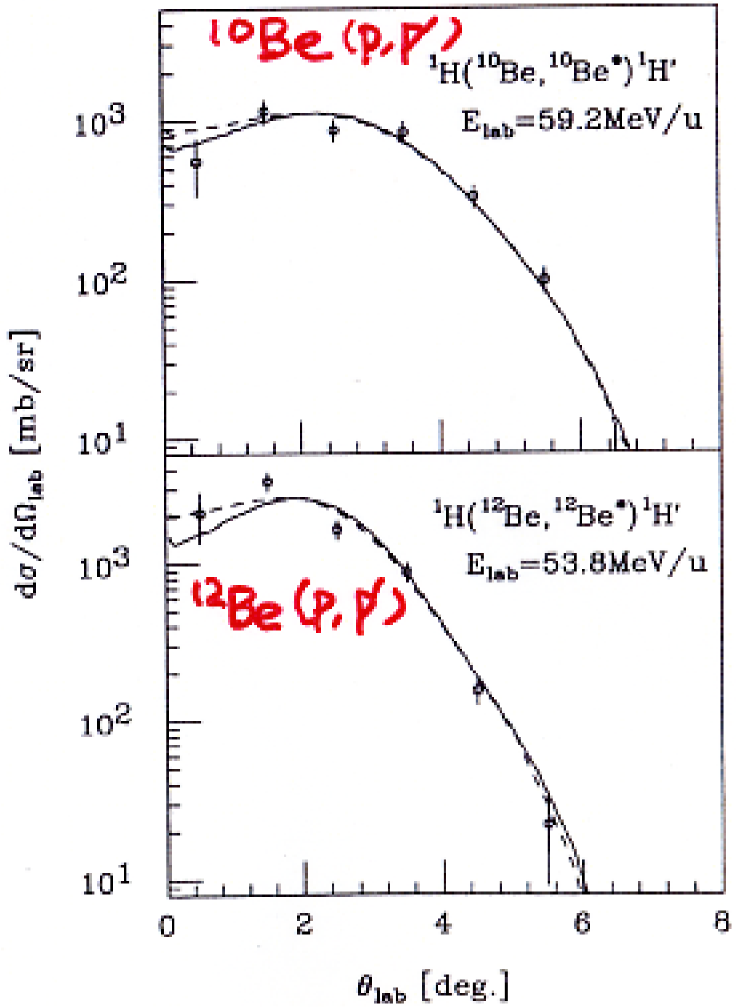
1^- state at E_x = 2.7MeV

Large deformation length of 2^+ state in ^{12}Be

Iwasaki et al., Phys. Lett. 481B (2000)7







Motivation

Breakdown of N=8 Shell Closure in ^{12}Be

Fragmentation [Navin et al., PRL 85 (2000) 266]:
$^{12}\mathrm{Be} \rightarrow ^{11}\mathrm{Be}(1/2^+, 1/2^-)$ **S-factor of s-state: 0.42**

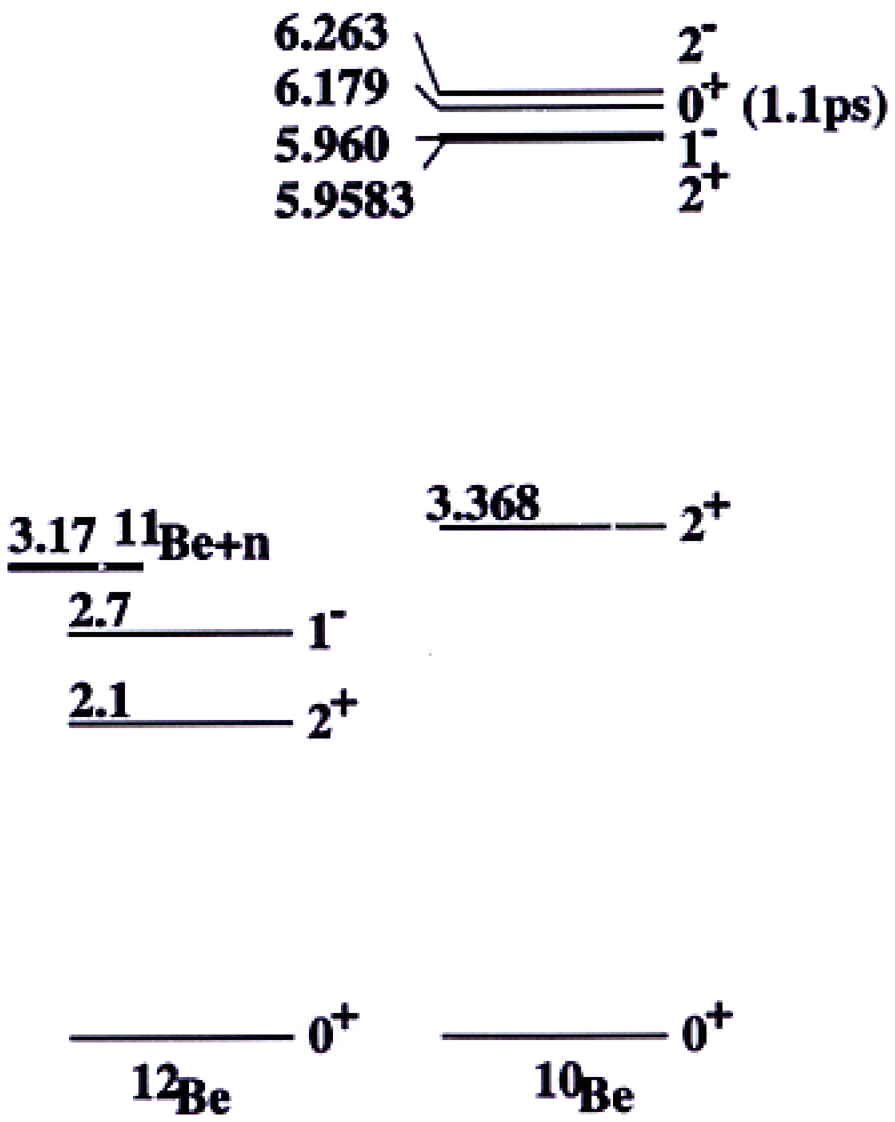
(p,p') [Iwasaki et al., PL B481 (2000) 7]:
Large deformation length (2 fm) of ground state

COULEX [Iwasaki et al., PL B491 (2000) 8]:
Low lying 1^- state (2.7 MeV) 'intruder state'

Where is the 2nd 0^+ state?

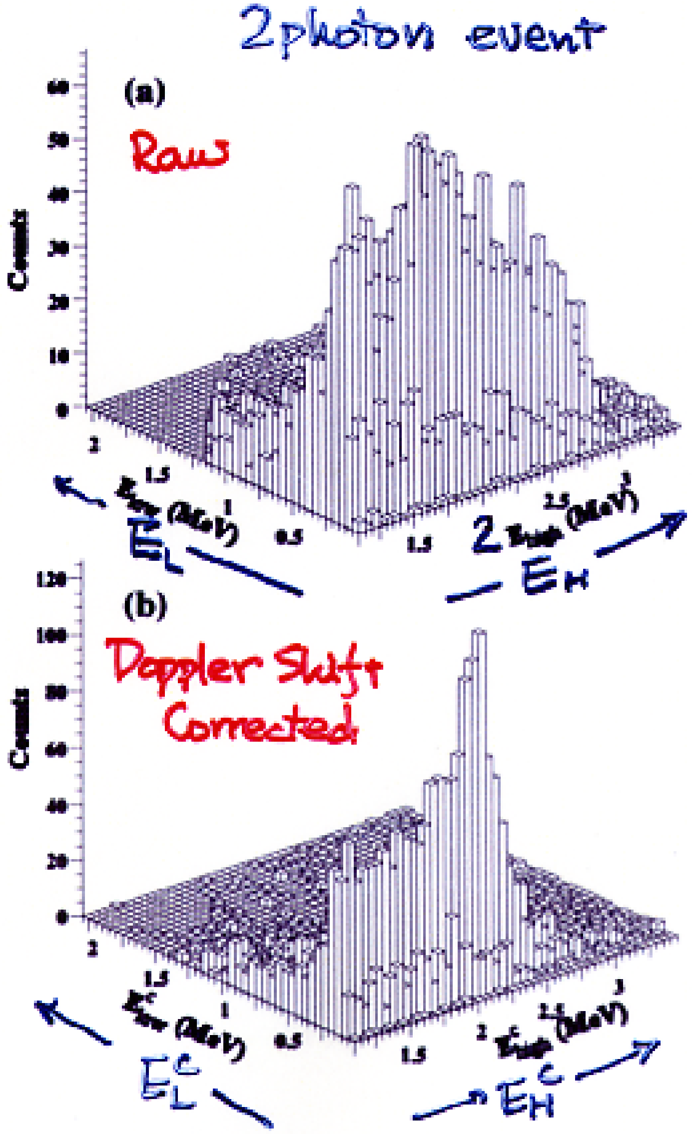
Possible decay channels (for full stripped ion):

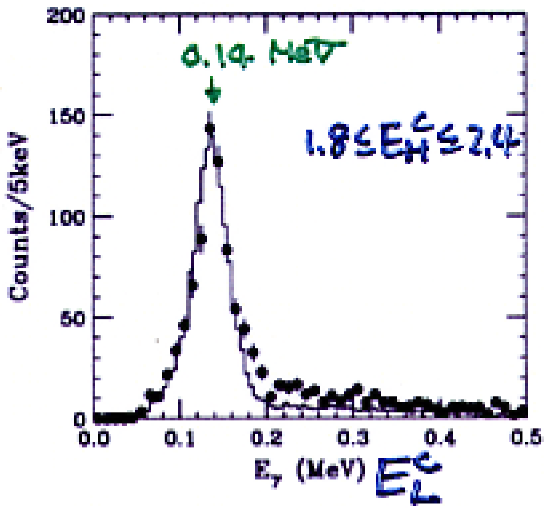
0 < Ex < 1.02 MeV : No decay (beta decay)
1.02 < Ex < 2.1 MeV : electron-positron emission
2.1 < Ex < 2.7 MeV : electron-positron emission
E2 : $0^+ \rightarrow 2^+$; $2^+ \rightarrow 0^+$
2.7 < Ex < 3.17 MeV : electron-positron emission
E1 : $0^+ \rightarrow 1^-$; $1^- \rightarrow 0^+$
E2 : $0^+ \rightarrow 2^+$; $2^+ \rightarrow 0^+$
3.17 MeV < Ex : neutron emission

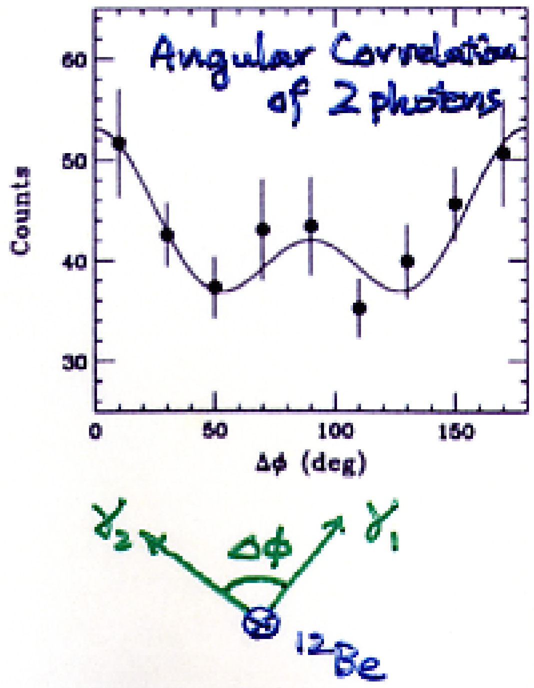


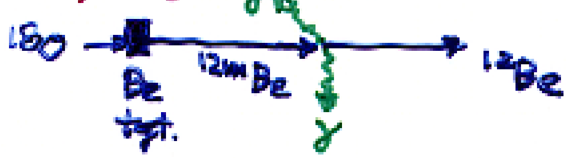
Isomeric 0^+ state in ^{12}Be

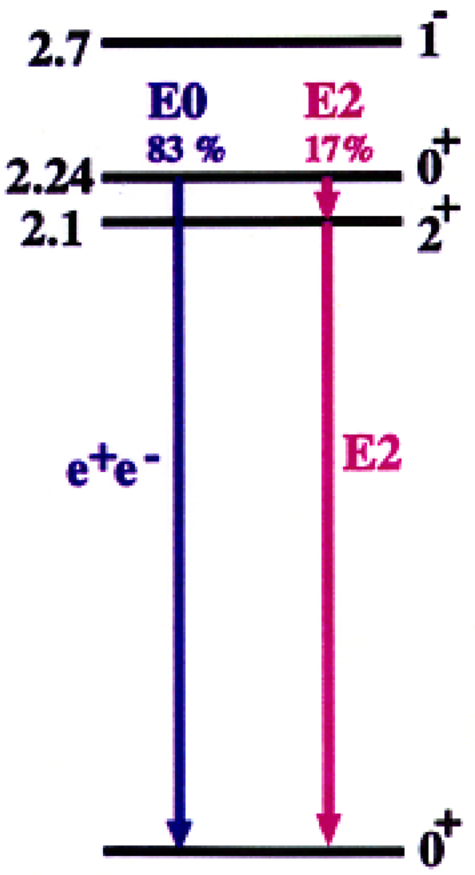
"in-flight decay of ^{12m}Be"











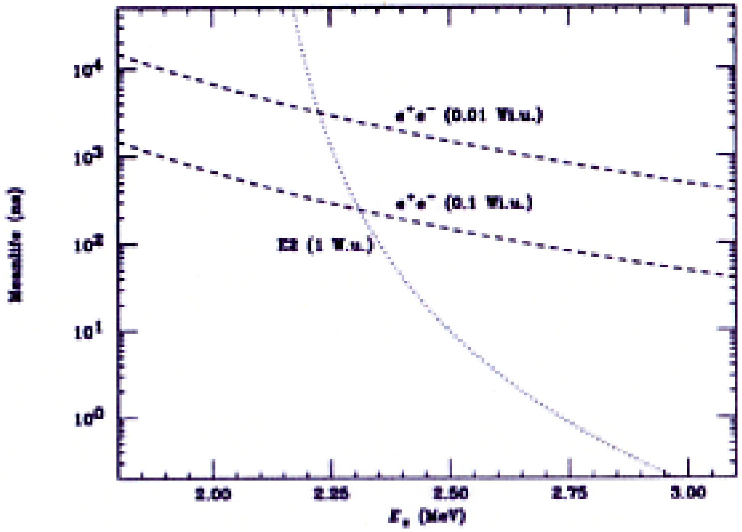
Meanlife of 0 state :

(probably) **nanosec to microsec**

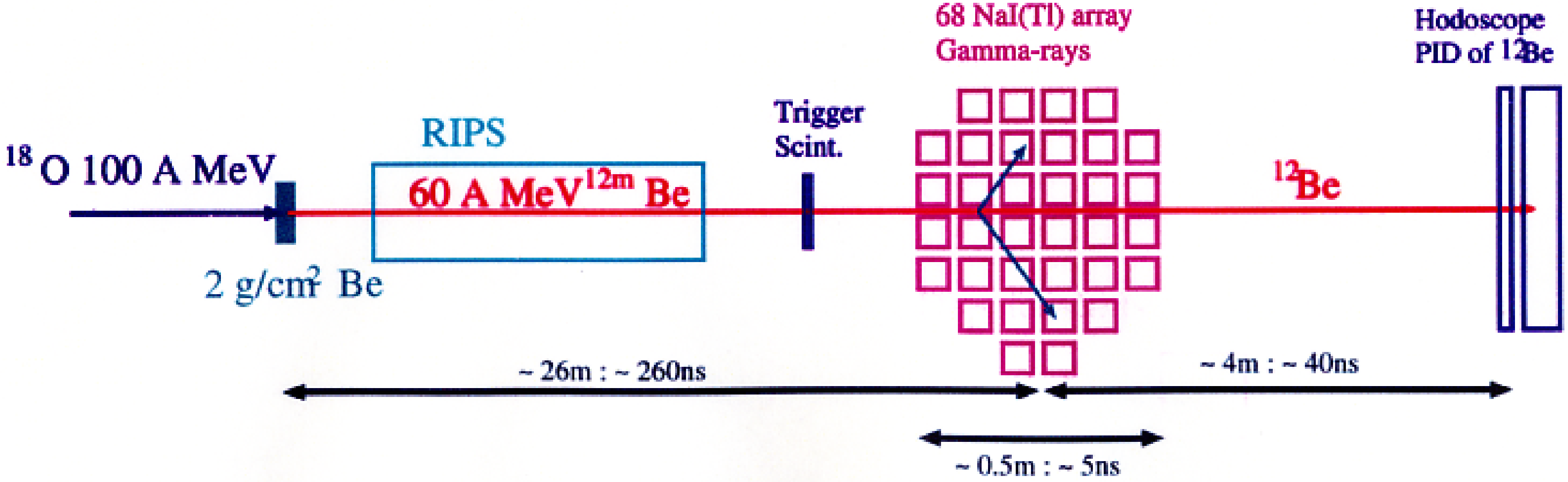
'ISOMER'

produced by projectile fragmentation

gamma rays of cascade decay



Experiment

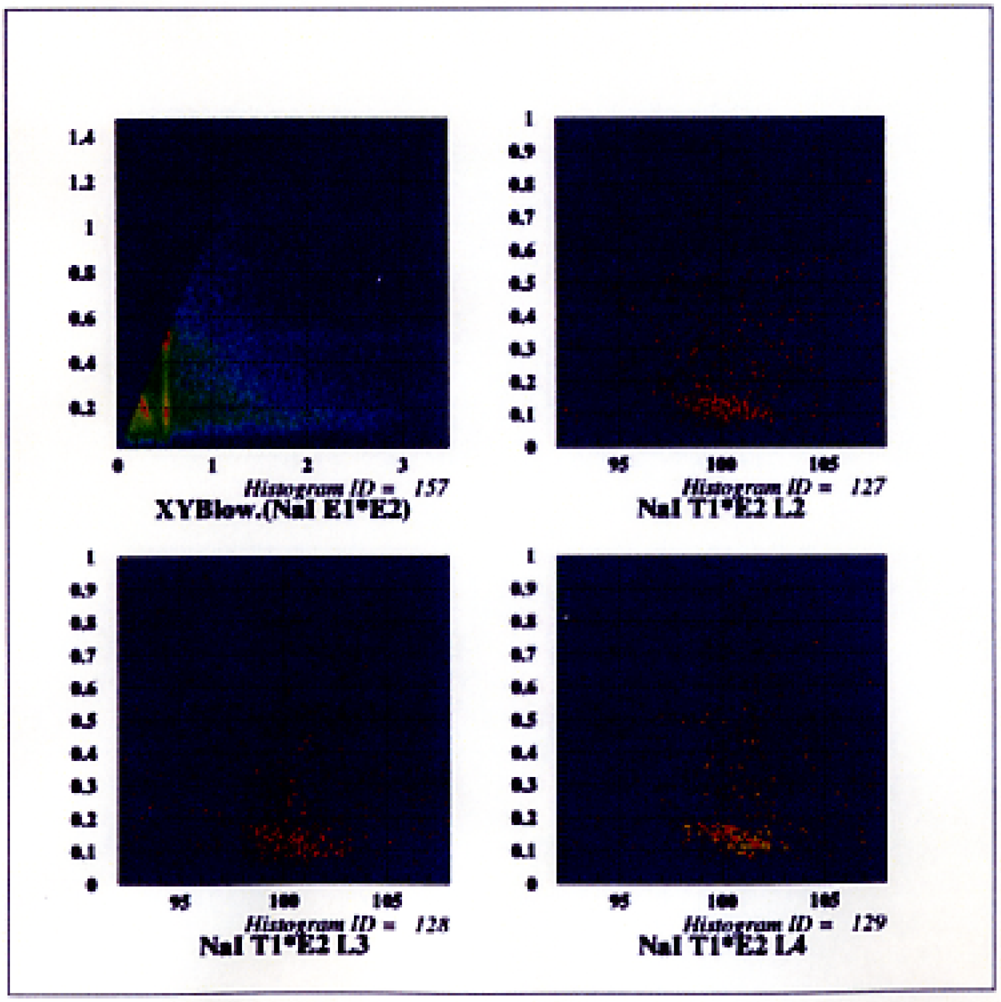


Doppler Shift Correction

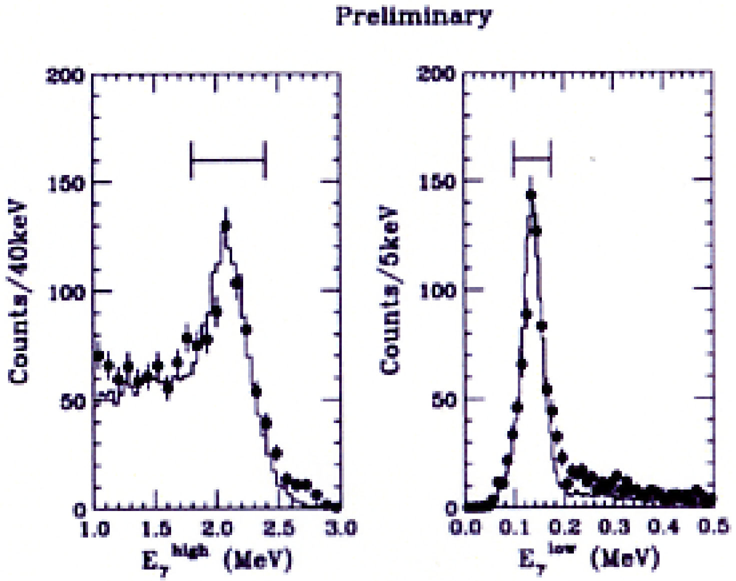
E1-E2 spectrum (E1>E2)

Broad locus at E1 ~ 2 MeV, E2 ~ 0.15 MeV

(Doppler Shift)



Doppler Shift Corrected Spectrum

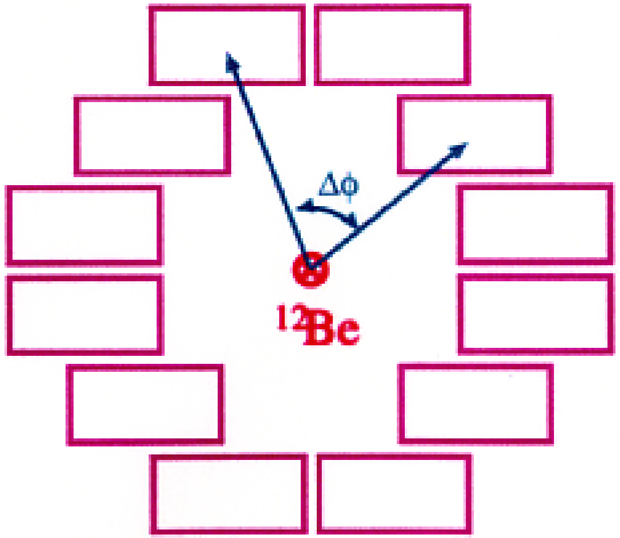


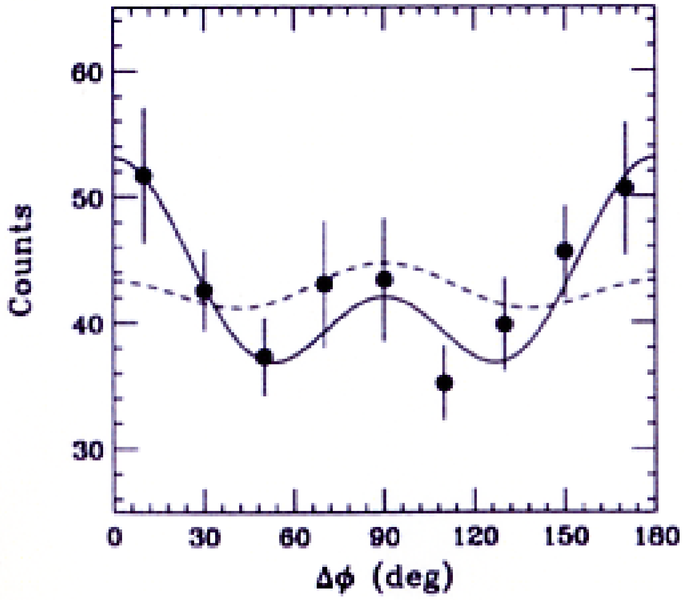
Doppler shifts as a function of Timing

0.14 MeV and 2.1 MeV gammas are emitted from in-flight ^{12} Be

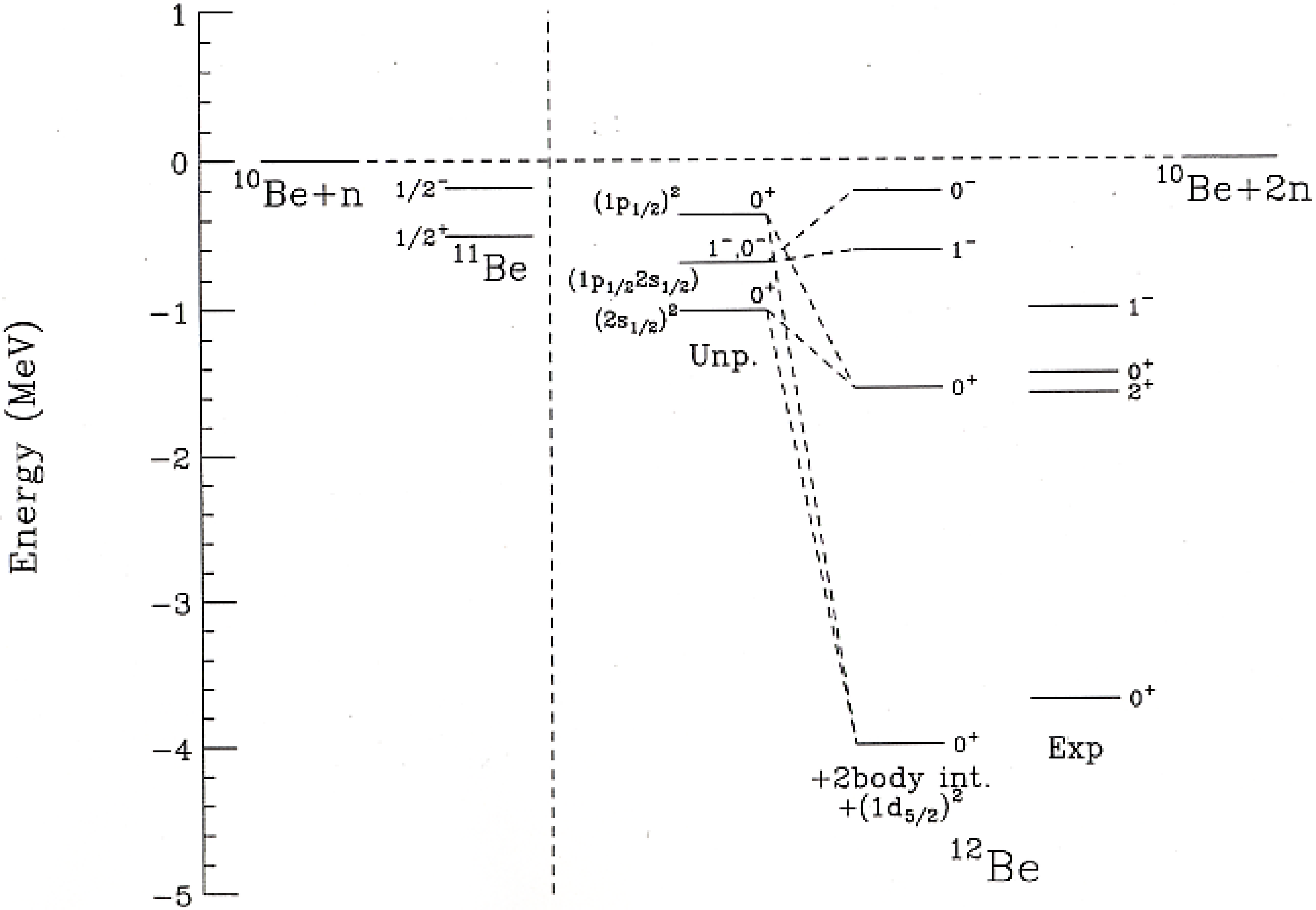
Simulation by GEANT

Angular Correlation





Solid line : 0 -> 2 -> 0
Dashed line : 2 -> 2 -> 0

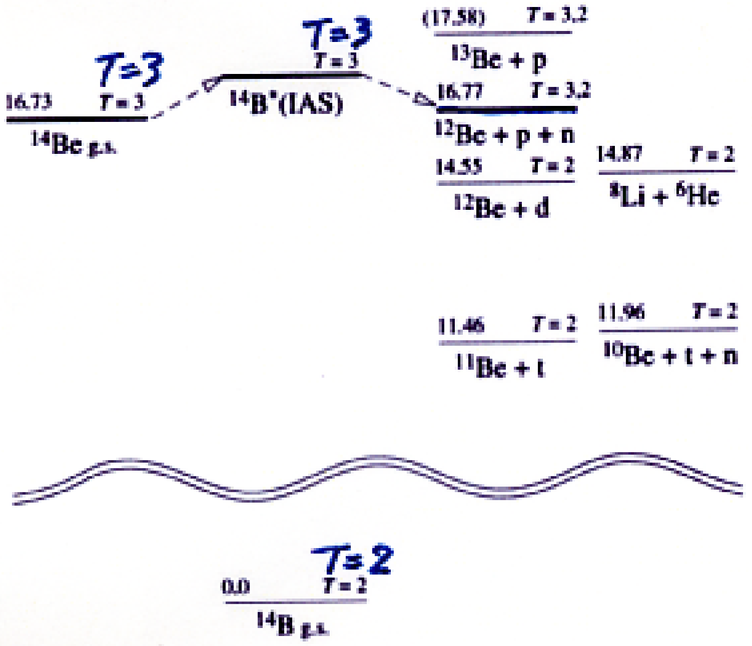


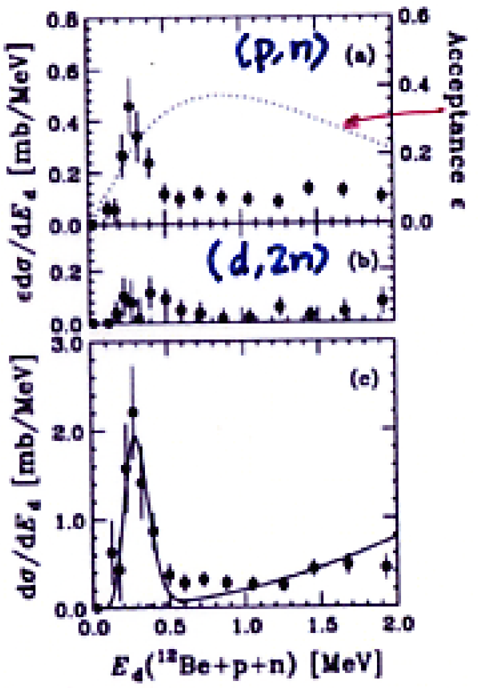
Energy (MeV)
1
0
−1
−2
−3
−4
−5
10Be+n
1/2−
1/2+
11Be
(1p1/2)2
0+
1−,0−
(1p1/22s1/2)
0+
(2s1/2)2
Unp.
0−
1−
0+
0+
+2body int.
+(1d5/2)2
12Be
10Be+2n
1−
0+
2+
0+
Exp

$^{1}H(^{14}Be, ^{14}B^{*}[IAS])n$ at 74 A MeV

Rikkyo-CNS-Tokyo-RIKEN

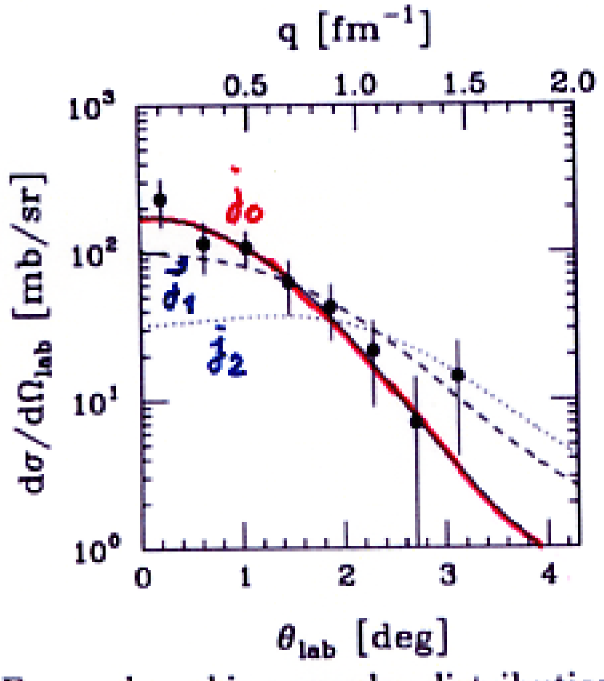
Takeuchi et al., Phys. Lett. B515 (2001) 255





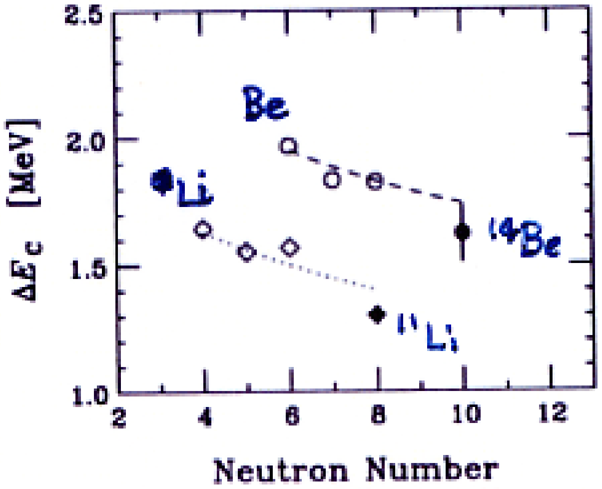
Only the ^{12}Be+p+n channel has $T = 3$ among various open channels

No Fermi transition for (d,2n)



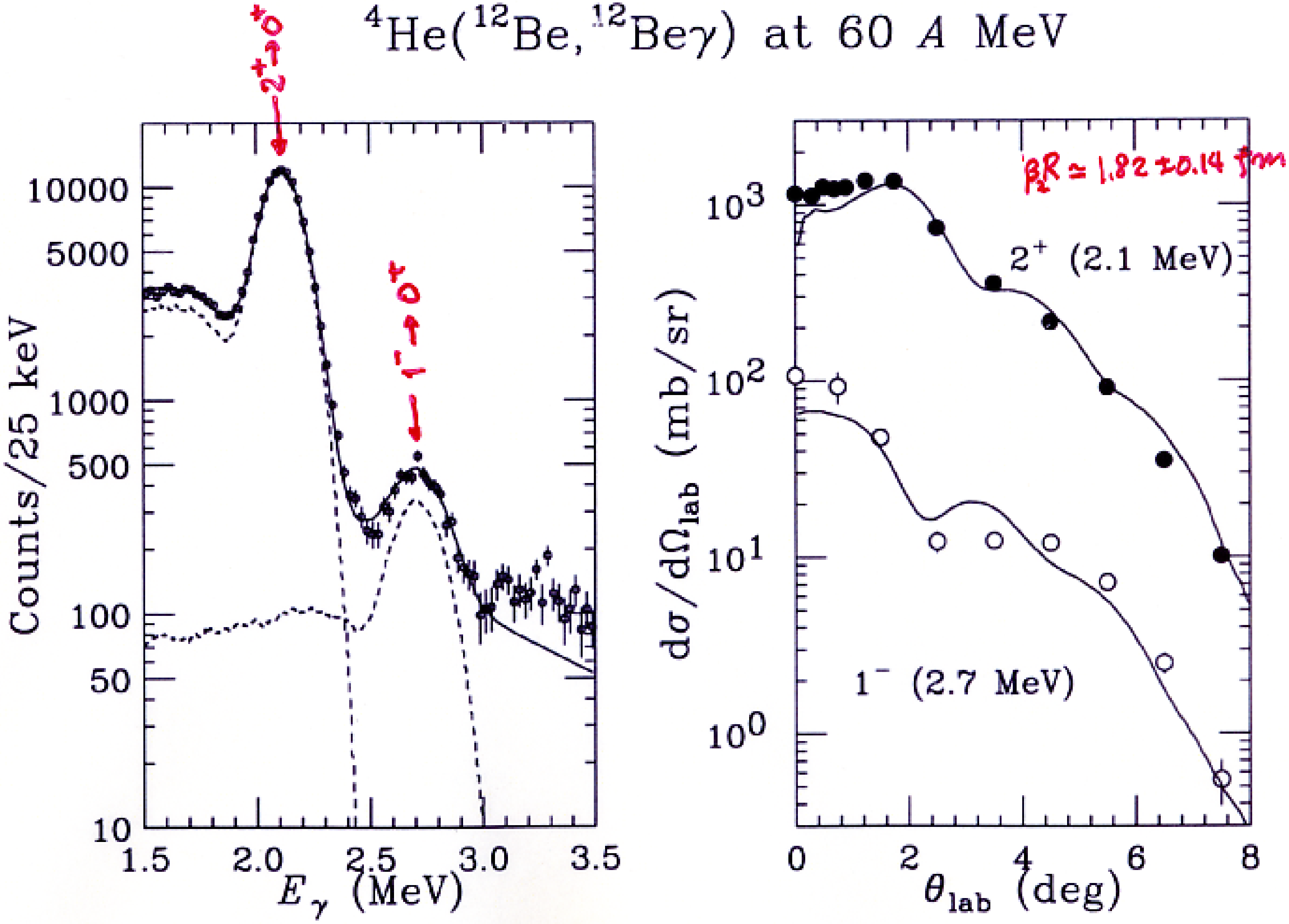
Forward peaking angular distribution ($\ell = 0$)

$$E_x\left({}^{14}B^*(T=3)\right) = 17.06 \pm 0.02 \text{ MeV}$$
$$\text{FWHM}(\simeq \Gamma) = 0.11 \pm 0.05 \text{ MeV}$$
$$\Gamma_{sp}(\ell = 0) = 0.24 \text{ MeV}$$
$$\Gamma_{sp}(\ell = 2) = 0.001 \text{ MeV}$$



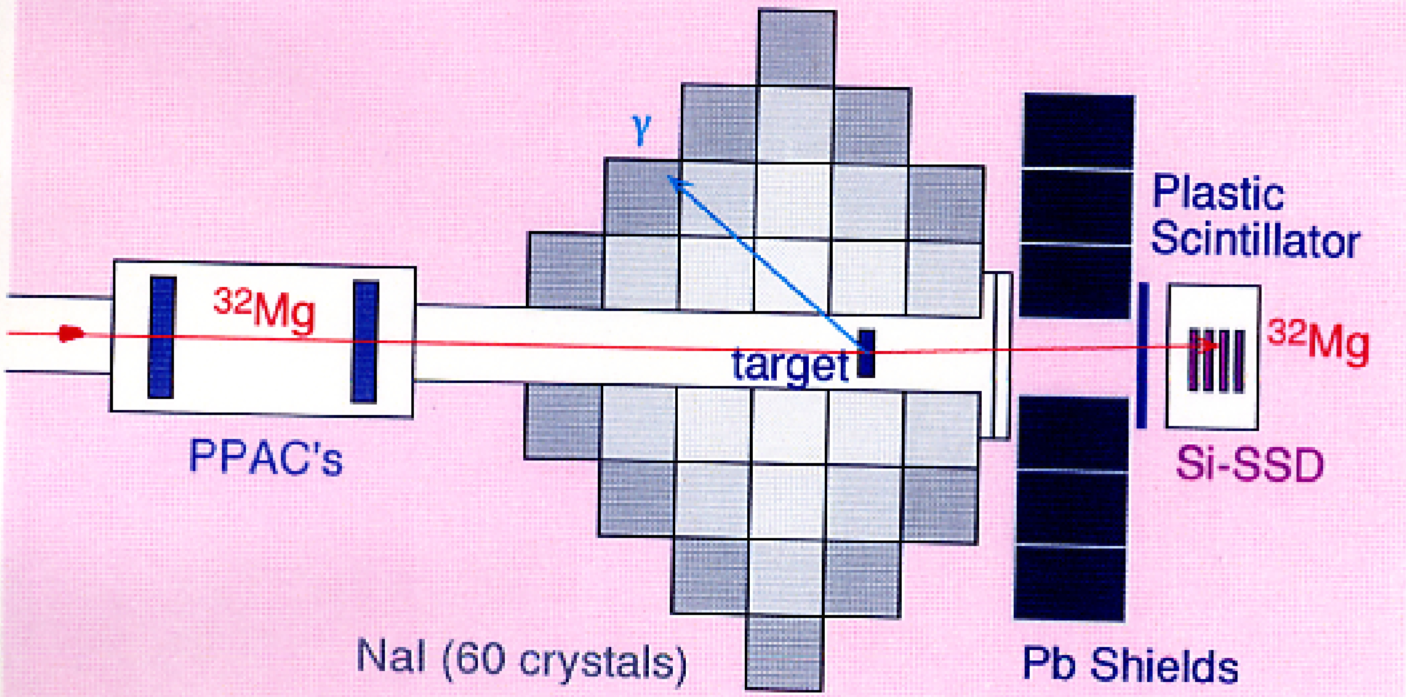
Small ΔE_C for ^{14}Be and ^{11}Li

$^4He(^{12}Be, ^{12}Be\gamma)$ at 60 A MeV

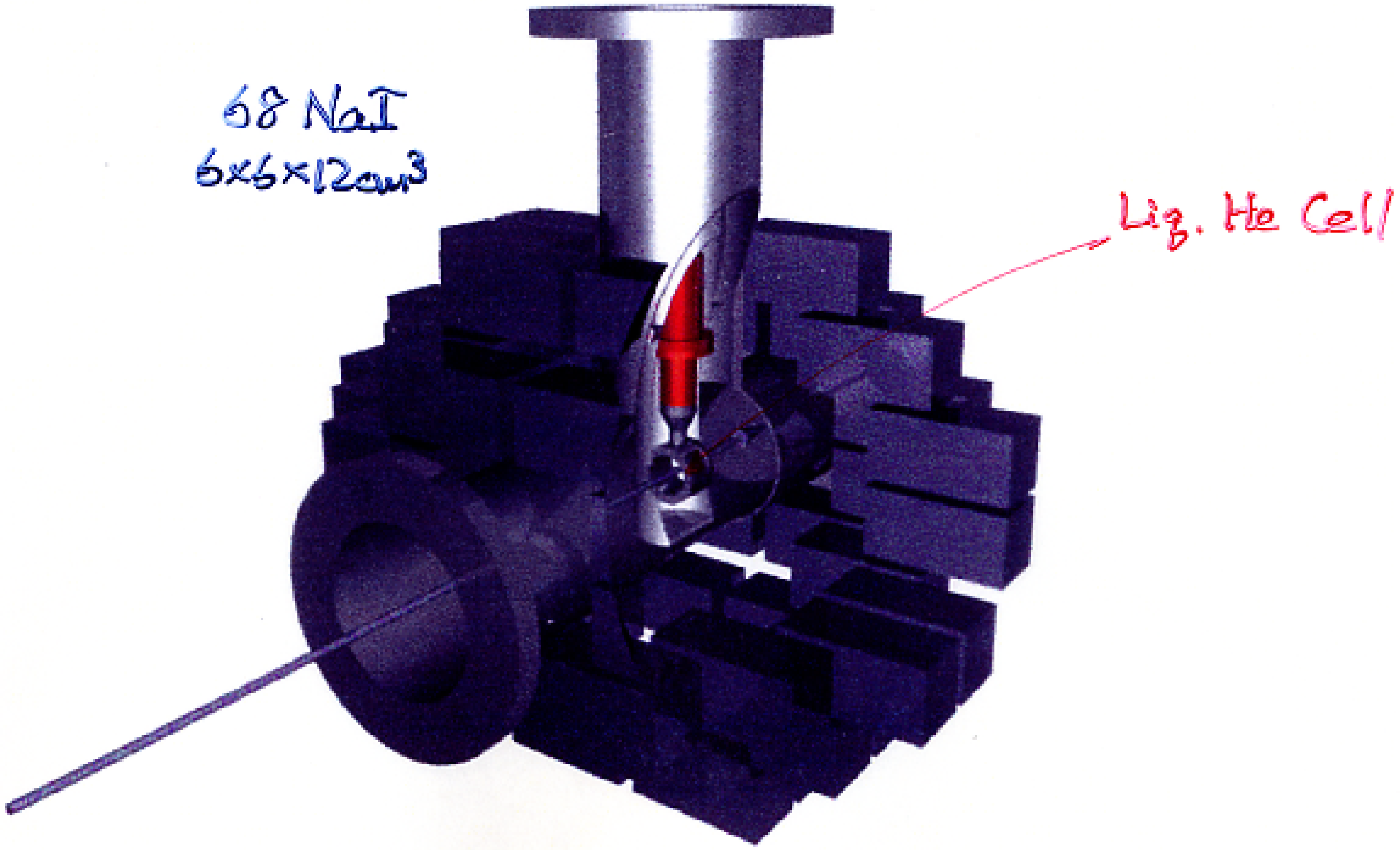


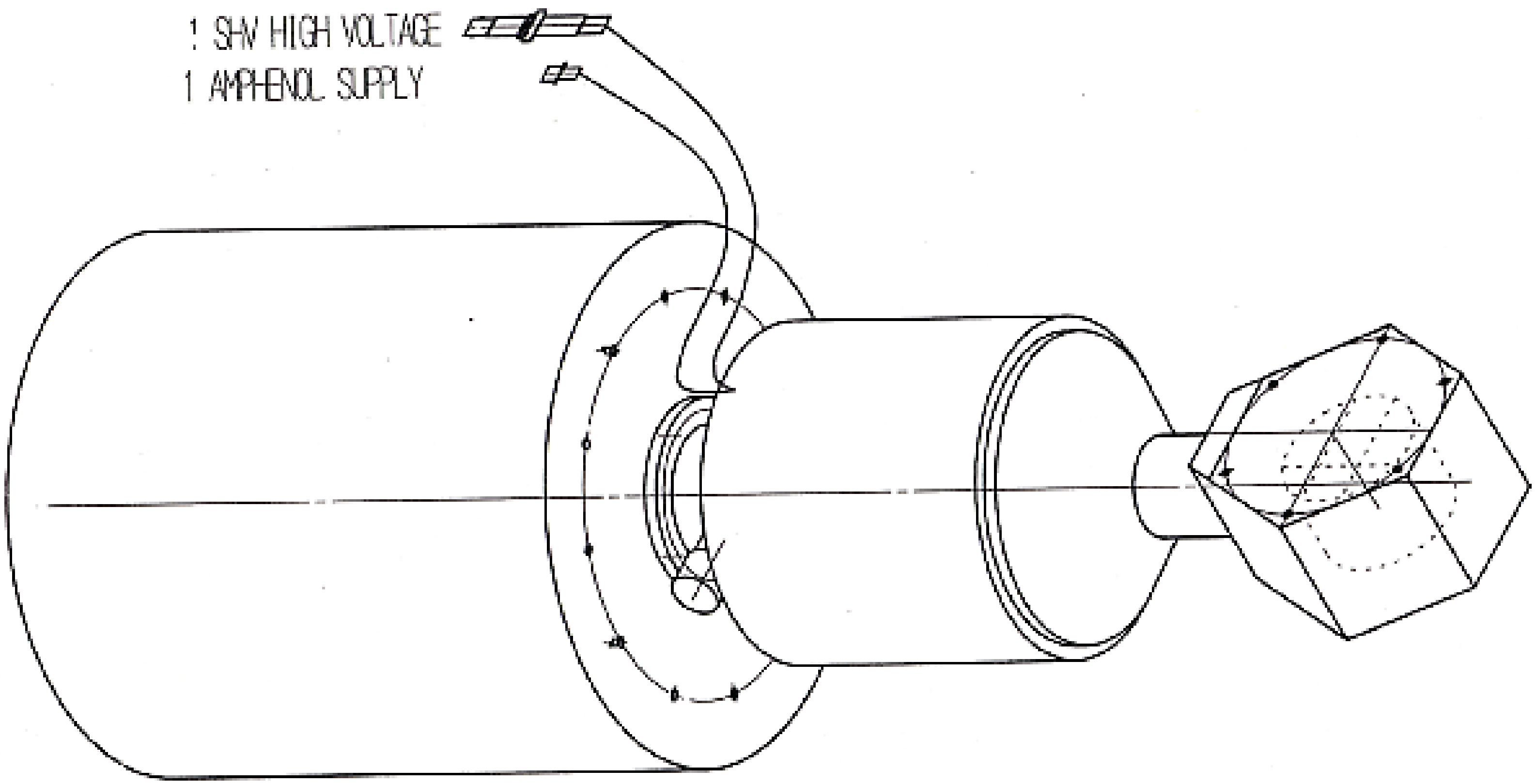
$^{208}Pb(^{32}Mg, ^{32}Mg^{*}\gamma)^{208}Pb$

Experimental Setup



Motobayashi et al., PLB 346 ('95) 9

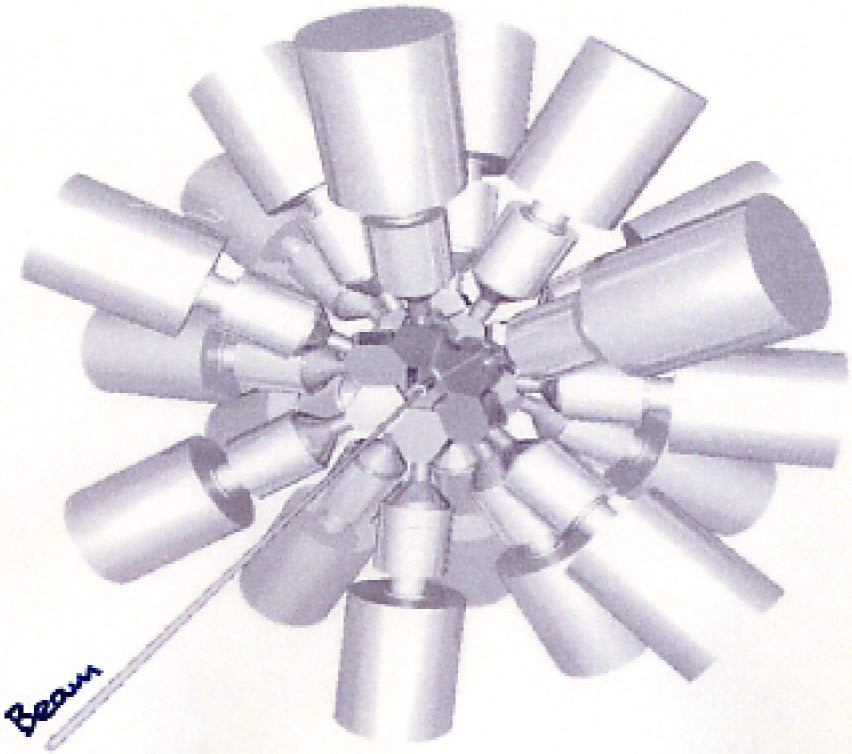

68 NaI
6×6×12cm³
Liq. He Cell



1 SHV HIGH VOLTAGE
1 AMPHENOL SUPPLY

Array Configuration

- Locates 18 detectors around 90 degree with respect to beam



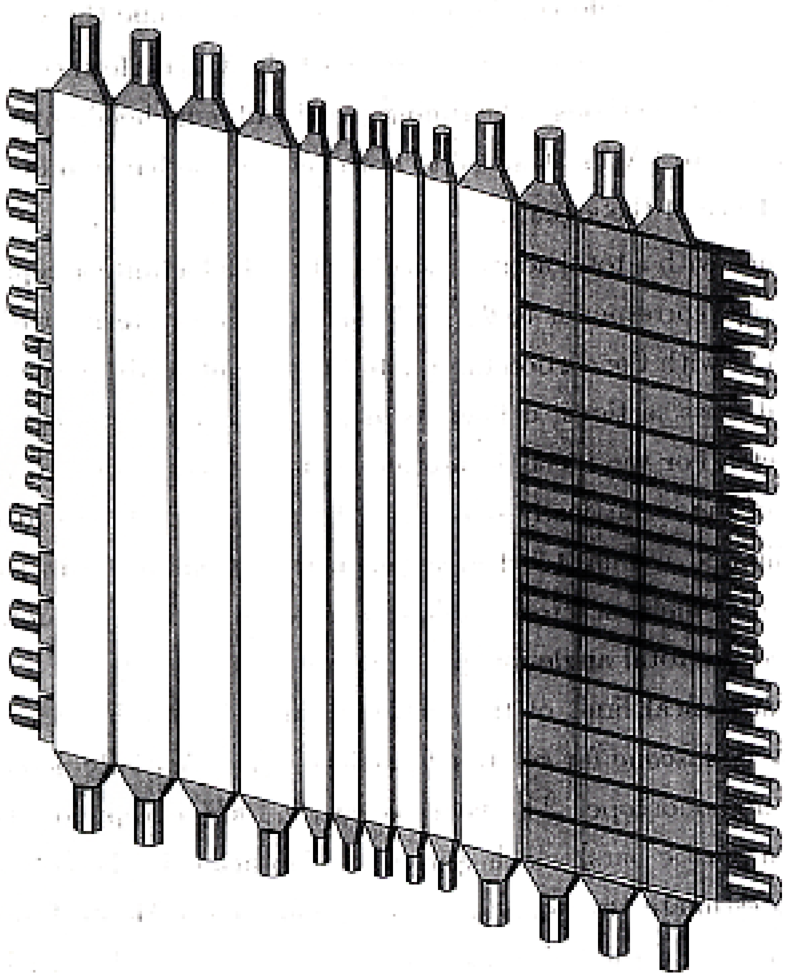


Figure 3.4: Schematic view of the plastic scintillator hodoscope. The hodoscope consisted of thirteen 5 mm thick ΔE- and sixteen 60 mm thick E-plastic scintillators.

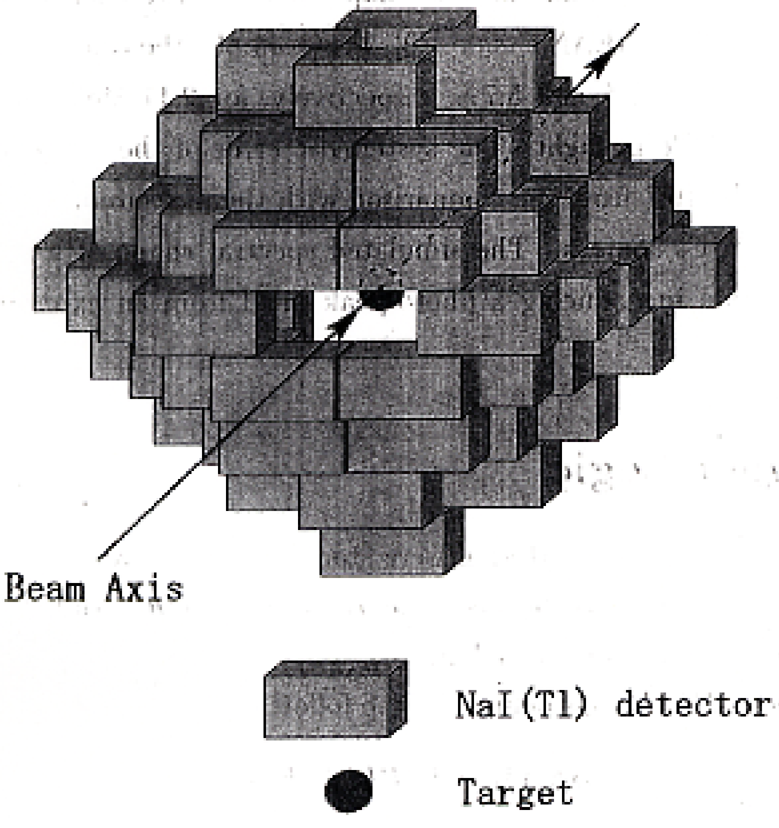


Figure 3.5: A granular array of 55 NaI(Tl) detectors.

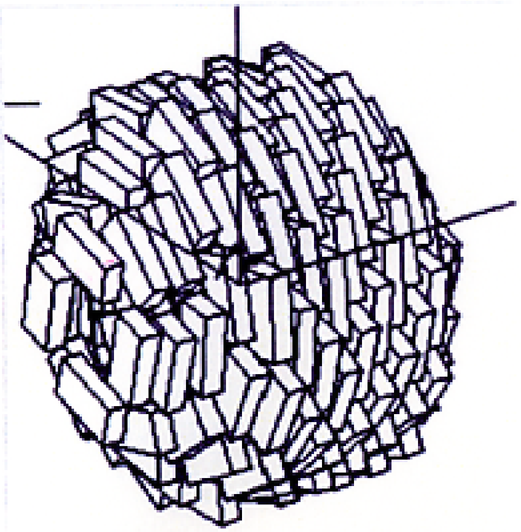
NaI(Tl) Array

Geometry

crystal
4cm × 8cm × 16cm
160 crystals
radius of "ball" (NaI center) : 30 cm

Performance

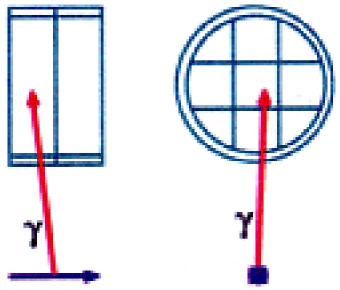
angular resolution : 8 deg
full-energy-peak efficiency at 1 MeV : 30 %
intrinsic energy resolution : 70 keV for 1 MeV
energy resolution of Doppler shift correction:
70 keV for 1 MeV γ from β=0.3 particle



Germanium Array

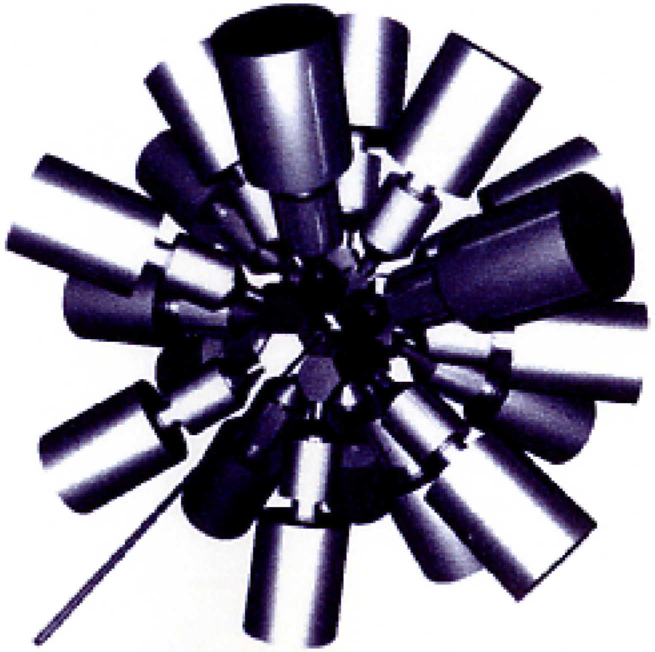
Geometry

crystal
planar type : direction of γ-ray // electrode
active volume : $2cm^2 \times 6cm^2$
segmentation : 3×3
2 crystals in the same cryostat = 1 detector
18 detectors (36 crystals) :
around 70, 90, 110 degree
radius of "ring" (Ge center) : 11 cm



Performance

angular resolution : 1 deg (pulse shape analysis)
full-energy-peak efficiency at 1 MeV : 5 %
intrinsic energy resolution : < 3 keV for 1 MeV
energy resolution of Doppler shift correction:
8 keV for 1 MeV γ from β=0.3 particle



検出器の構成

荷電粒子検出器