The study of the high-spin isomer beam production via the fragmentation reaction at 350 MeV/u

K.Kawata [1)]

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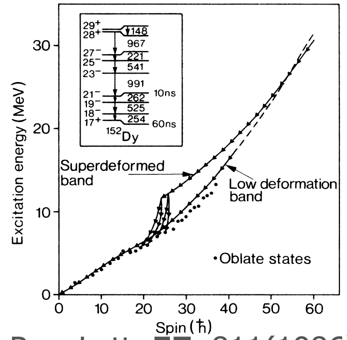
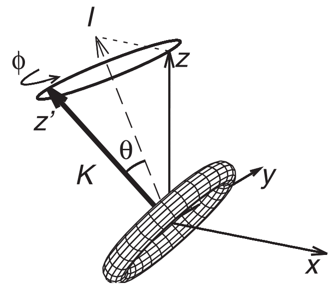
Introduction

- **Isomers** :longer life excited state(>1 ns), Spin-gap, Deformed and K
- High-spin isomers: valuable probes
  - nuclear structure, nuclear astrophysics, and applied research.
    - The interaction at the higher level
    - Nuclear reaction
    - Hyper deformation
    - Torus



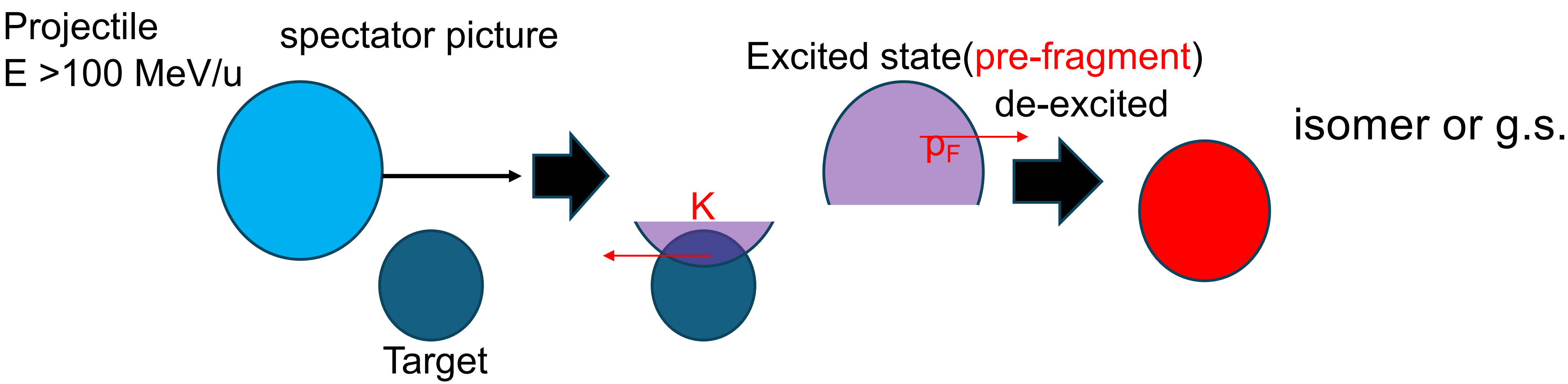
Phys. Rev. Lett. **57**, 811(1986)

- The unstable beam produced by fragmentation
- The selective production and separation of specific isomeric states remain challenging.



PHYSICAL REVIEW C **90**, 034314 (2014)

Fragmentation



The momentum width is spread by Fermi motion.(G.H. Formula)

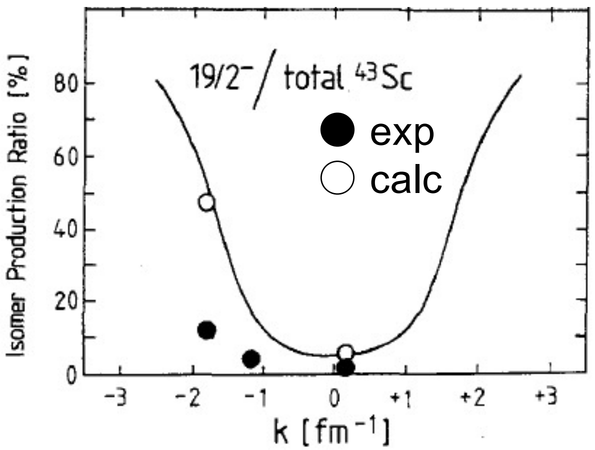
- $\sigma = \sigma_0 \sqrt{\frac{A_f(A_p - A_f)}{A_p - 1}}$, $\sigma_0 = 90\ MeV/c$

A.S. *Goldhaber Physics Letters B* **53** 306308 (1974)

・Isomer and g.s. are produced for the secondary beam via the pre-fragment

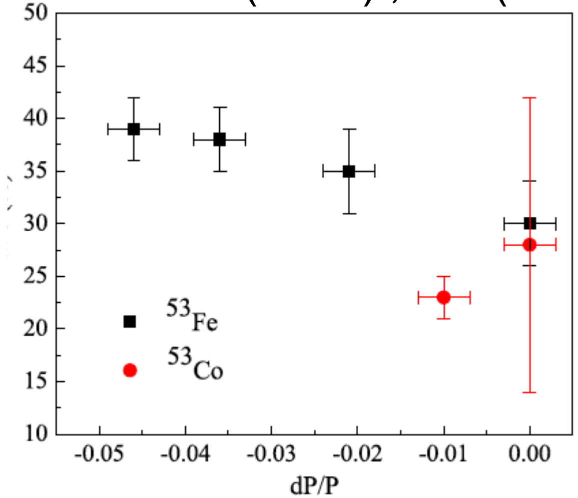
Previous study in isomer production

^{46}Ti to ^{43}Sc(19/2-)



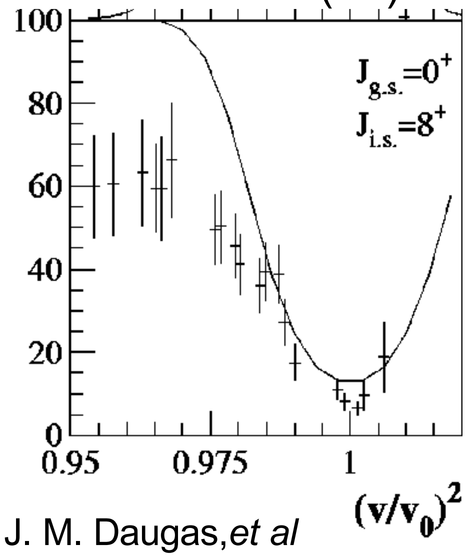
W.-D. Schmidt-Ott, *et al*
Zeitschrift für Physik A Hadrons and Nuclei 350 215--219 (1994)

^{78}Kr to ^{53}Fe(19/2-) ,^{53}Co(19/2-)



X. L. Tu *et al*
PRC **95**,014610(2017)

^{92}Mo to ^{88}Zr(8+)



J. M. Daugas,*et al*
Phys. Rev. C **63** 064609 (2001)

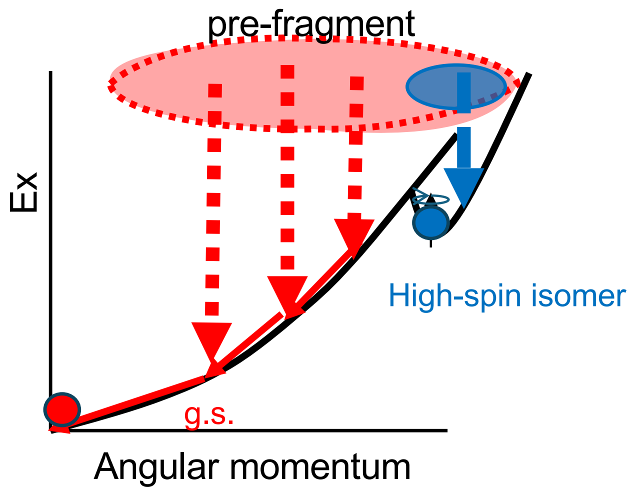
・Isomer ratio depends on the momentum transfer

・The theoretical calculation suitable for each experimental condition is under discussion.（De jong *Nucler.Phys A* ***4***, 435444 (1997))

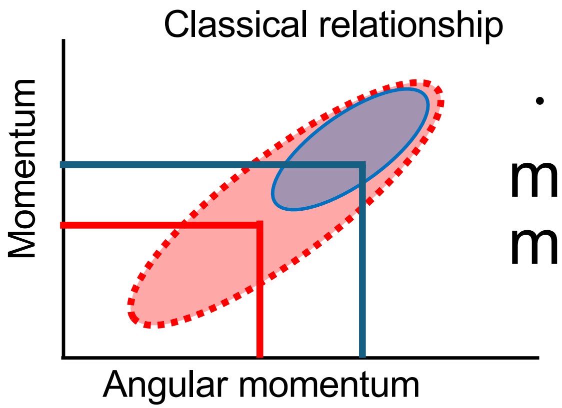
Purpose

- To explore an effective way to produce various unstable beams, including the high-spin isometric state.
- To clarify the momentum transfer to the isomer in fragmentation

Pre-fragment production and decay



・A high-spin isomer can restrict the angular momentum.



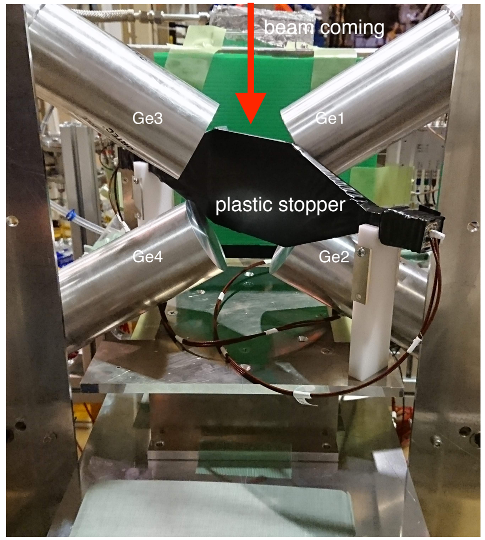
・The momentum distribution with and without isomer may provide the relationship between transferred linear momentum and angular momentum.

Experiment @HIMAC

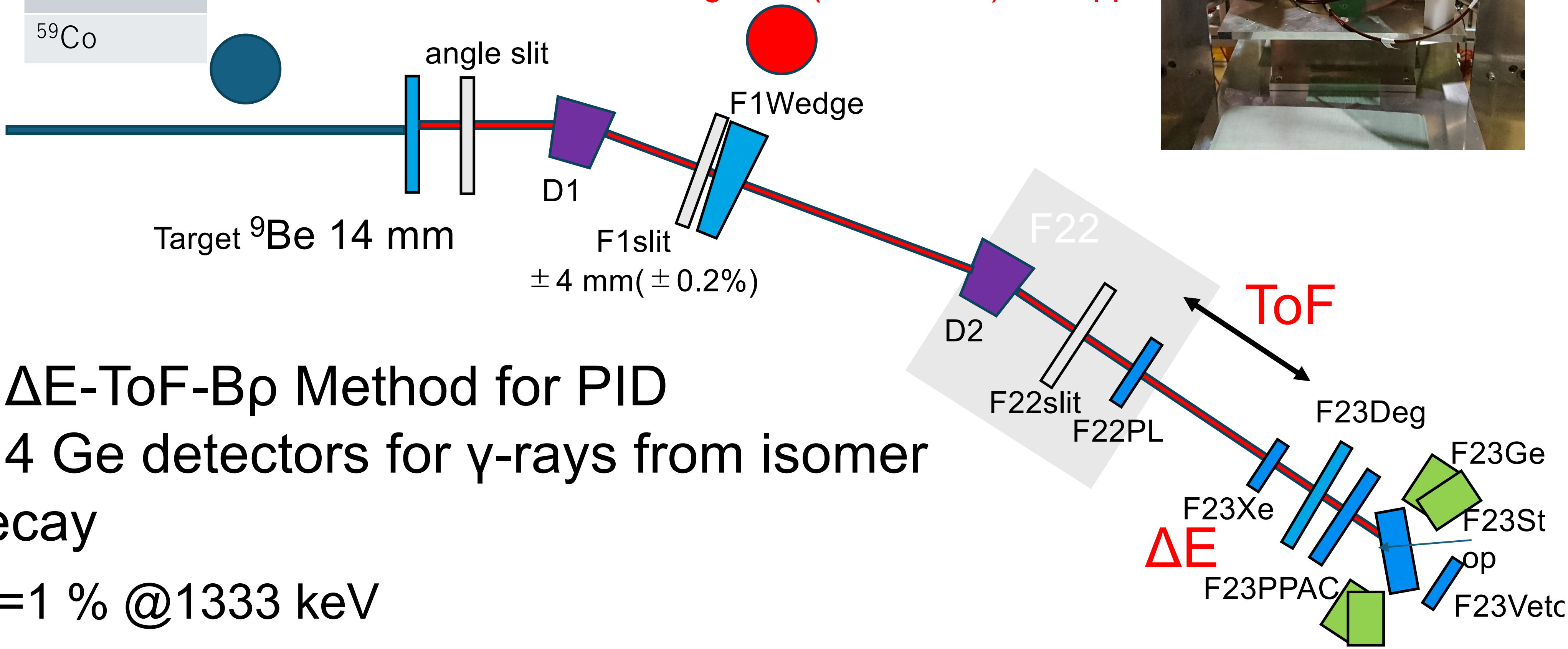
Projectile
^{58}Ni
^{59}Co

Primary(350 MeV/u) ~10^7 pps

Fragment	L_{iso}
^{52}Fe	10
^{53}Fe	8
^{54}Co	6



Fragment:(300 MeV/u) ~10^3 pps



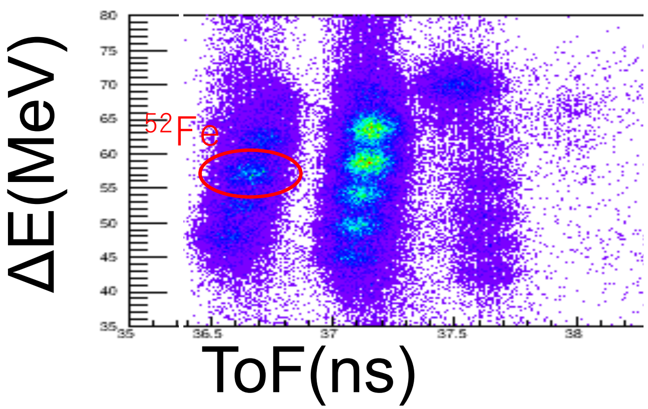
・ΔE-ToF-Bρ Method for PID

・4 Ge detectors for γ-rays from isomer decay

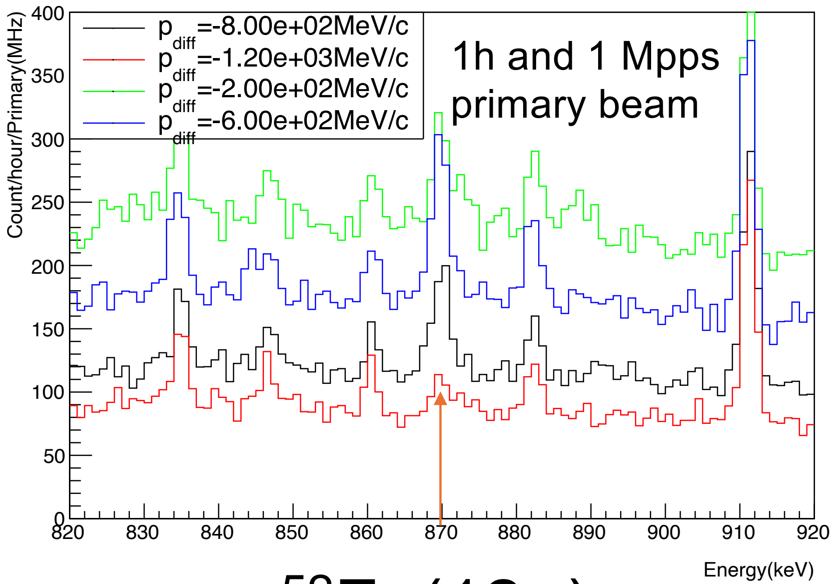
ε_γ=1 % @1333 keV

Analysis of yield of the isomer and g.s.

PID

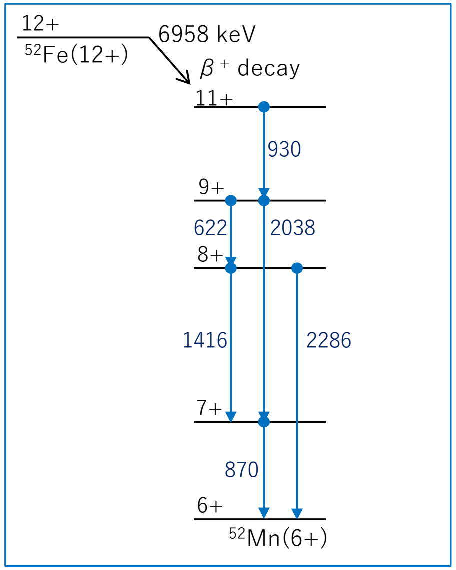


γ-ray Energy plot



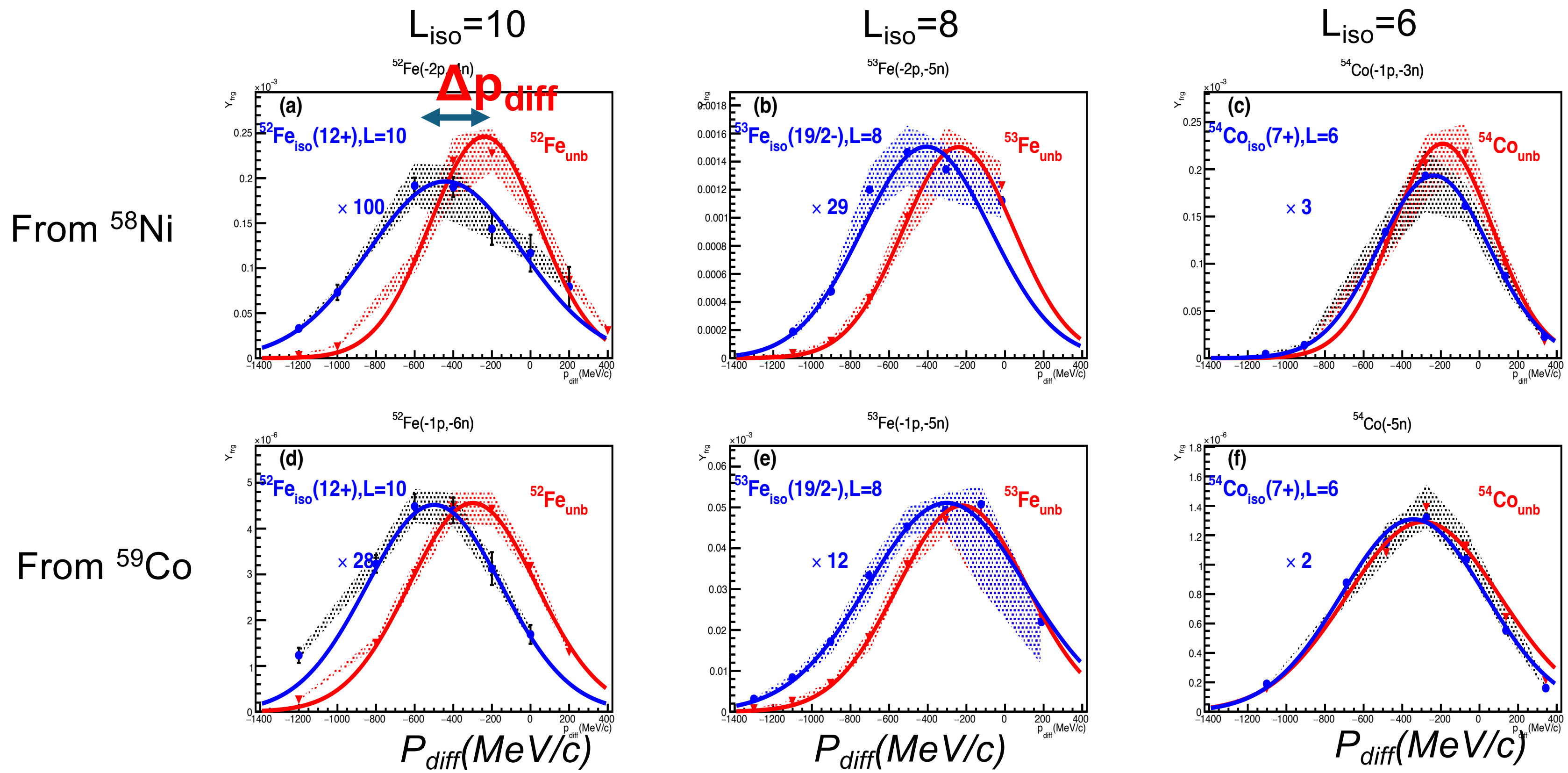
$^{52}Fe(12+)$

$^{52}Fe(12+)$ decay scheme



- Fragment :ΔE-ToF plot
- Isomer : γ-ray energy plot

Result & Discussion: momentum distribution



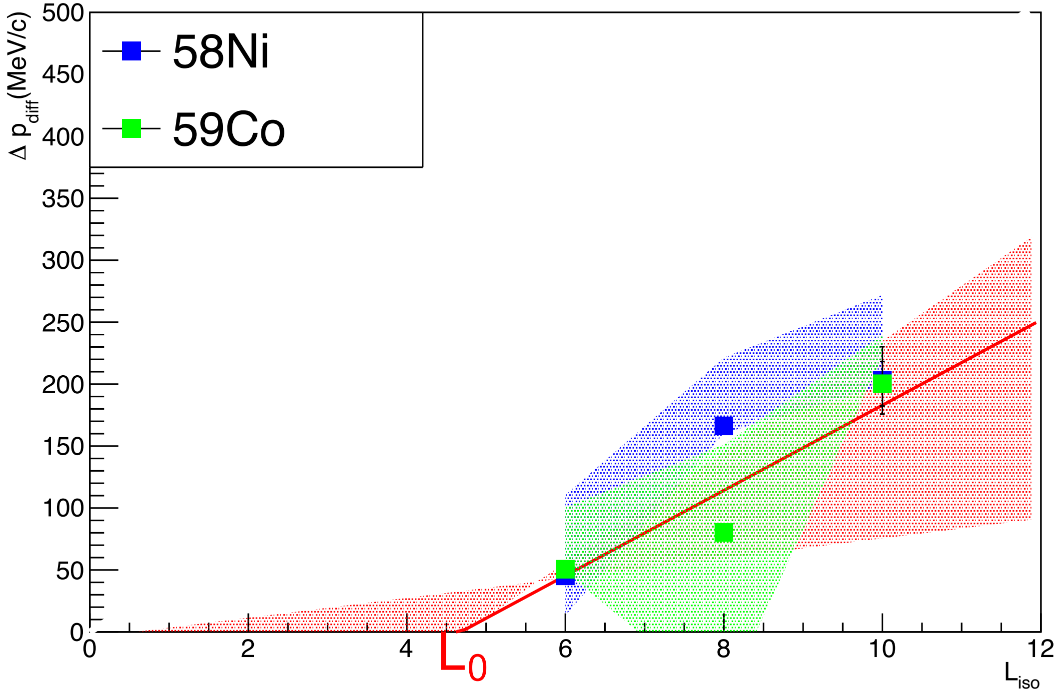
g.s.

isomer

P_{diff}=0 MeV/c
: the same velocity on the reaction

- The distribution of the isomer decelerated the distribution of g.s .
- The larger the L_{iso}, the more g.s. and isomer seems to deviate.

Results: Correlation (L_{iso} vs Δp_{diff})



Fitting function

$$\Delta p_{\mathrm{diff}} = a_0 \times (L_{\mathrm{iso}} - L_0)$$

$1/a_0 = R_{prj} = 5.58 \pm 0.30 +^{4.62}_{-0.58}$ fm

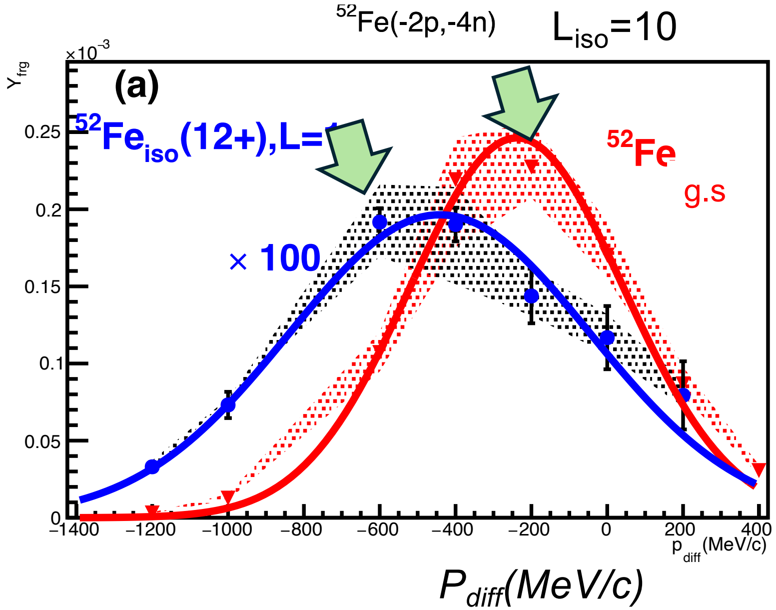
$L_0 = 4.58 \pm 0.02 +^{0.13}_{-1.08}$ $\hbar$

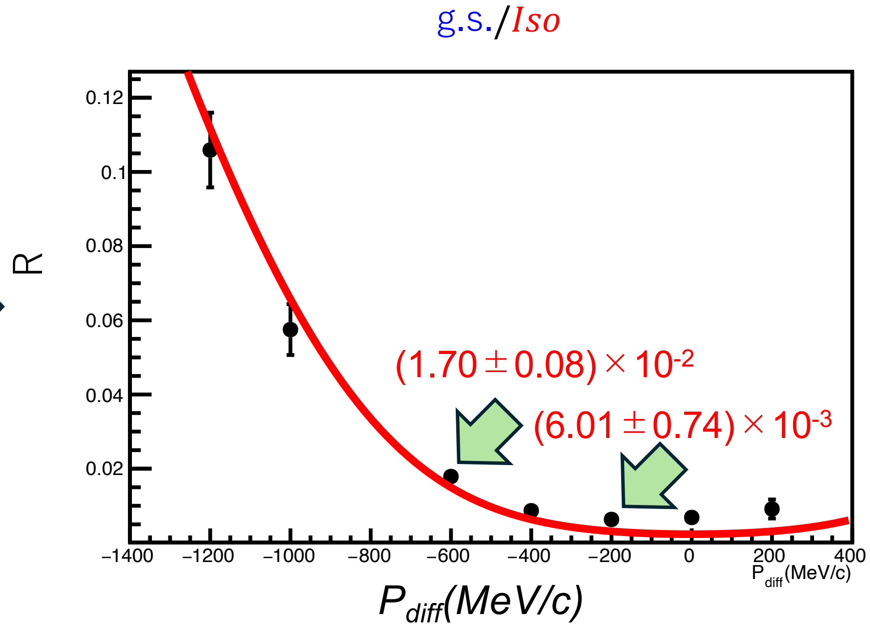
- Δp_{diff} and L_{iso} are correlated
- Radius of ^{58}Ni:1.3*A^1/3~4.7 fm

・The fragmentation shows the peripheral reaction on the projectile surface.

・L_0 shows the limited angular momentum in the g.s. momentum distribution.

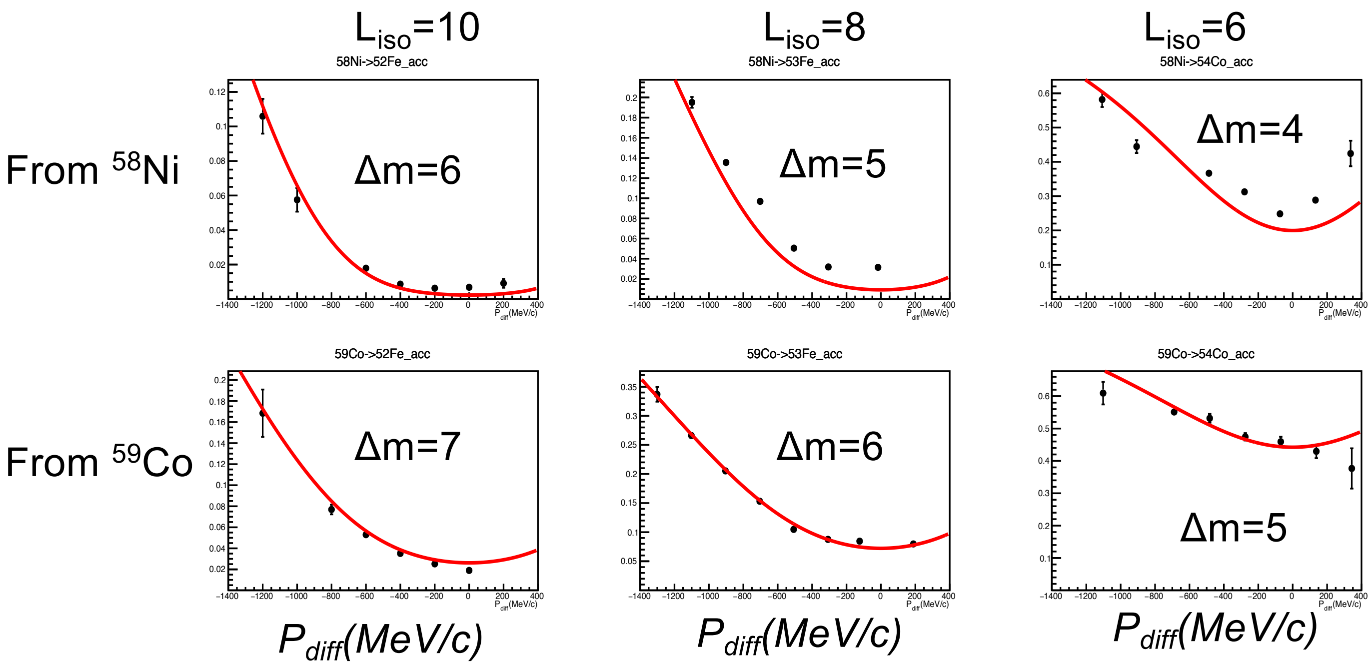
Result & Discussion: Isomer ratio





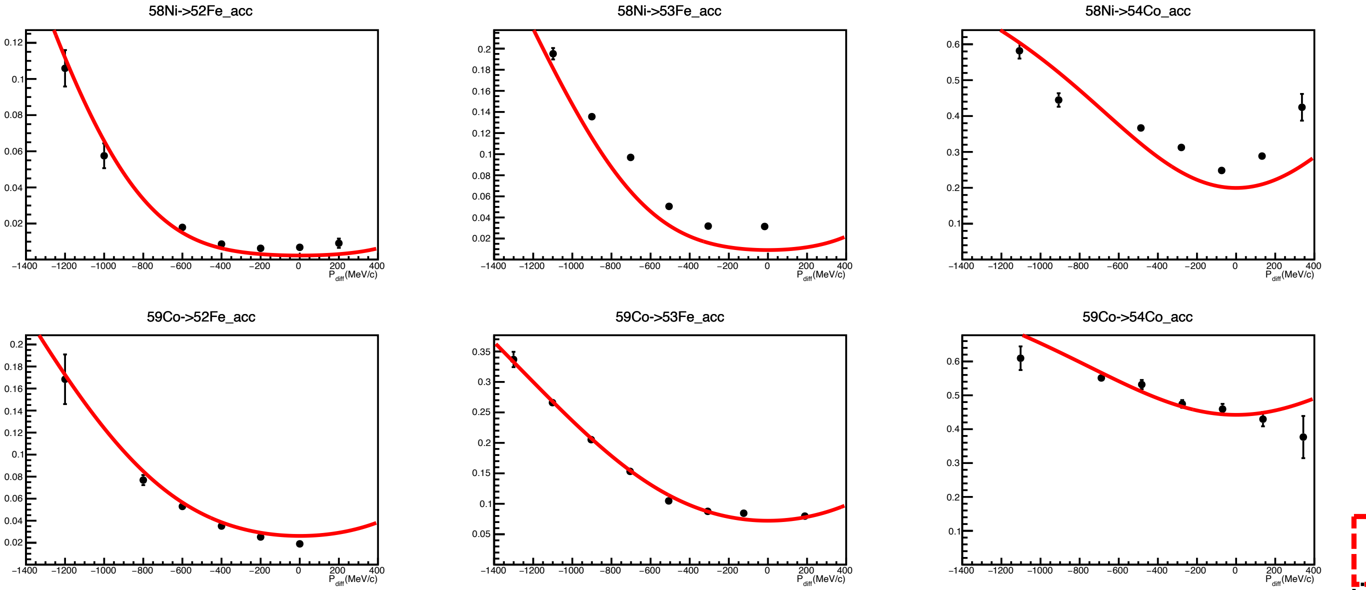
- R increases with large momentum transfer.
- R: isomer is about 3 times as many as g.s.

Result & Discussion: Isomer ratio



- R depends on the L_{iso}
- R depends on the mass loss(Δm)

Result & Discussion: Isomer ratio



original dejong

$$P_{\text{them}}(L) = \frac{2L+1}{\langle L_f^2 \rangle} \exp\left(-\frac{L(L+1)}{\langle L_f^2 \rangle}\right)$$

$$R_{th} = \int_{L_{iso}}^{\infty} dL P_{them}(L)$$

De jong *Nucler.Phys A* ***4***, 435444 (1997)

・Spin cut off parameterization

$$\langle L_f^2 \rangle = 2\sigma_f^2 + \langle L_p^2(p_{\text{diff}}) \rangle$$

$$\sigma_f^2 = \langle j_z^2 \rangle \frac{(A_p - A_f)(\nu A_p + A_f)}{(\nu+1)^2 (A_p - 1)}$$

$$\langle L_p^2(p_{\text{diff}}) \rangle = (\alpha_q r_{\text{prj}} p_{\text{diff}})^2 + L_{\text{prj}}^2$$

α_q~0.2

Red is a new parameter

・The phenomenological calculation with dejong can be adapted to the R.

・The spin cut-off parameter can be quenched.

Conclusion

・Systematic measurement of the momentum distribution by changing the kind of projectile, fragment, and isomer.

・The angular momentum of the high-spin isomer correlates with the linear momentum.

・The projectile fragmentation shows the reaction near the projectile surface.

・The angular momentum of the fragment can be restricted by a high-spin isomer.

・The isomer ratio depends on the P_{diff}.

Thank you for listening

backup

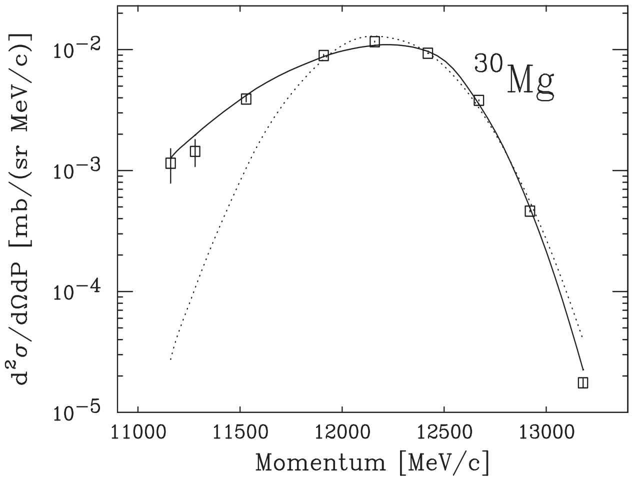
Introduction

- **Isomers** are excited nuclear states with lifetimes longer than 1 ns, due to factors such as spin gaps, nuclear deformation, or K.
- High-spin isomers in rare unstable beams are valuable probes for nuclear structure, nuclear astrophysics, and applied research.
  - Information about the interaction at the higher level
  - Nuclear reaction from the high-spin state and the excited state
  - Hyper deformation
- Many of the unstable nuclei in various facilities are produced by fragmentation
- The selective production and separation of specific isomeric states remain challenging.

Contents

- Introduction
  - high-spin isomer
  - fragmentation
- Purpose
- Experiment

Fragmentation in previous study



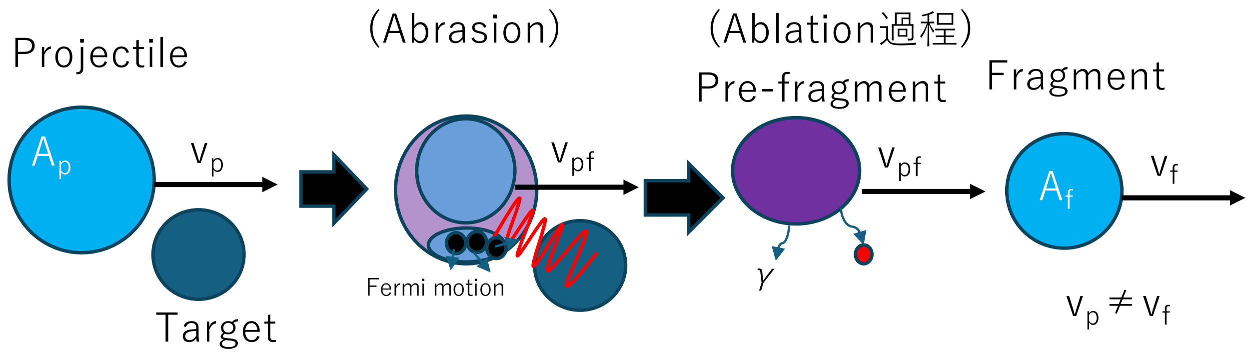
[1] A.S. *Goldhaber Physics Letters B* **53** 306308 (1974)
[2]K. Summerer *Phys. Rev. C* **61** 034607 (2000)
[3] Notani *Phys. Rev. C* **76** 044605 (2007)
[4] M. Tanaka *PhysRevC.***106**.014617(2022)
[5] J.-J. Gaimard *Nuclear Physics A* **531** 709745 (1991)
[6] De jong *Nucler.Phys A* ***4***, 435444 (1997)

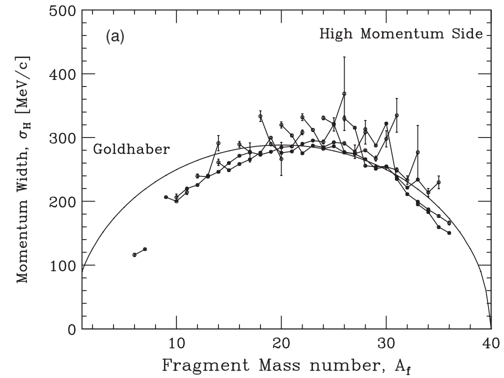
・Systematic measurements in g.s.:
:Cross-section[2], Momentum distribution[3], Momentum peak shift [3]such as isomer production
・Theoretical calculation study:
：Glauber model[4],Eikonal approximation[4],Gaimard-Schmidt method[5],EPAX[2]

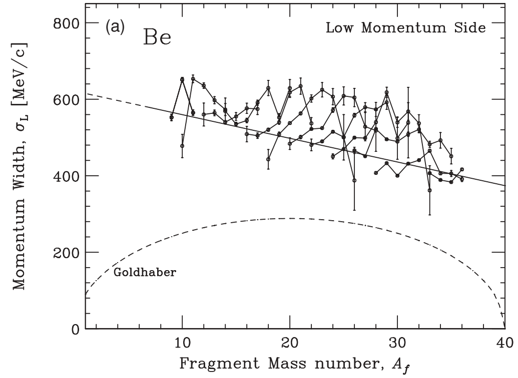
Widht

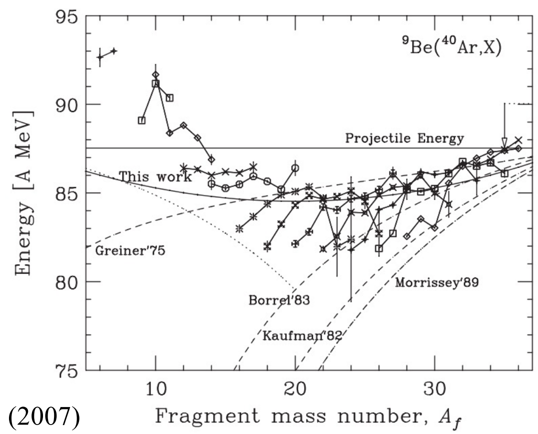
Model calculation

Notani



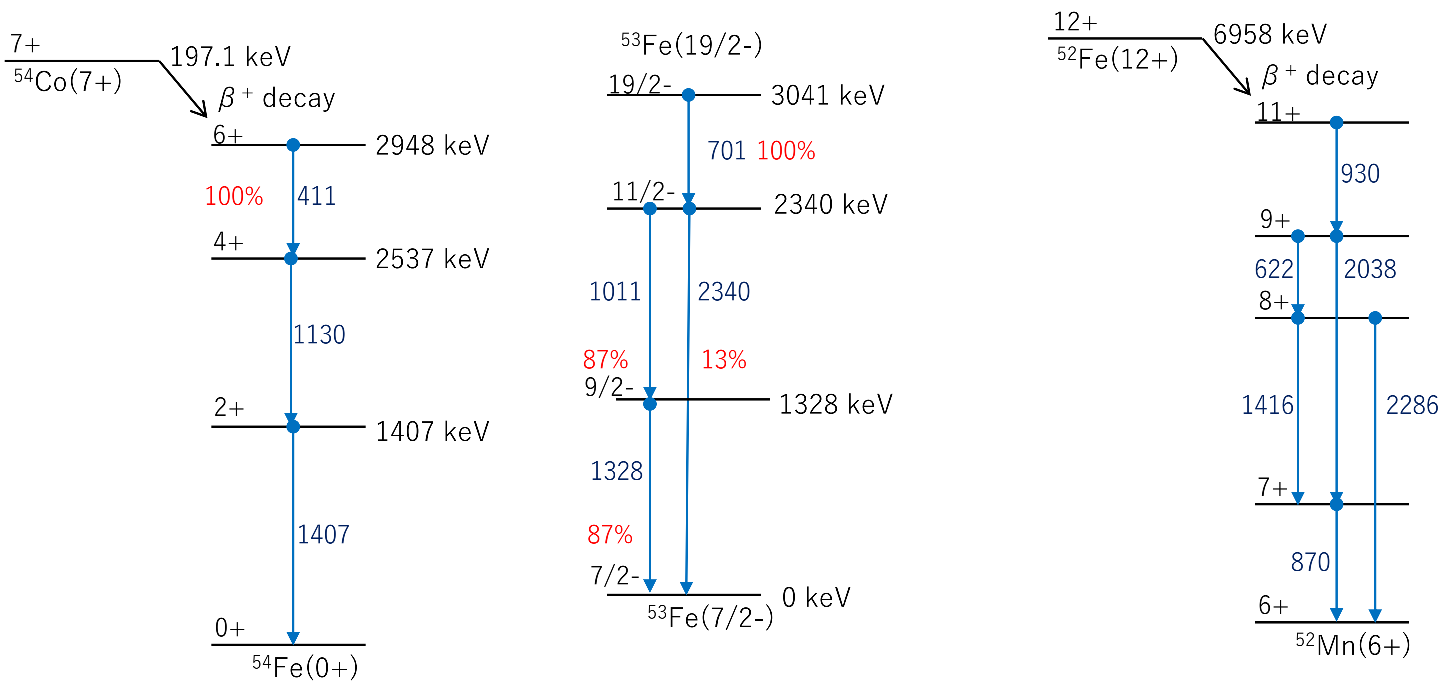






Phys. Rev. C **76** 044605 (2007)

Decay scheme of the isomer

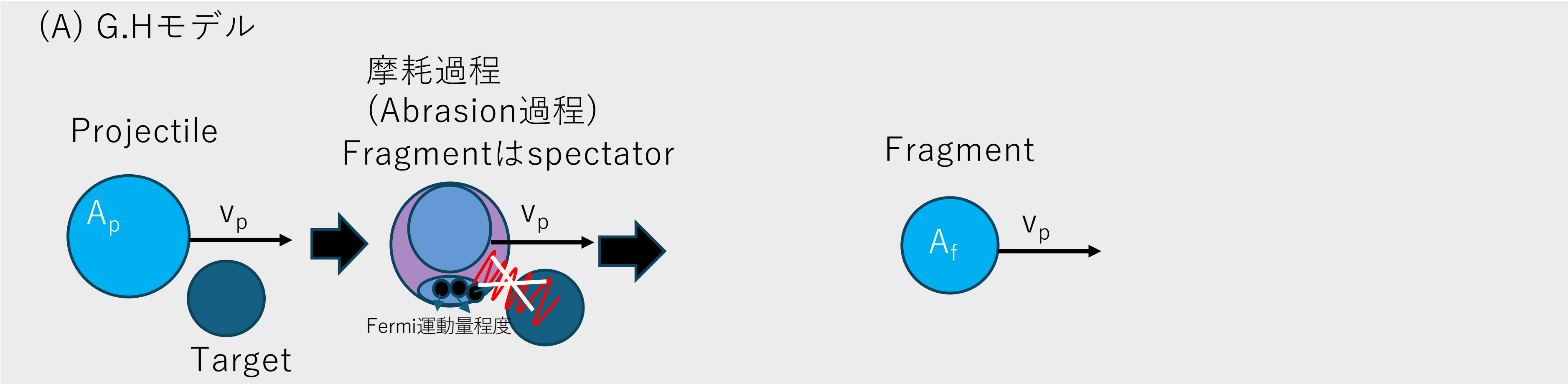


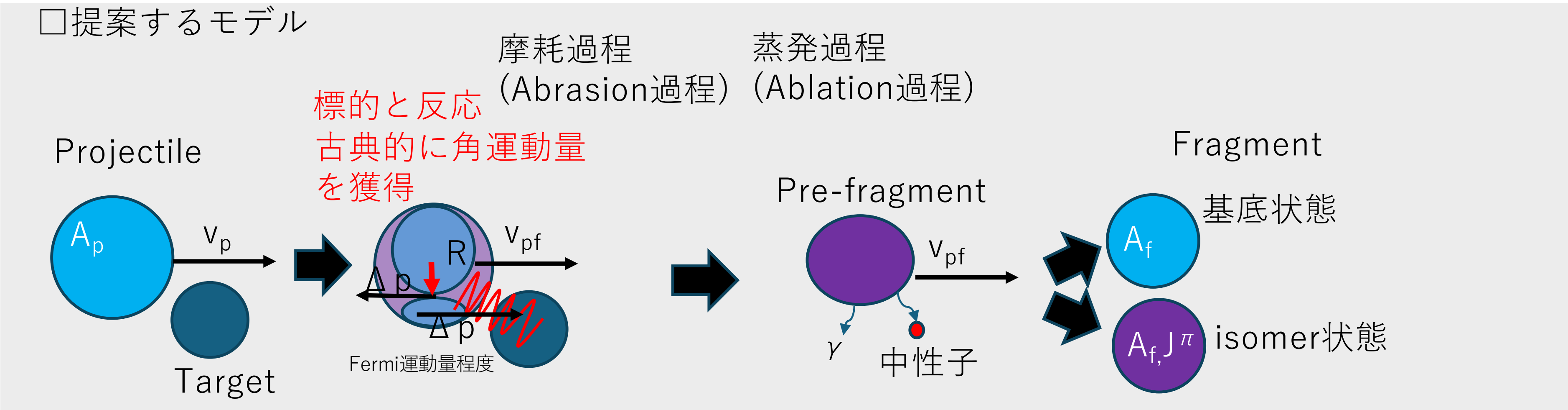
Abstract

High-spin nuclear isomers in rare unstable beams are important for studies in nuclear structure, nuclear astrophysics, and applied research. While fragmentation reactions, widely used at in-flight rare-isotope beam facilities, can produce a diverse range of nuclides, the selective and high-intensity production and separation of specific isomer states remain challenging. This study aimed to experimentally investigate the correlation between parallel momentum transfer and angular momentum transfer in fragmentation reactions, contributing to the development of selective beam production techniques for isomer states.

We focused particularly on previous studies [1] that showed an increase in the isomer ratio by selecting the tail of the fragment momentum distribution, with the goal of clarifying its physical origin. In this research, we investigated the correlation between angular momentum and parallel momentum transfer by selecting events from high-spin isomer states and comparing their momentum distributions with those of events primarily in the ground state.
The experiment was conducted at the SB2 beamline of the High-Energy Heavy-Ion Accelerator Facility (HIMAC). Primary beams of Ni and Co accelerated to 350 MeV/u irradiated a 14 mm thick Be target to produce nuclides around Fe through fragmentation reactions. The produced fragments were separated by a fragment
separator (two dipole magnets) and identified using the time-of-flight (ToF), energy loss(E), and magnetic rigidity (B) method.
Among the identified nuclides, de-excitation gamma rays from high-spin isomers Fe(12), Fe(19/2) and Co(7) were measured using four Ge detectors placed at the end of the
flight path with the particle identification.
As a result of the analysis, a clear tendency was observed for the relative production of high-spin isomers to increase in the region of large momentum transfer away from the center of the fragment momentum distribution (the tail of the distribution), consistent with previous studies [2][3]. Furthermore, by comparing the measured properties of multiple isomer states, a clear positive correlation was found between the magnitude of the imparted angular momentum and the parallel momentum transfer.
In this presentation, we will report these experimental results in detail and discuss the current understanding of the angular momentum generation mechanism in fragmentation reactions and its potential application to the production of high-purity, high-intensity isomer beams.

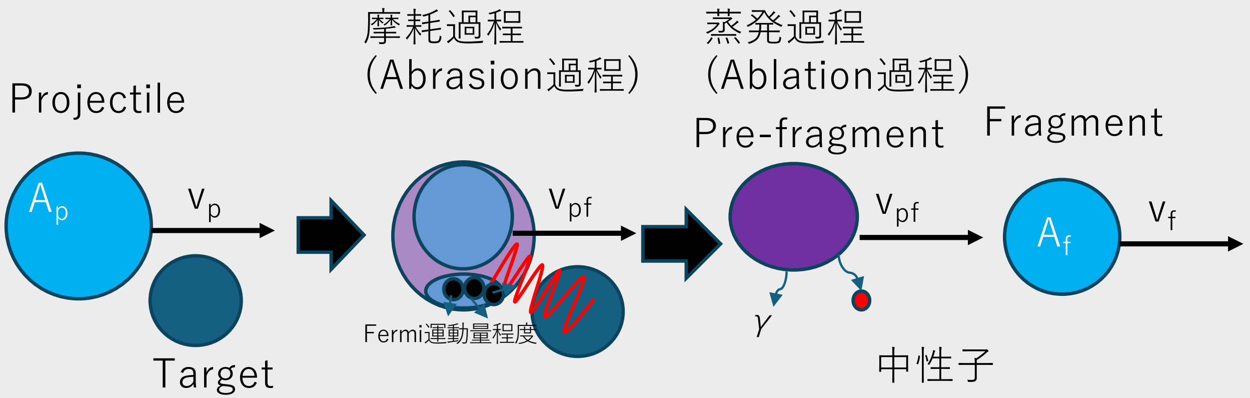
核破砕反応のモデル


(A) G.Hモデル
摩耗過程
(Abrasion過程)
Fragmentはspectator
Projectile
Ap
vp
Target
vp
Fermi運動量程度
Fragment
Af
vp

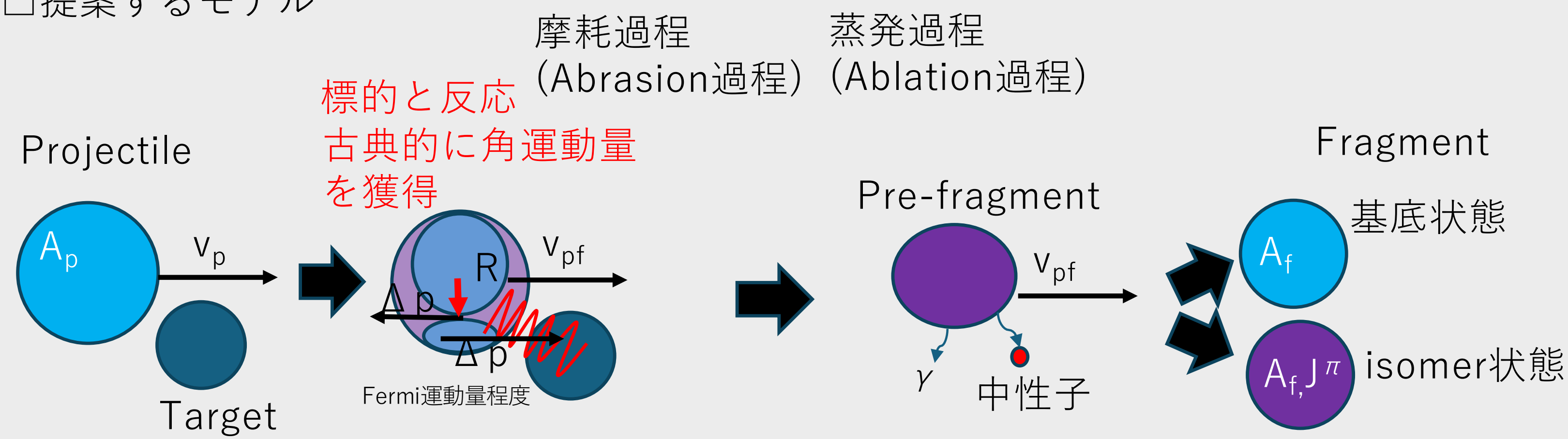

□提案するモデル
摩耗過程
(Abrasion過程)
蒸発過程
(Ablation過程)
標的と反応
古典的に角運動量
を獲得
Projectile
Ap
vp
Target
R
vpf
Δp
Δp
Fermi運動量程度
Pre-fragment
vpf
γ
中性子
Fragment
Af
基底状態
Af,Jπ
isomer状態

核破砕反応のモデル

(B) Notaniモデル

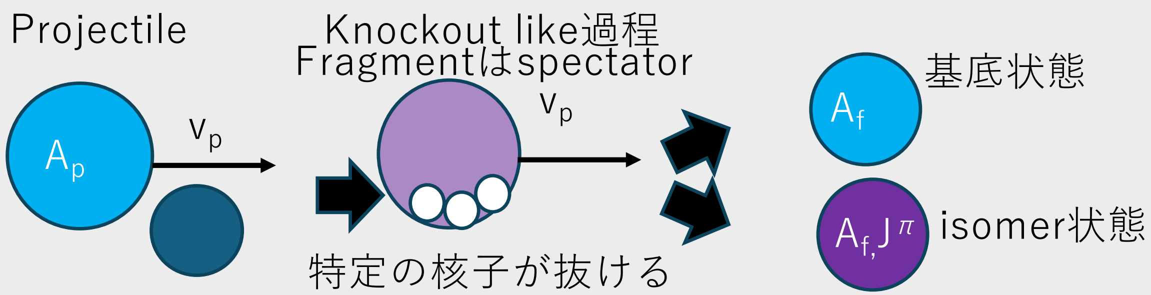


□提案するモデル

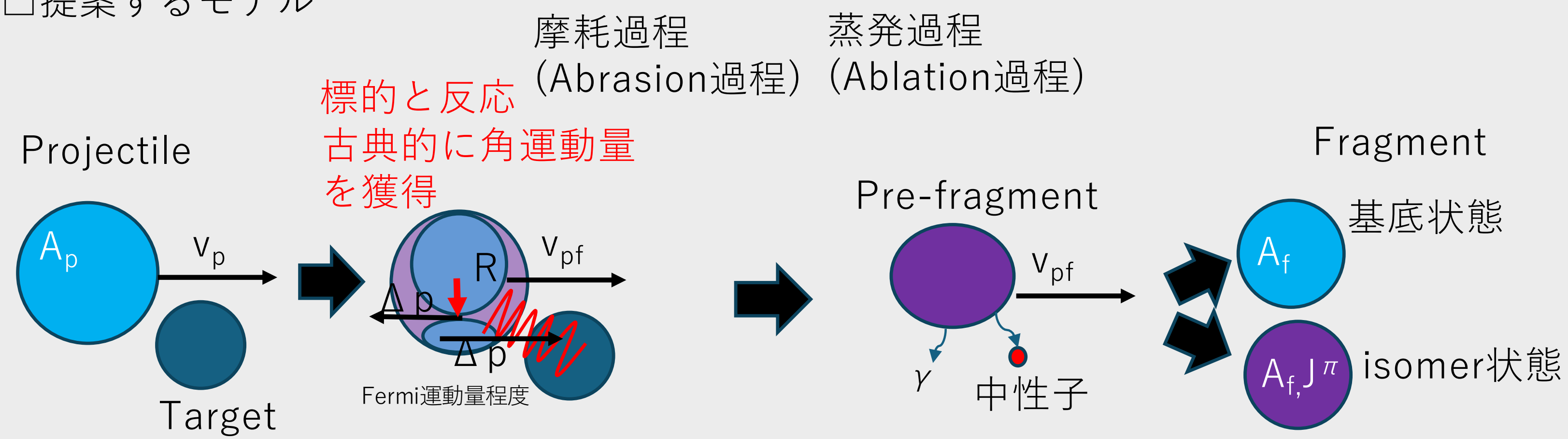


核破砕反応のモデル

(C) Schmitdt-Ottモデル

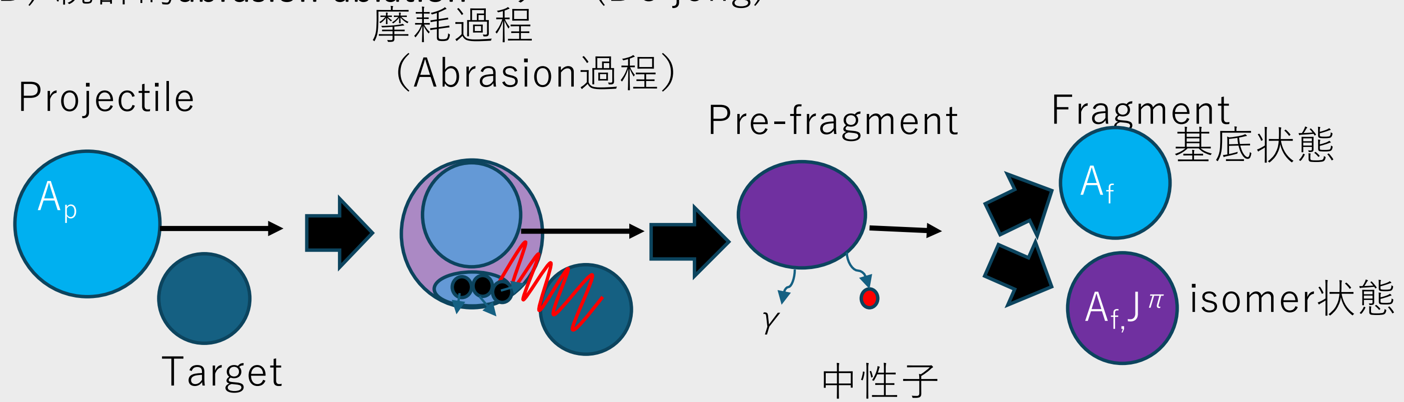


□提案するモデル

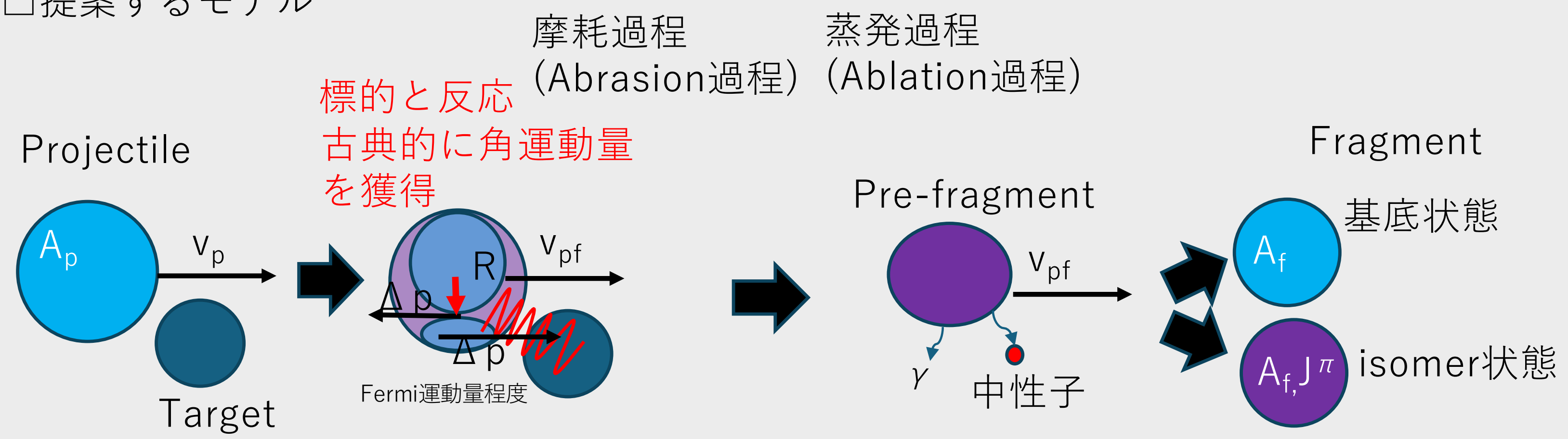


核破砕反応のモデル

(D) 統計的**abrasion-ablation**モデル(De jong)

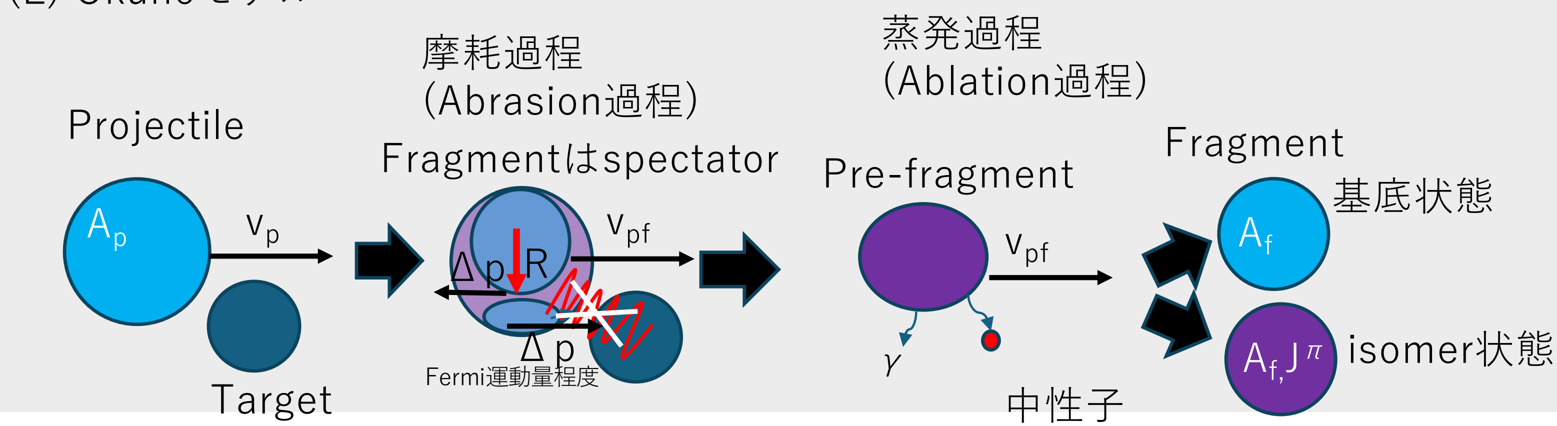


□提案するモデル



核破砕反応のモデル

(E) Okunoモデル



□提案するモデル