Optimal reaction energy for synthesis of **element 119** via ^{51}**V**+^{248}**Cm** reaction probed by **quasielastic barrier distribution**

RIKEN Nishina Center / Kyushu University (Japan)
Masaomi Tanaka

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for nSHE collaboration[1-18]

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[11] Graduate School for Science, Kyushu University, Japan
[12] Joint Institute for Nuclear Physics and Applications administered by UTK, USA
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[15] Osaka University, Japan
[16] Tohoku University, Japan
[17] JAEA, Japan
[18] IMP, China

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M. Tanaka *et al.*,
"Probing Optimal Reaction Energy for Synthesis of Element 119 from 51V+248Cm Reaction with Quasielastic Barrier Distribution Measurement"

Facility Upgrade for SuperHeavy Element (SHE) research at RIKEN

Discovery of Nihonium at RIKEN

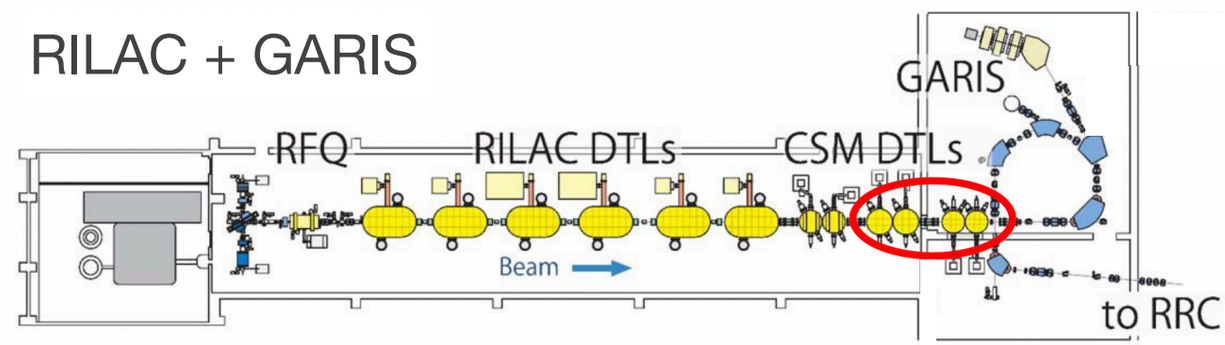
$^{209}Bi(^{70}Zn,n)^{278}Nh$ | Cold fusion reaction

@ RILAC + GARIS

RIKEN **L**inear **Ac**celerator **Ga**s-filled **R**ecoil **I**on **S**eparator

Courtesy of H. Sakai (RIKEN)

RILAC + GARIS



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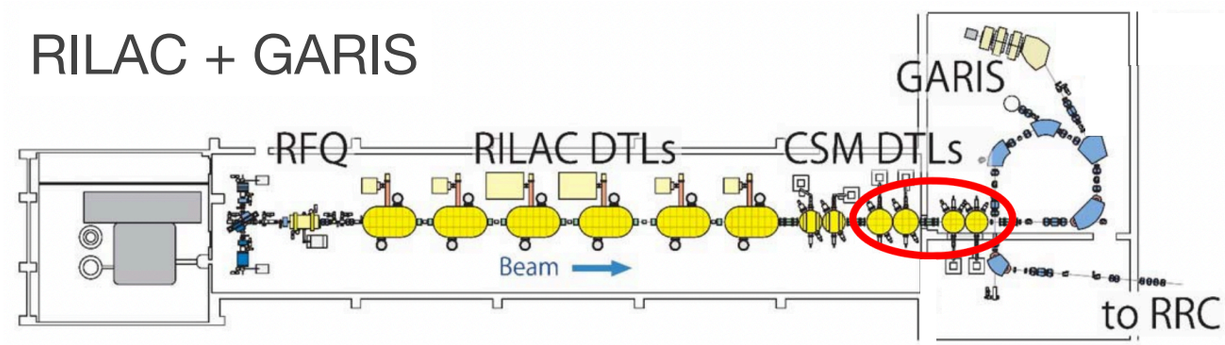

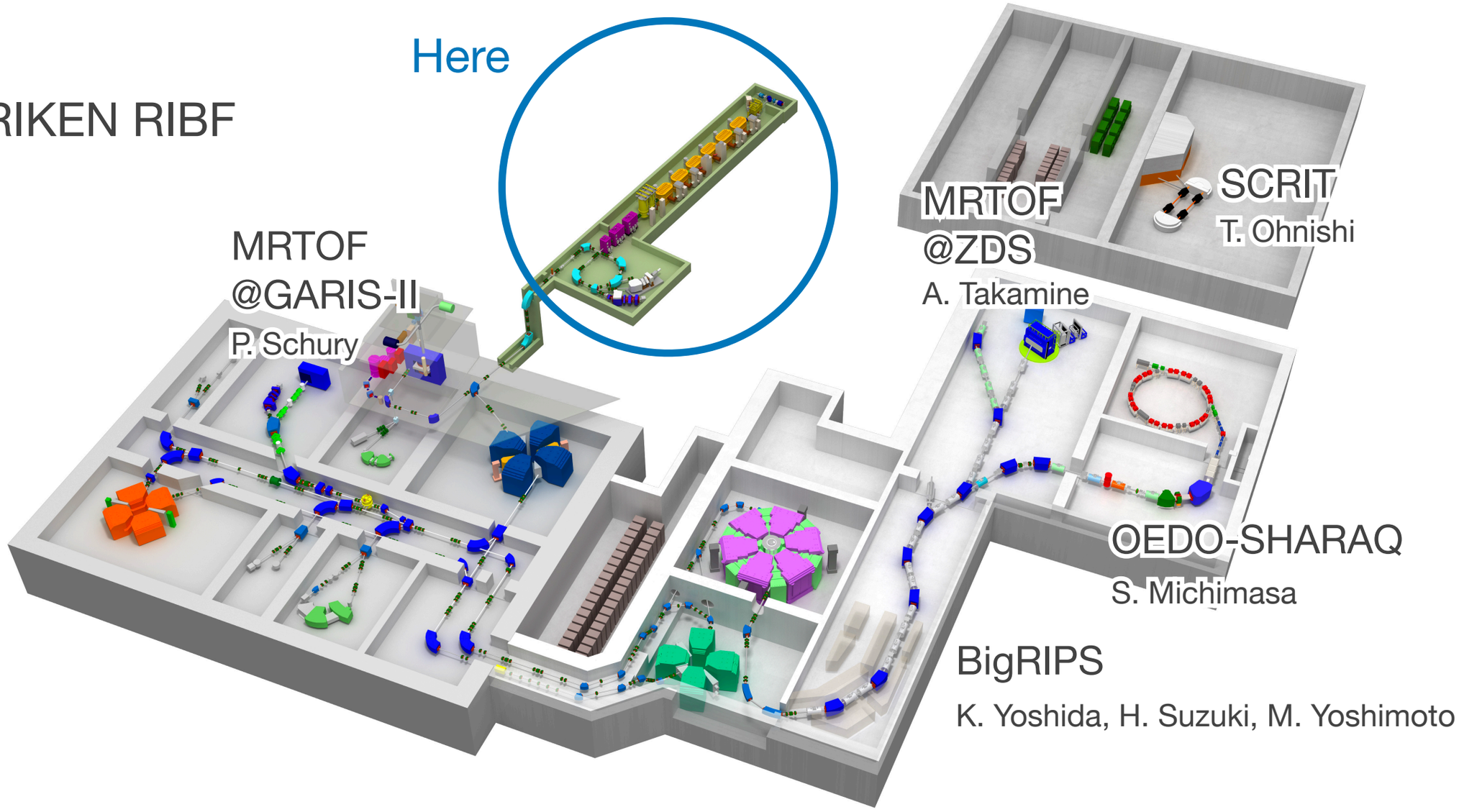

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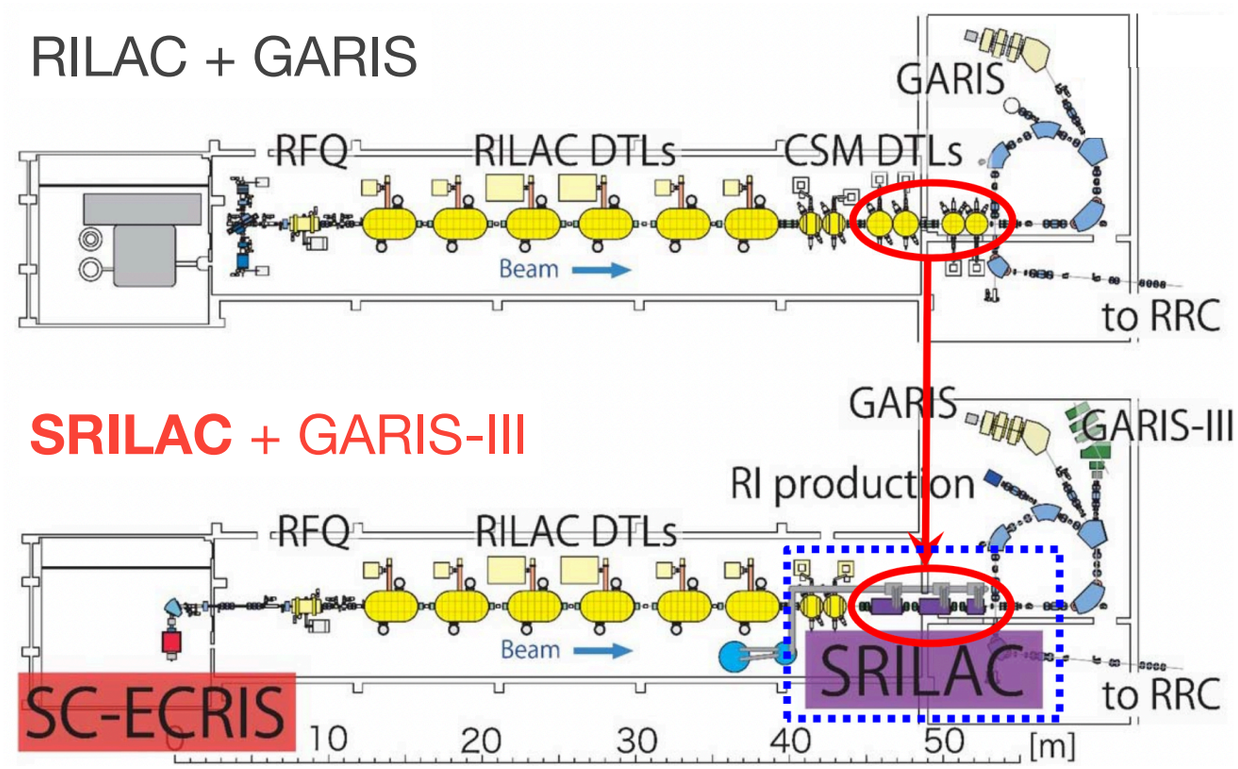
Facility upgrade for new element search *Z* = 119

Target reaction

$^{248}Cm(^{51}V,xn)^{299-x}$**119** | Hot fusion reaction

Courtesy of H. Sakai (RIKEN)



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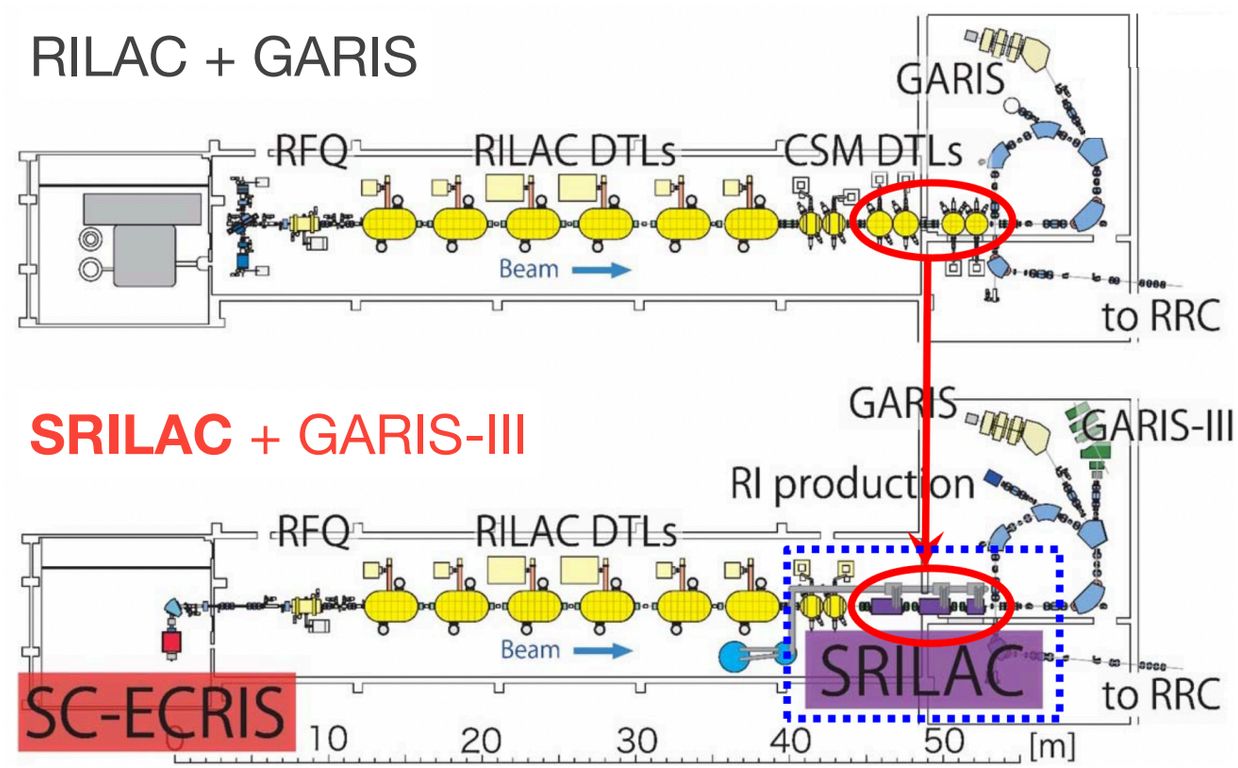

Facility upgrade for new element search *Z* = 119

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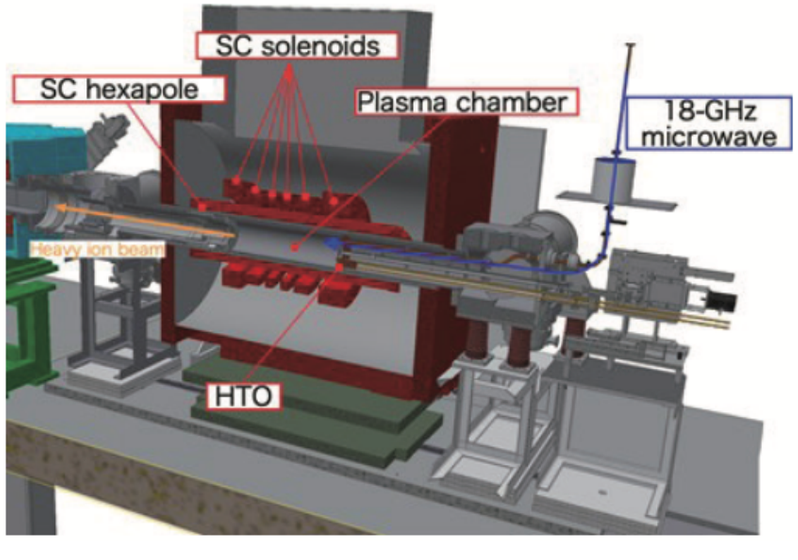
$^{248}Cm(^{51}V,xn)^{299-x}$**119** | Hot fusion reaction

"First Beam from SRILAC"
RIKEN Accel. Prog. Rep. **54** (2021).

SC-ECRIS

Super**C**onducting **ECR** **I**on **S**ource

Higher intensity



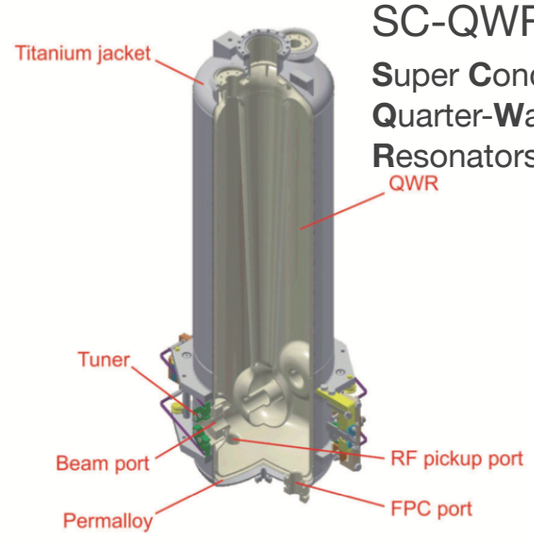
SRILAC

SuperConducting **RI**KEN **Lin**ac

Higher energy (up to 6.5 MeV/*u*)

SC-QWR x 10

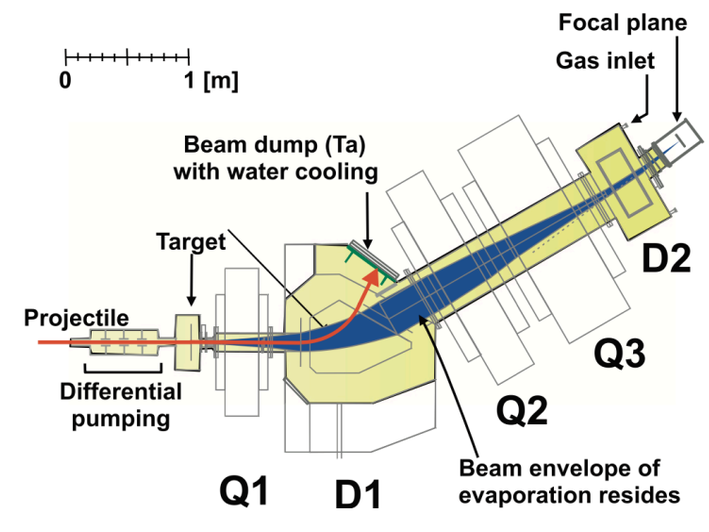
Super **C**onducting **Q**uarter-**W**avelength **R**esonators



GARIS-III

Gas-filled **R**ecoil **I**on **S**eparator **III**

Optimized for **Hot fusion reaction**



In this talk, …

We need a "**recipe**" to synthesize element 119 with high efficiency as much as possible.

Quasielastic barrier distribution of $^{51}V+^{248}Cm$ from quasielastic backscattering measurement

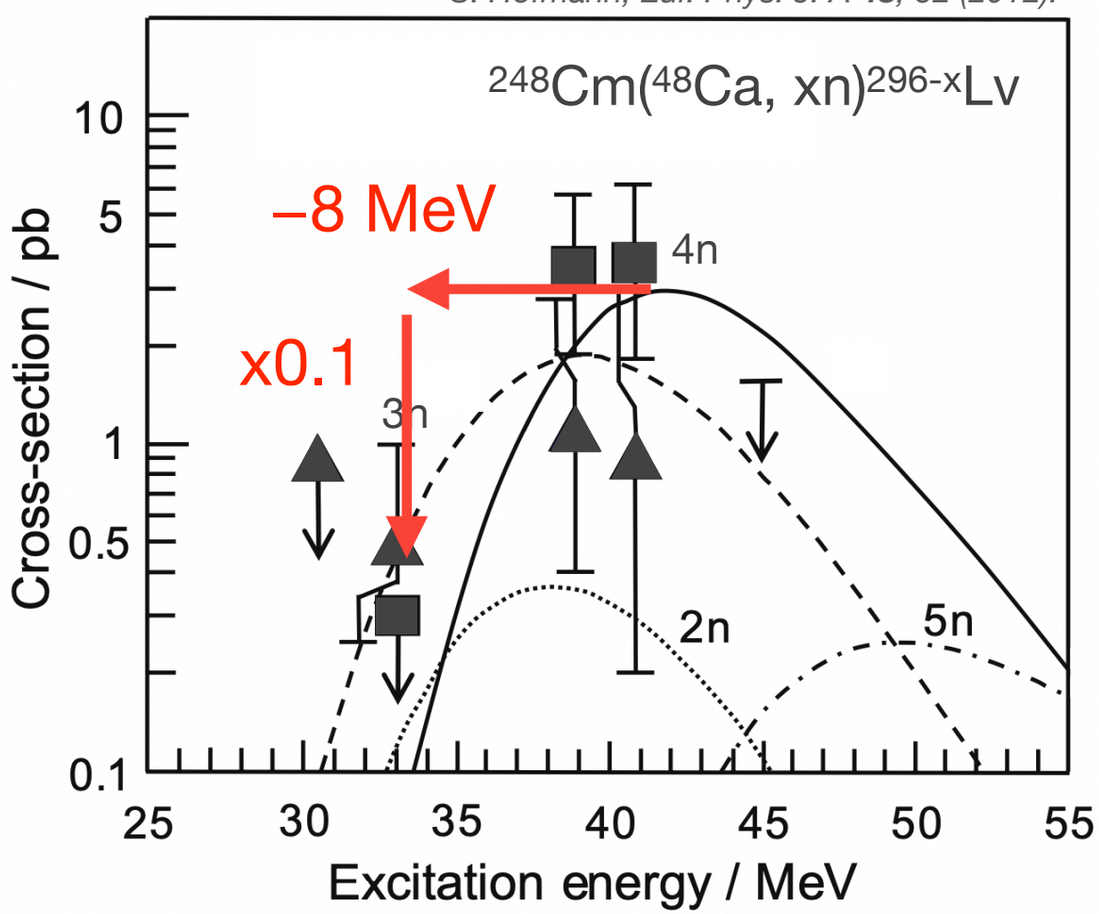
▼

Optimal reaction energy of **$^{248}Cm(^{51}V,xn)^{299-x}119$ reaction** for element-119 synthesis at RIKEN

Theoretical prediction of $^{248}Cm(^{51}V, xn)^{299-x}119$

Sensitivity of reaction energy on σ_{ER}

*S. Hofmann, Eur. Phys. J. A **48**, 62 (2012).*



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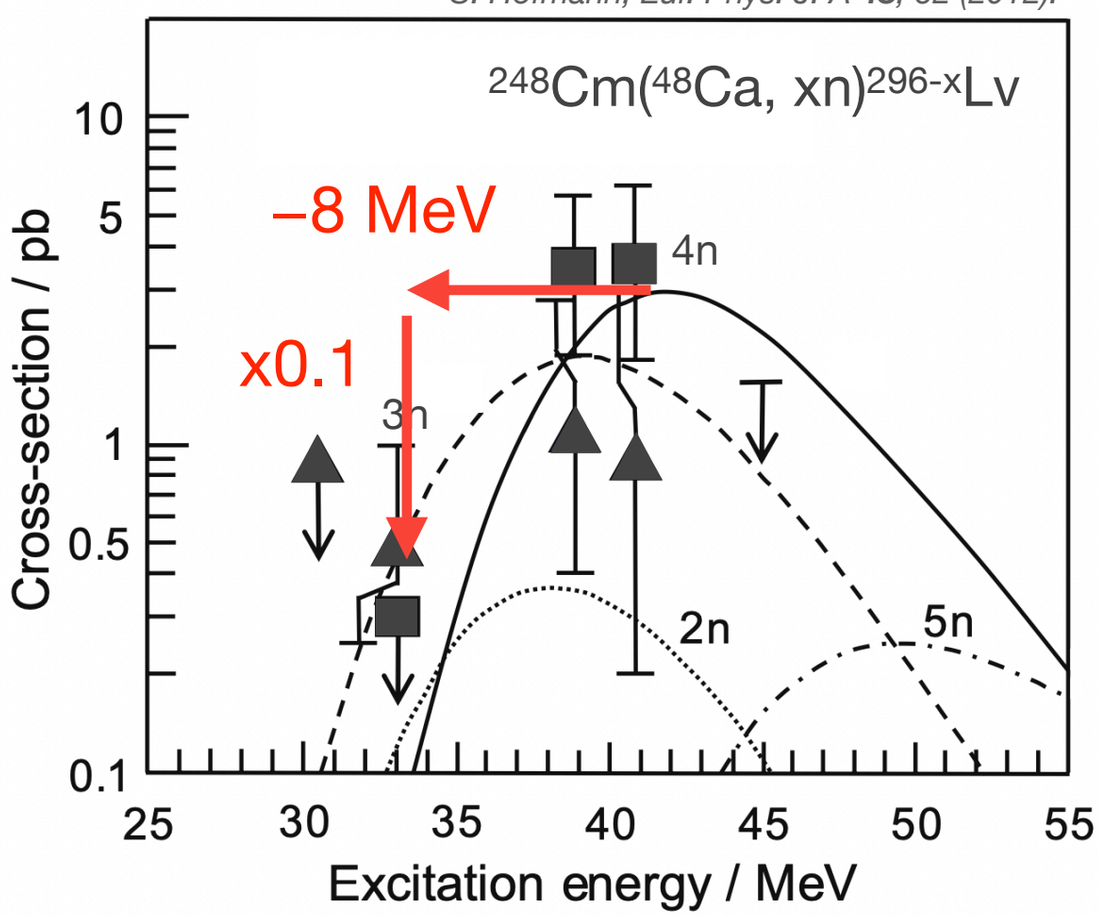


Prediction of $^{248}Cm(^{51}V, xn)^{299-x}119$

- σ_{ER} < 100 fb

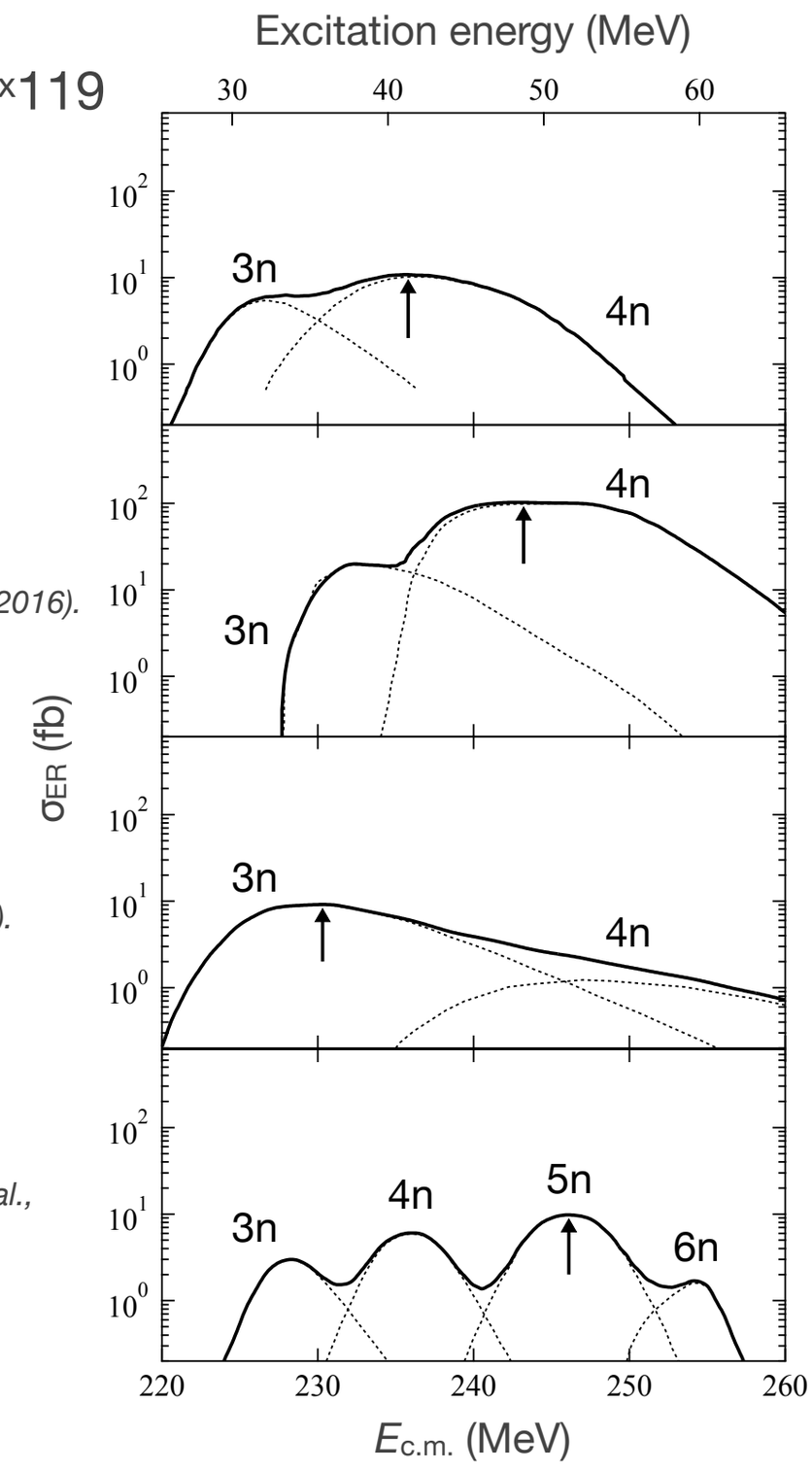
$^{248}Cm(^{51}V, xn)^{299-x}119$

*L. Zhu et al., PRC **89**, 024615 (2014).*

*N. Ghahramany et al., Eur. Phys. J. A **52**, 287 (2016).*

*X.-J. Lv et al., PRC **103**, 064616 (2021).*

*K. Swiek-Wilczyńska et al., PRC **99**, 054603 (2019).*



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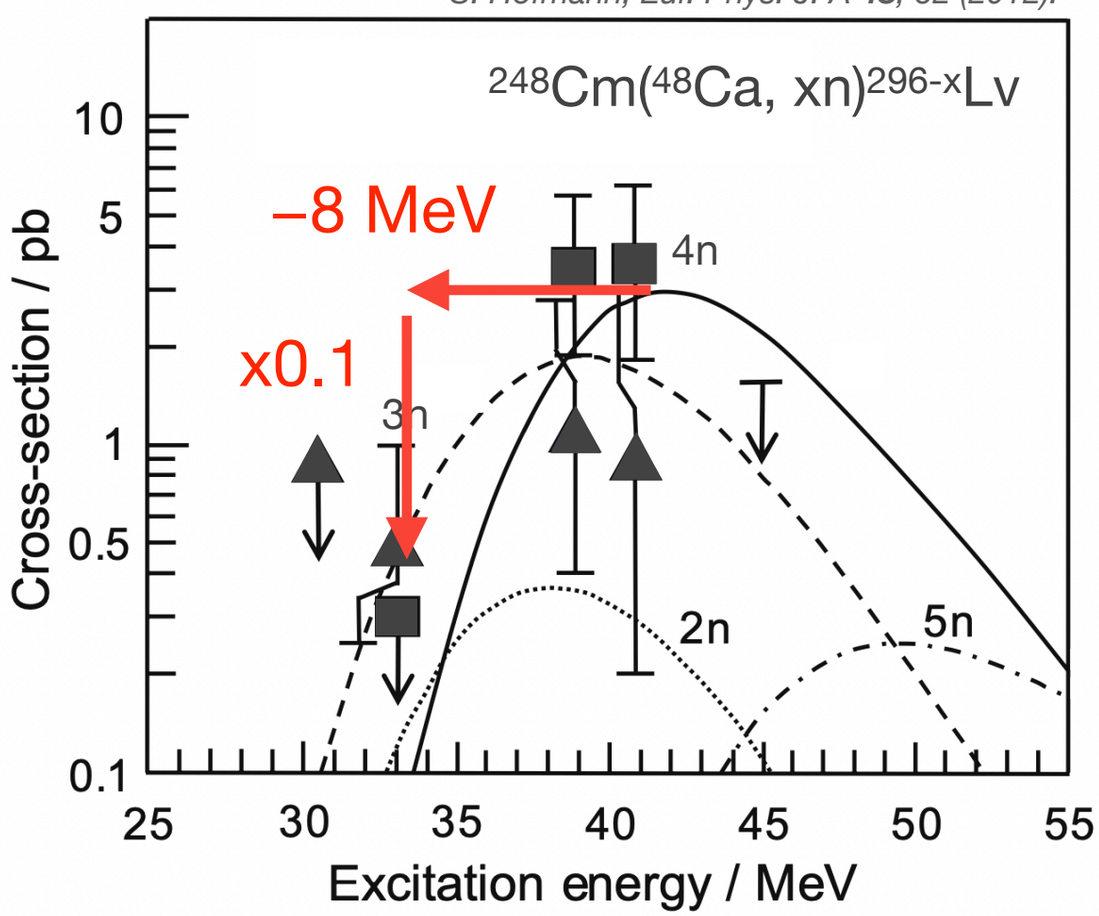

Prediction of $^{248}Cm(^{51}V, xn)^{299-x}119$

- σ_{ER} < 100 fb
- Optimal energy | **~15 MeV deviation**

→ Desirable to estimate optimal energy based on **experimental information.**

$^{248}Cm(^{51}V, xn)^{299-x}119$

*L. Zhu et al., PRC **89**, 024615 (2014).*

*N. Ghahramany et al., Eur. Phys. J. A **52**, 287 (2016).*

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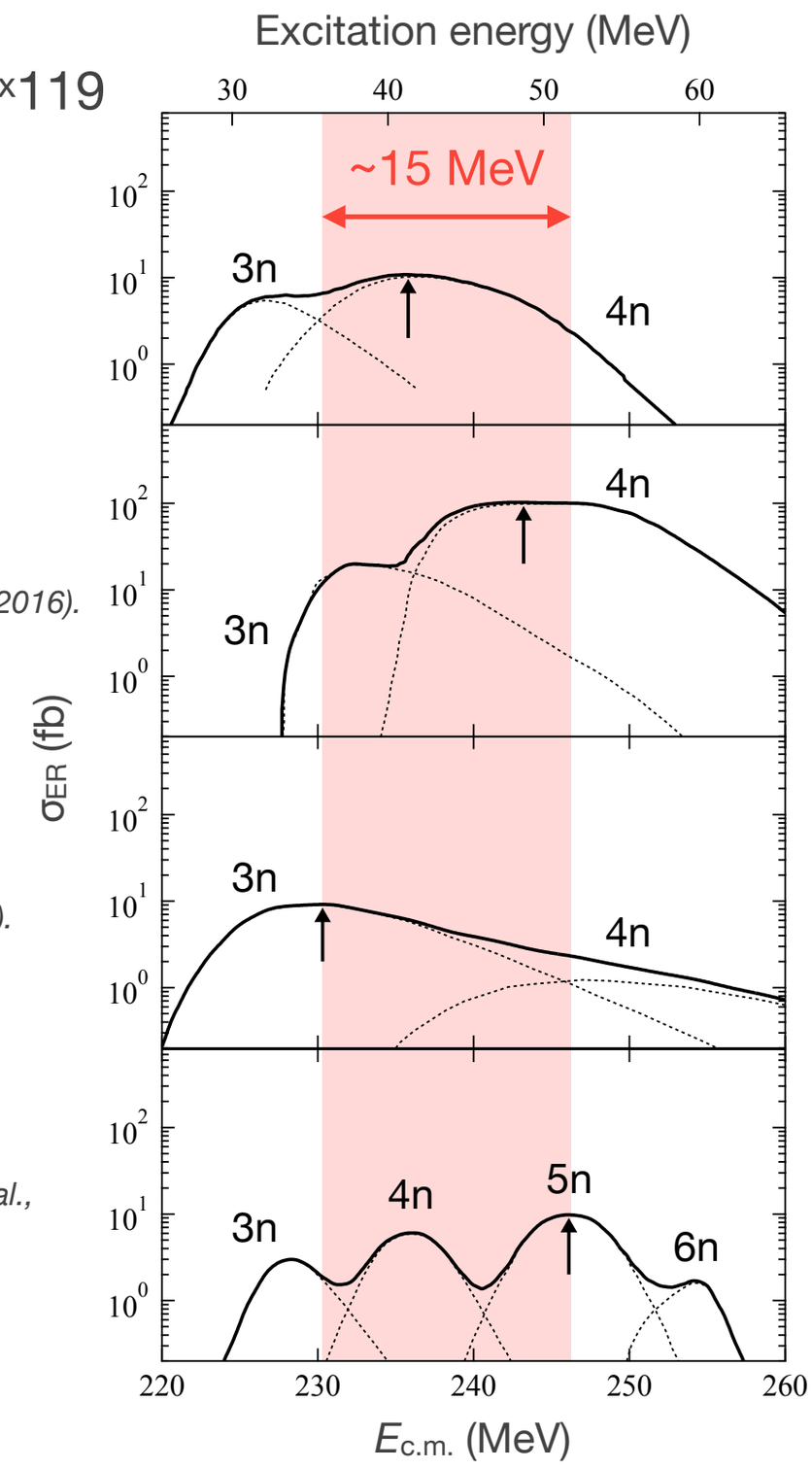
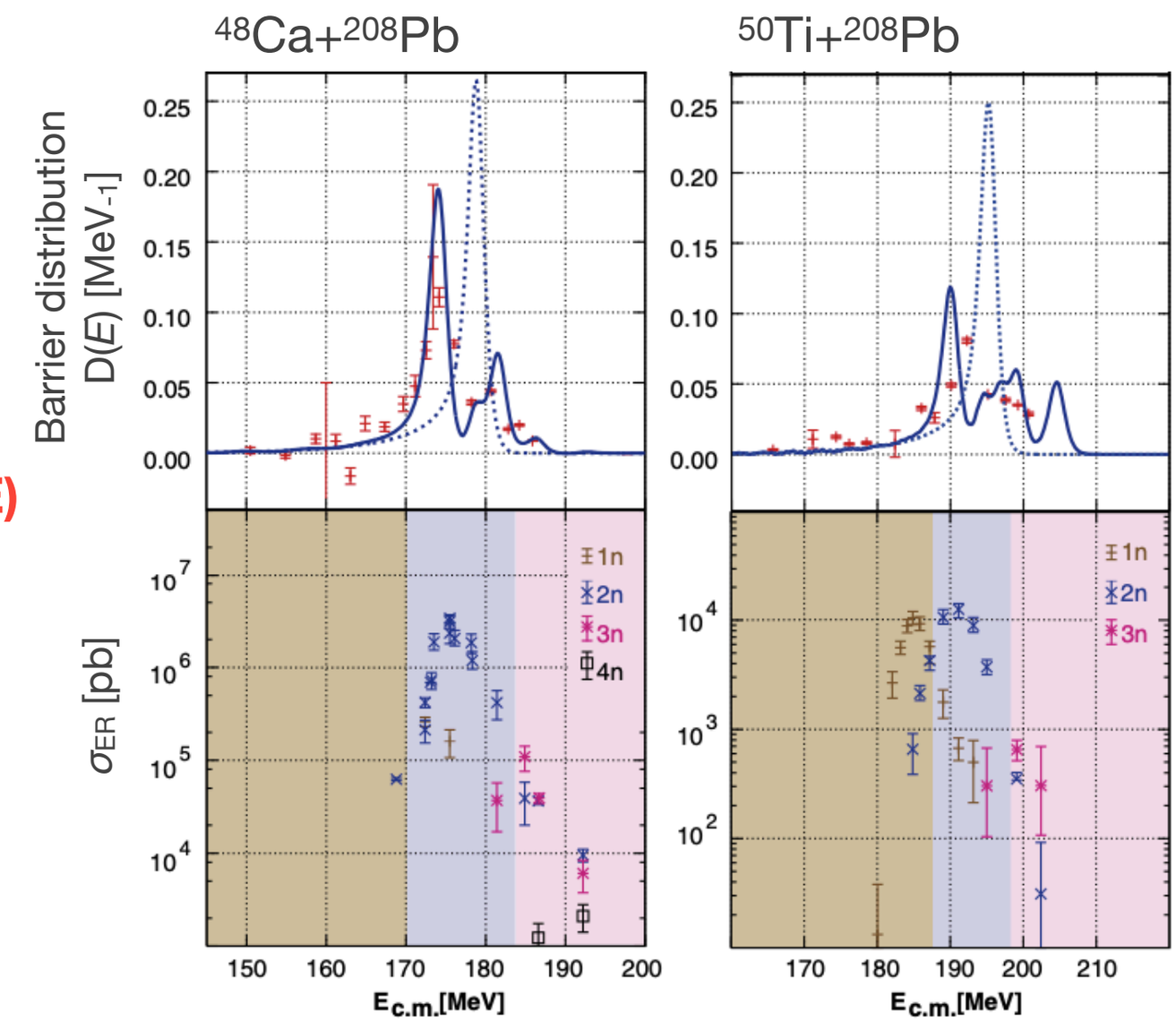


Relation between QE barrier distribution and σ_{ER} in cold fusion

Systematic barrier distribution studies in heavy-mass systems

*S. Mitsuoka et al., PRL **99**, 182701 (2007).*
*S.S. Ntshangase et al., PLB **651**, 27 (2007).*
*G. Kaur et al., Acta Phys. Pol. **49**, 651 (2018).*
*T. Tanaka et al., J. Phys. Soc. Jpn. **87**, 014201 (2018).*
*T. Niwase et al., JPS Conf Proc. **32**, 010022 (2020).*

*T. Tanaka et al., J. Phys. Soc. Jpn. **87**, 014201 (2018).*



Peak of barrier distribution ≒ Peak of $\sigma_{ER}(E)$

Method is ready to deduce optimal energy for ^{248}Cm(^{51}V,xn)$^{299-x}$119.

Purpose of this study

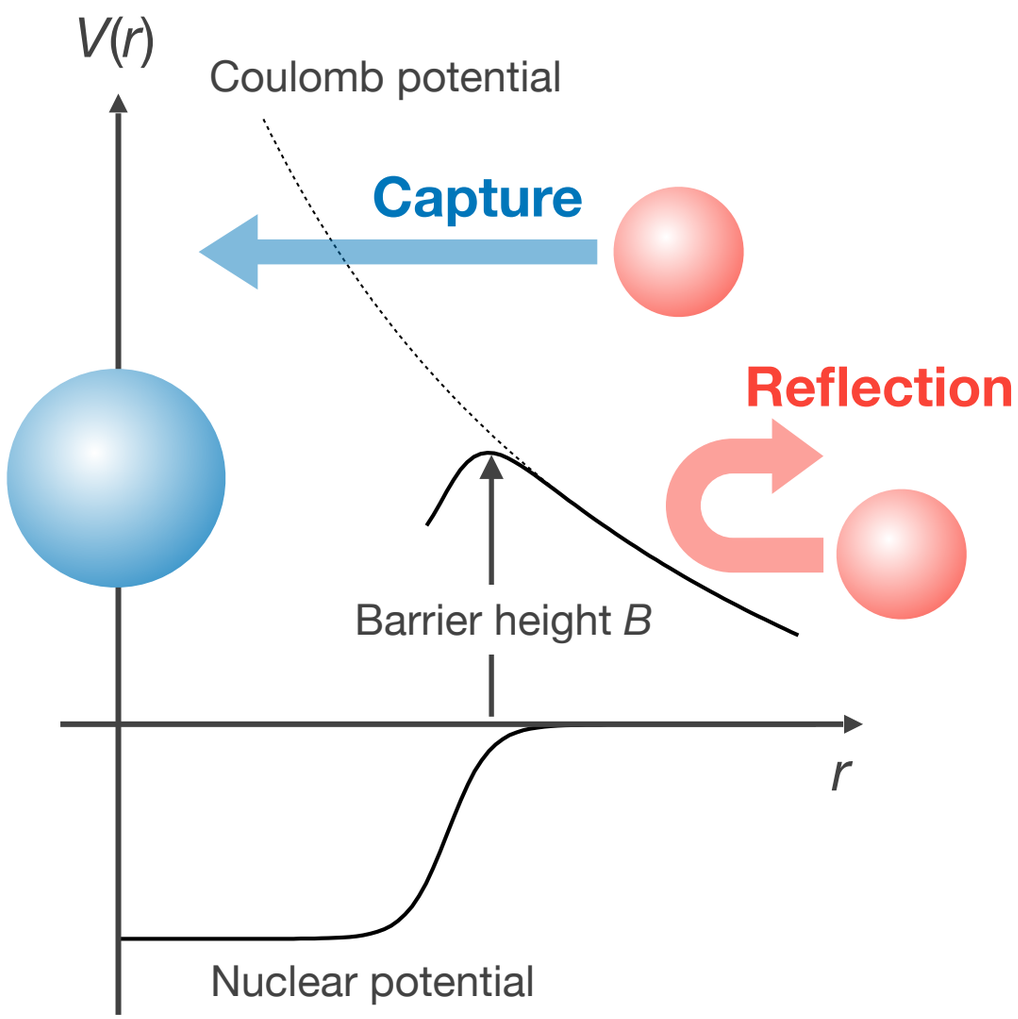
Method

Extract quasielastic barrier distribution of $^{51}V+^{248}Cm$ system from **quasielastic backscattering measurement**.

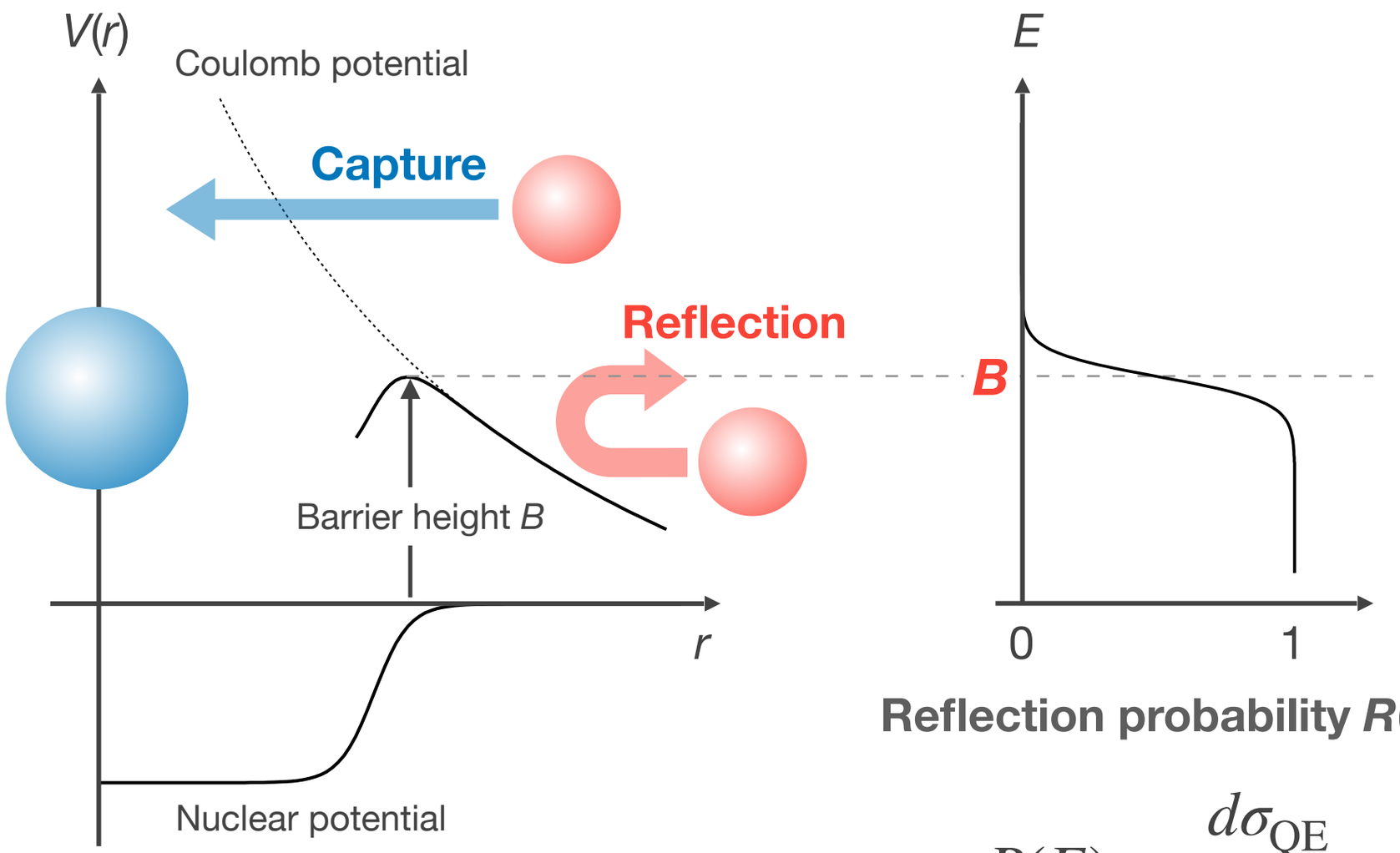
Purpose

Deduction of optimal reaction energy of $^{248}Cm(^{51}V, xn)^{299-x}119$ based on **experimental information**.

Principle of experiment



Quasielastic barrier distribution

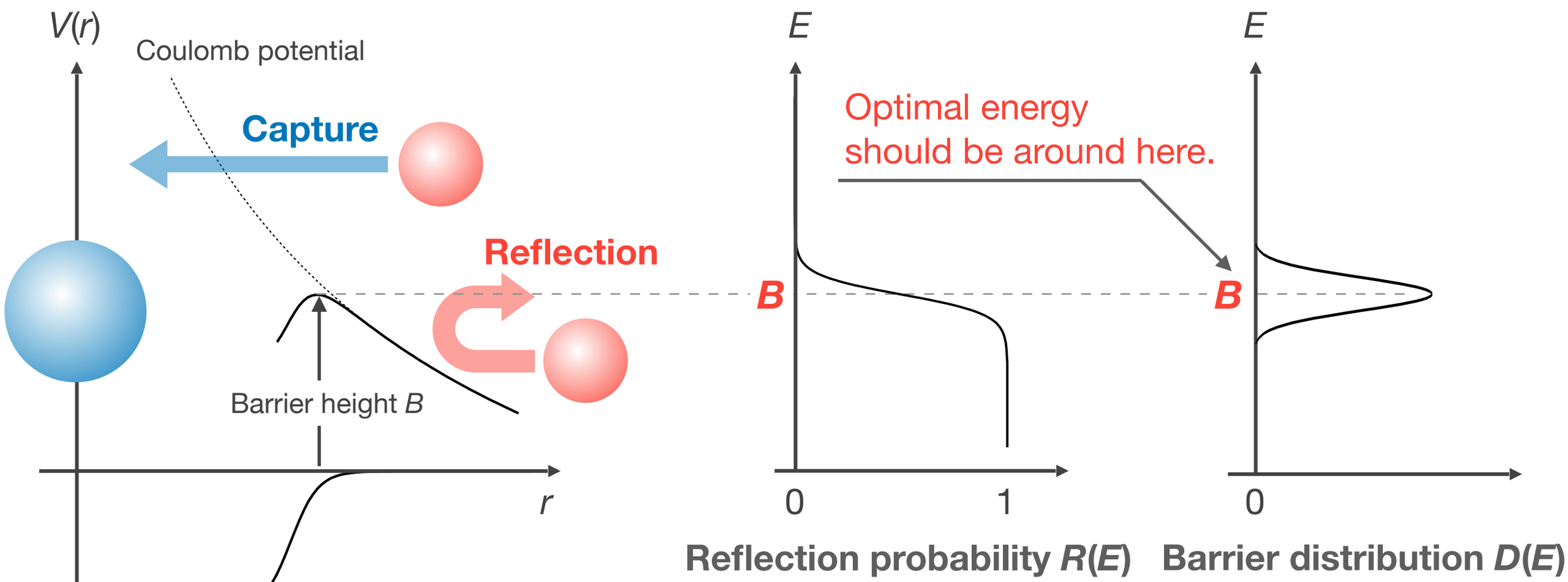


Reflection probability *R*(*E*)

$$R(E) = \frac{d\sigma_{\mathrm{QE}}}{d\sigma_{\mathrm{Ruth}}}$$

Measurement of
excitation function of quasielastic(QE) backscattering to Rutherford scattering ($d\sigma_{QE}/d\sigma_{Ruth}$)
by detecting non-captured projectiles.

Quasielastic barrier distribution



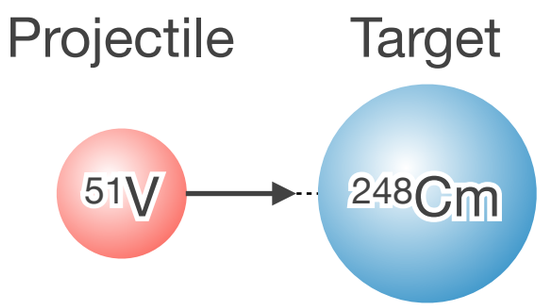
$$R(E) = \frac{d\sigma_{\mathrm{QE}}}{d\sigma_{\mathrm{Ruth}}} \qquad D(E) = -\frac{dR(E)}{dE}$$

Measurement of
excitation function of quasielastic(QE) backscattering to Rutherford scattering ($d\sigma_{QE}/d\sigma_{Ruth}$)
by detecting non-captured quasielastic projectiles.

→ **Experimentally deduce optimal reaction energy.**

Method to detect non-captured particle

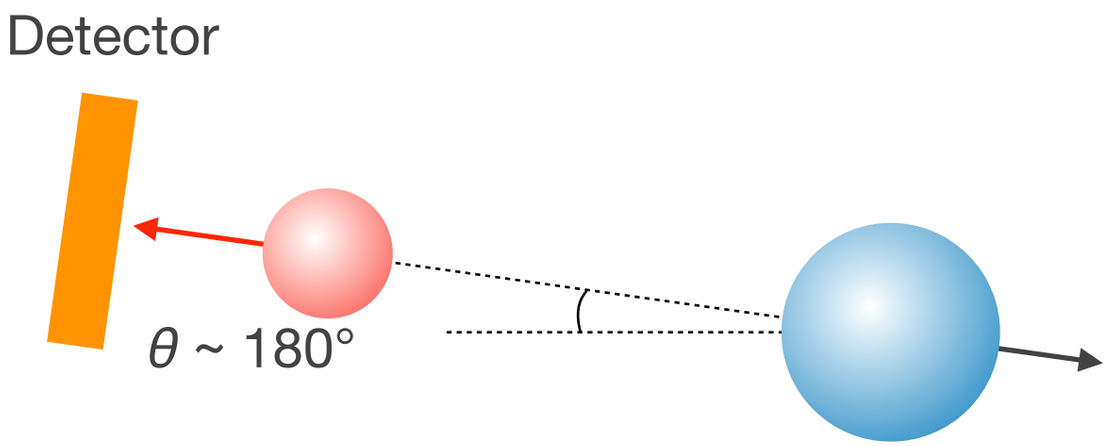
Detection of **quasielastic** particles



Conventional method

Detection of
projectile-like events backscattered at θ ~180°

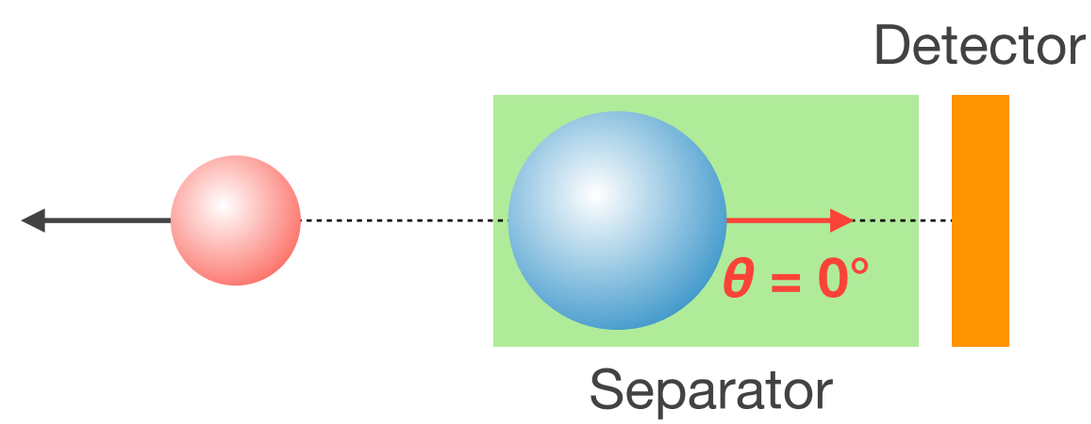
*S. Mitsuoka et al., PRL **99**, 182701 (2007).*
*S,S, Ntshangase et al., PLB **651**, 27 (2007).*
*G. Kaur et al., Acta Phys. Pol. **49**, 651 (2018).*
etc.



Present method @RIKEN

Detection of
target-like events recoiled at θ = 0°
using recoil-mass separator
(⇄ projectile-like events backscattered at θ = 180°)

*T. Tanaka et al., J. Phys. Soc. Jpn. **87**, 014201 (2018).*
*T. Niwase et al., JPS Conf Proc. **32**, 010022 (2020).*
*T. Tanaka et al., PRL **124**, 052502 (2020).*



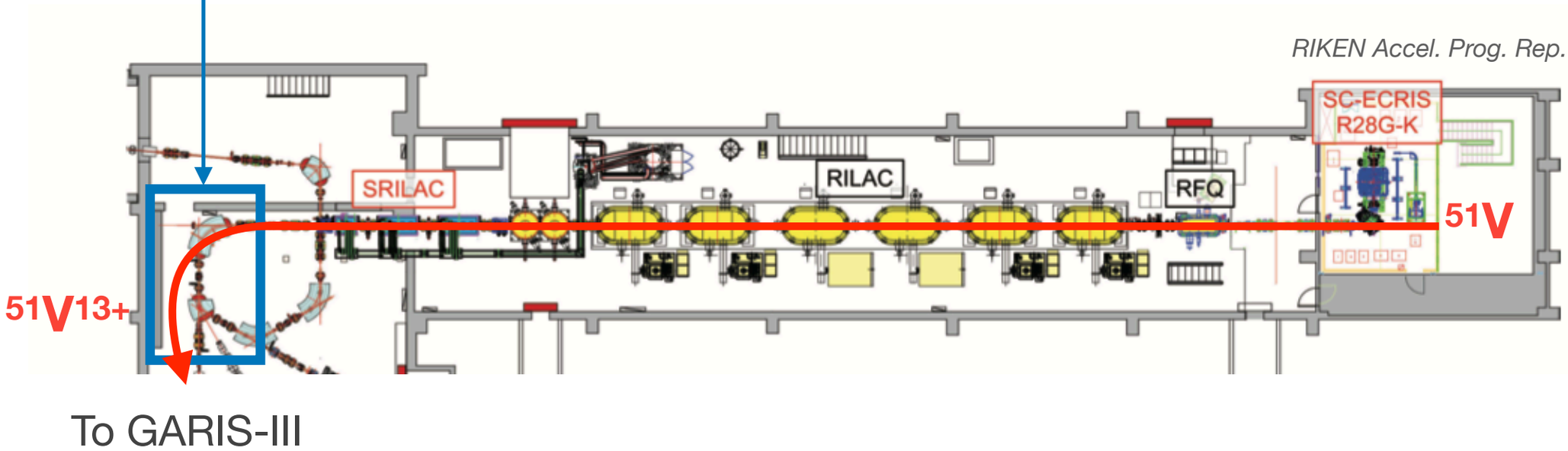
Directly measure QE barrier **at L ~ 0**.
(Most important component of ER production)

Experimental setup

SRILAC facility at RIKEN

Measurement of incident energy
0.1% accuracy by 90° bending magnet & TOF device

RIKEN Accel. Prog. Rep. ***54****, S1 (2021)*



Projectile ($^{51}V^{13+}$)

- Energy | E_{inc} = 247.3-324.4 MeV (incident energy)
  E_{cm} = 182.1-247.1 MeV (c.m. energy)
- Intensity | < 25 pnA
- Data | **39** data points with **2-MeV step**

Experimental setup @GARIS-III

Target

$^{248}Cm_2O_3$ (483 ug/cm^2) on Ti backing (1.31 mg/cm^2)

$$R(E) = \frac{d\sigma_{QE}}{d\sigma_{Ruth}} \propto \frac{N_{QE}[^{248}Cm]}{N_{Ruth}[^{51}V]}$$

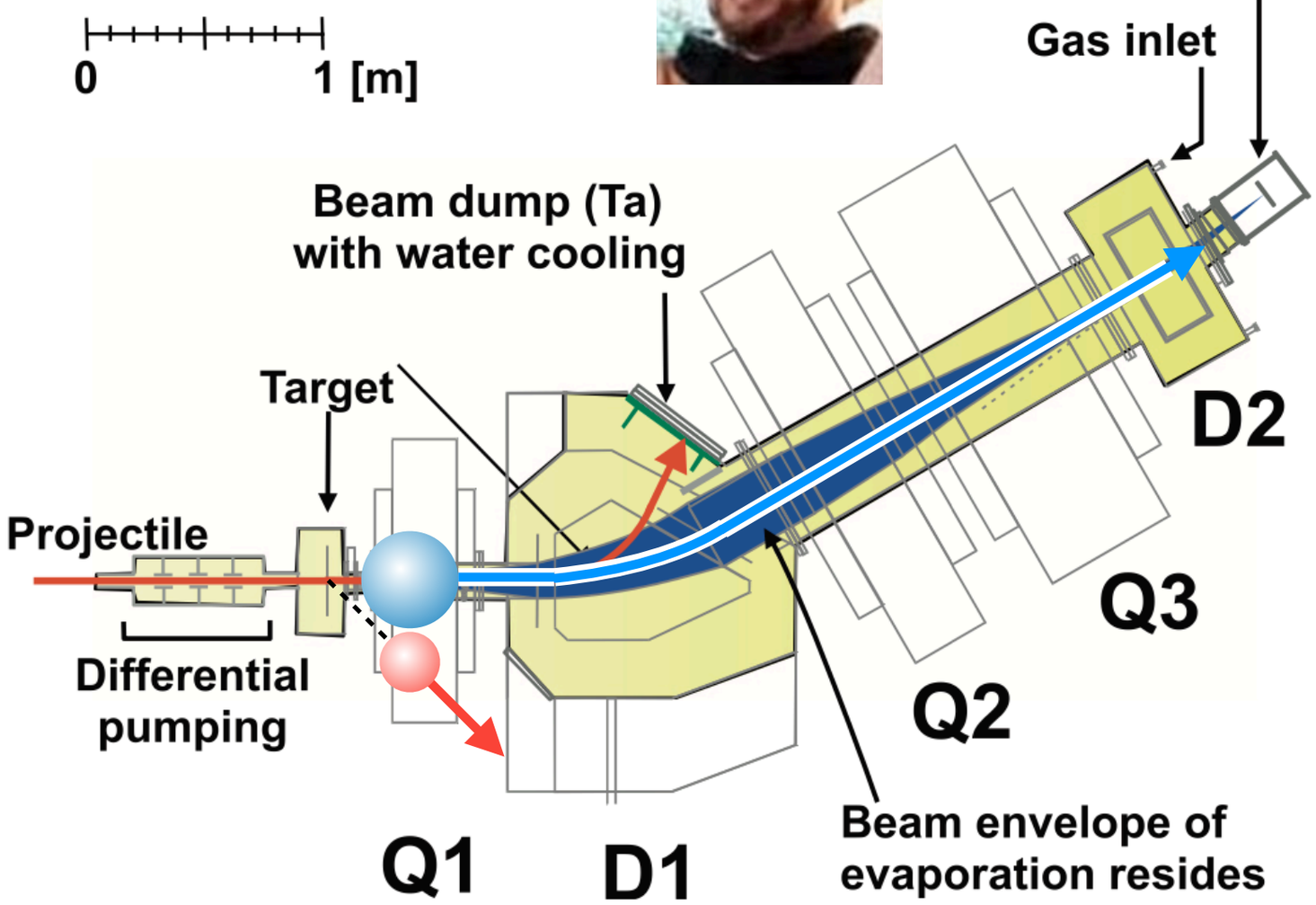
Gas-filled recoil ion separator GARIS-III

Same specifications as GARIS-II

*D. Kaji et al., NIM B **317**, 311 (2013)*

Detailed in

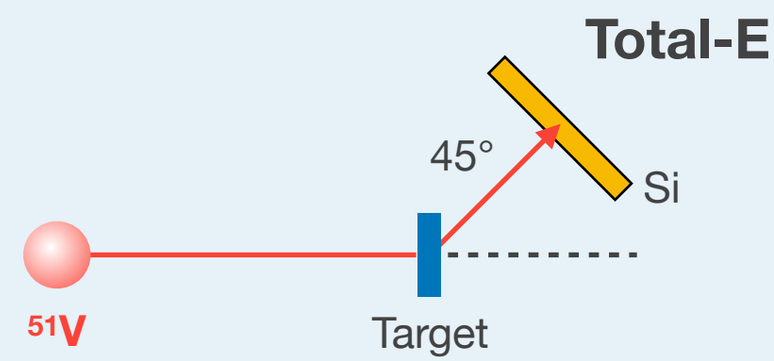
Pierre Brionnet's poster (PS-9-2)



@ Target chamber

Counting of

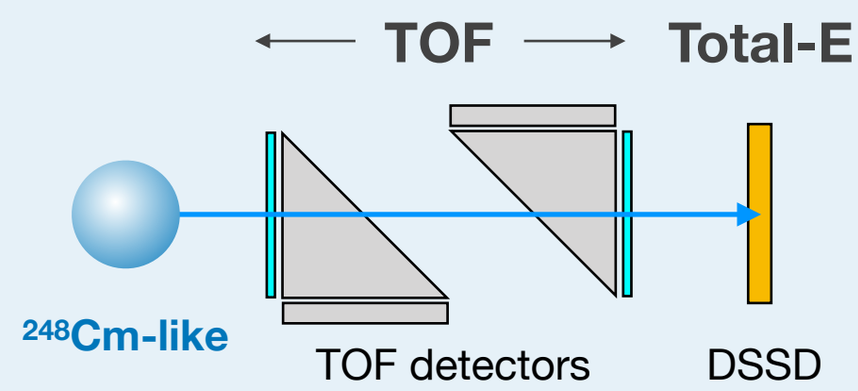
Rutherford scattered ^{51}V events



@ Final focal plane

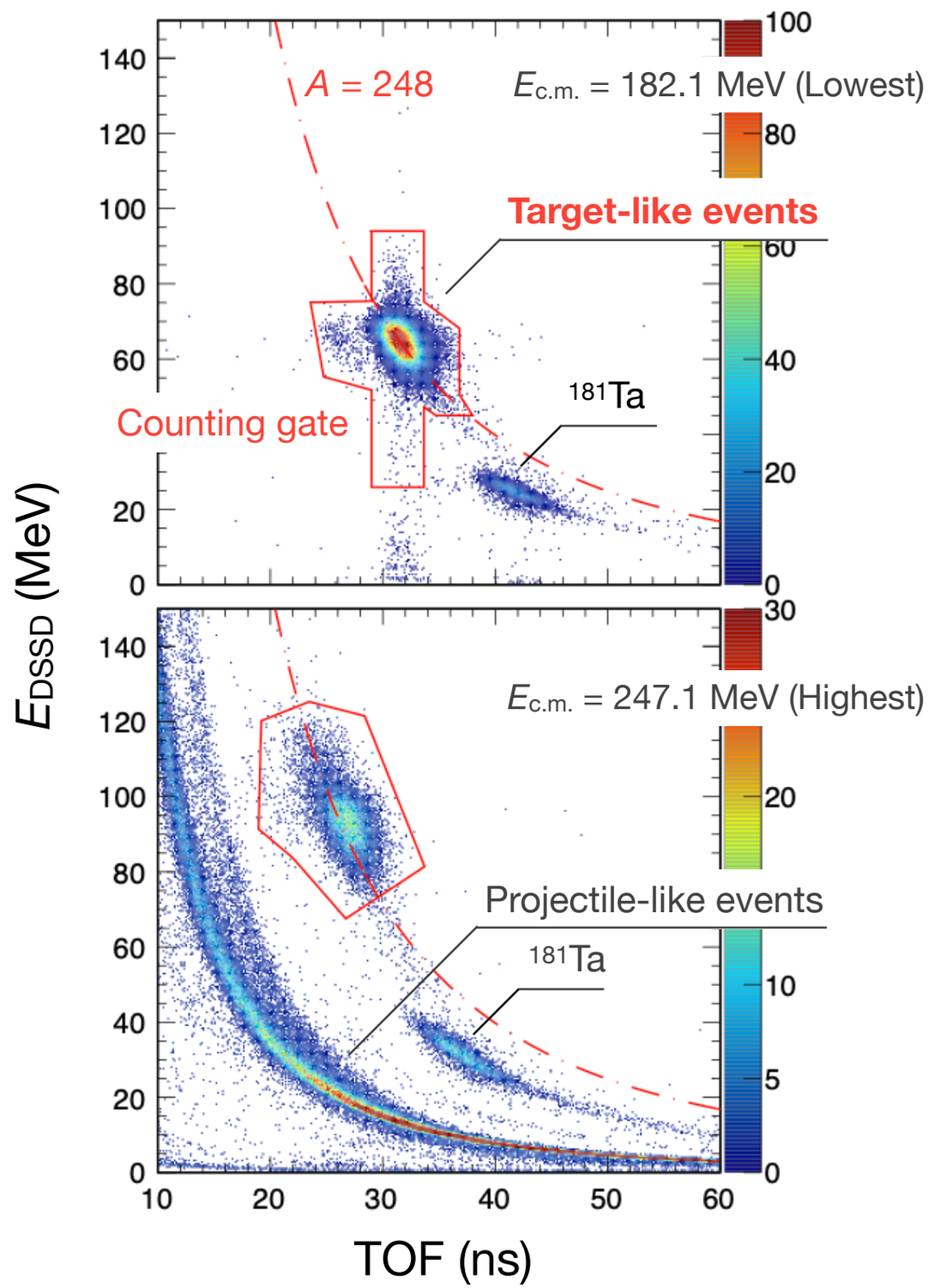
Counting of

target(^{248}Cm)-like events



Example of PID for target-like events

Target-like events were clearly identified.



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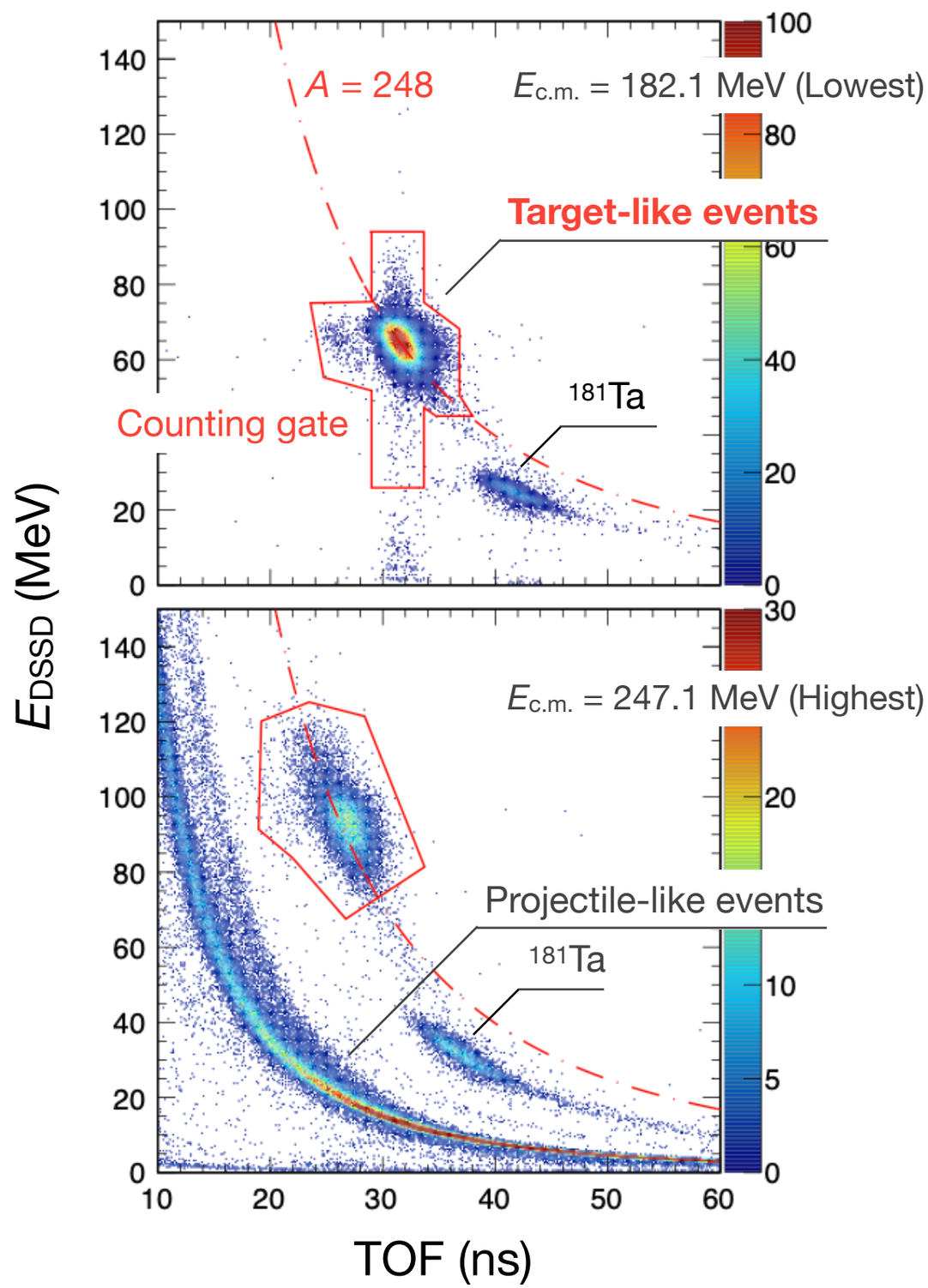

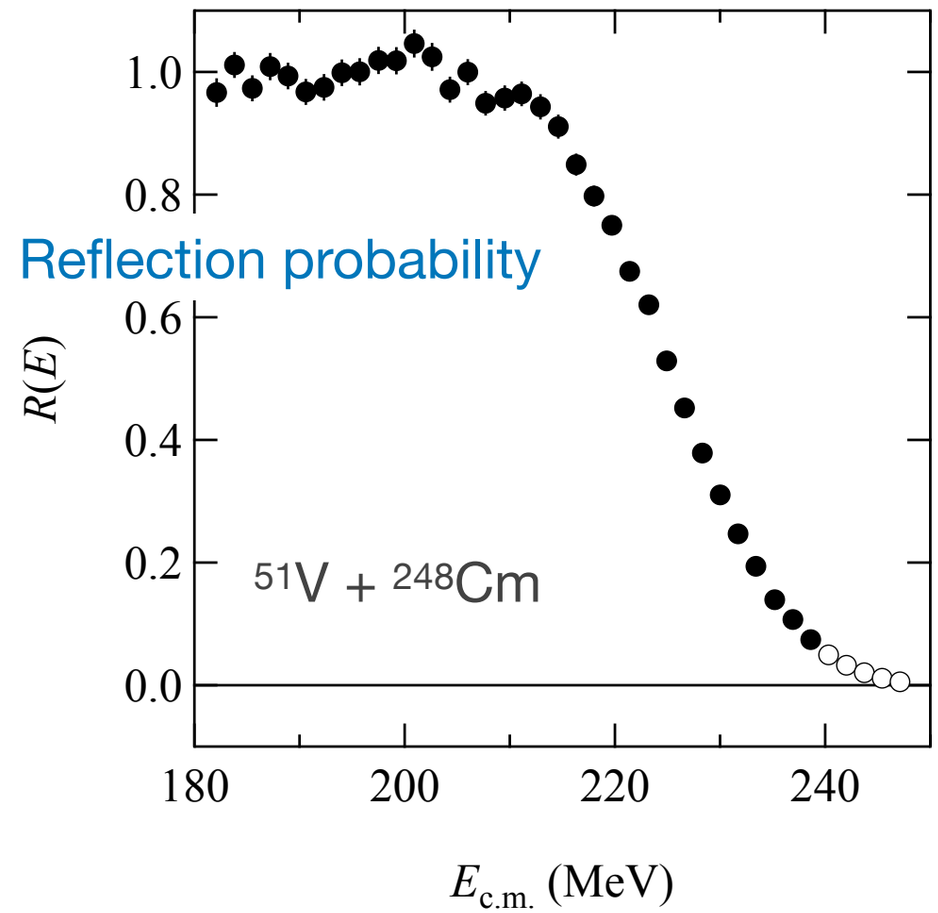

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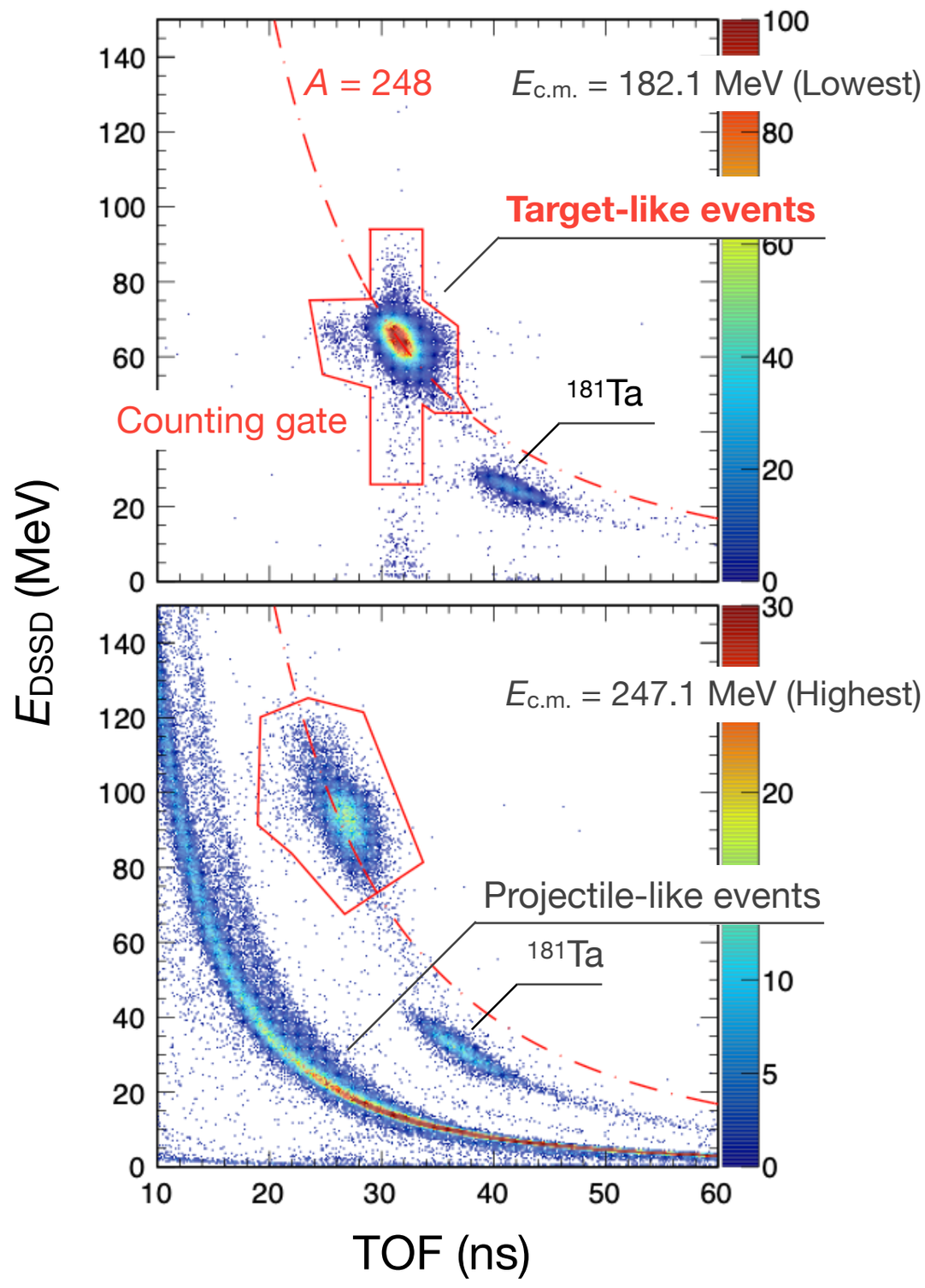
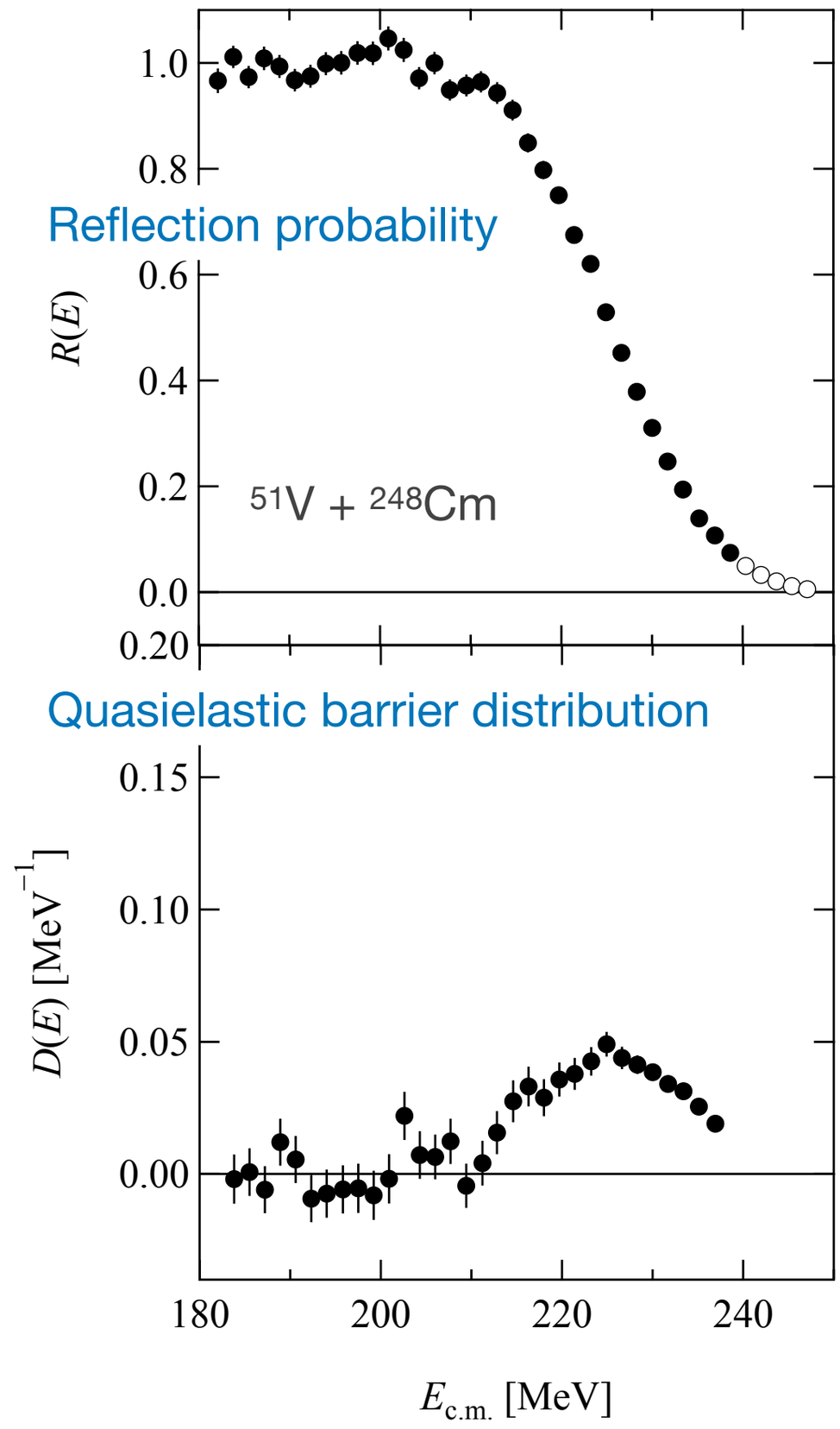




Comparison with coupled-channels (CC) calculations

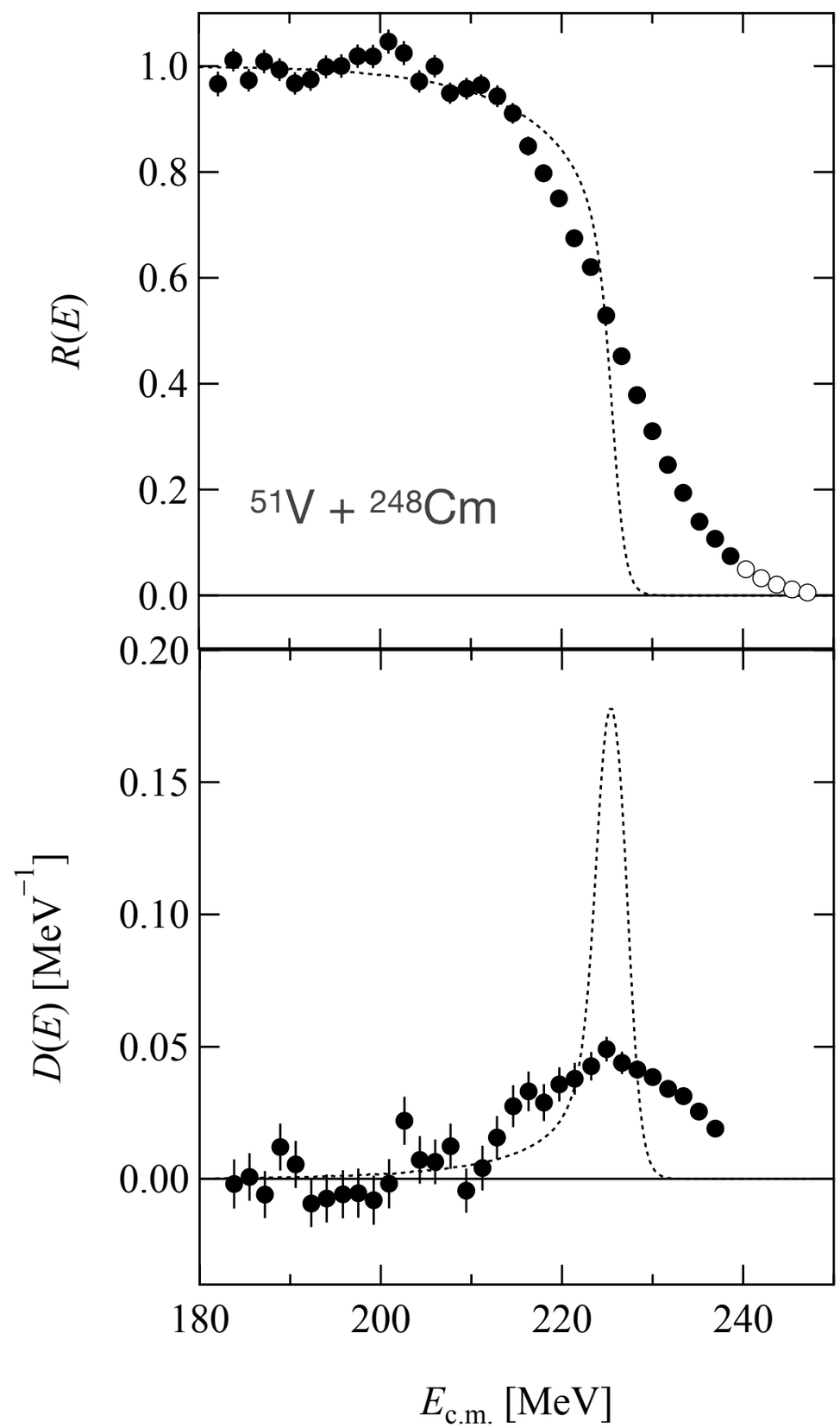
Coupled-channels calc. using CCFULL code

K. Hagino et al., Comput. Phys. Commun. ***123****, 143 (1999).*

Single-channel calculation

Optical potential with empirical parameters

O. Akyüz and A. Winther,
in Proceedings of the International School of Physics "Enrico Fermi," (1979).



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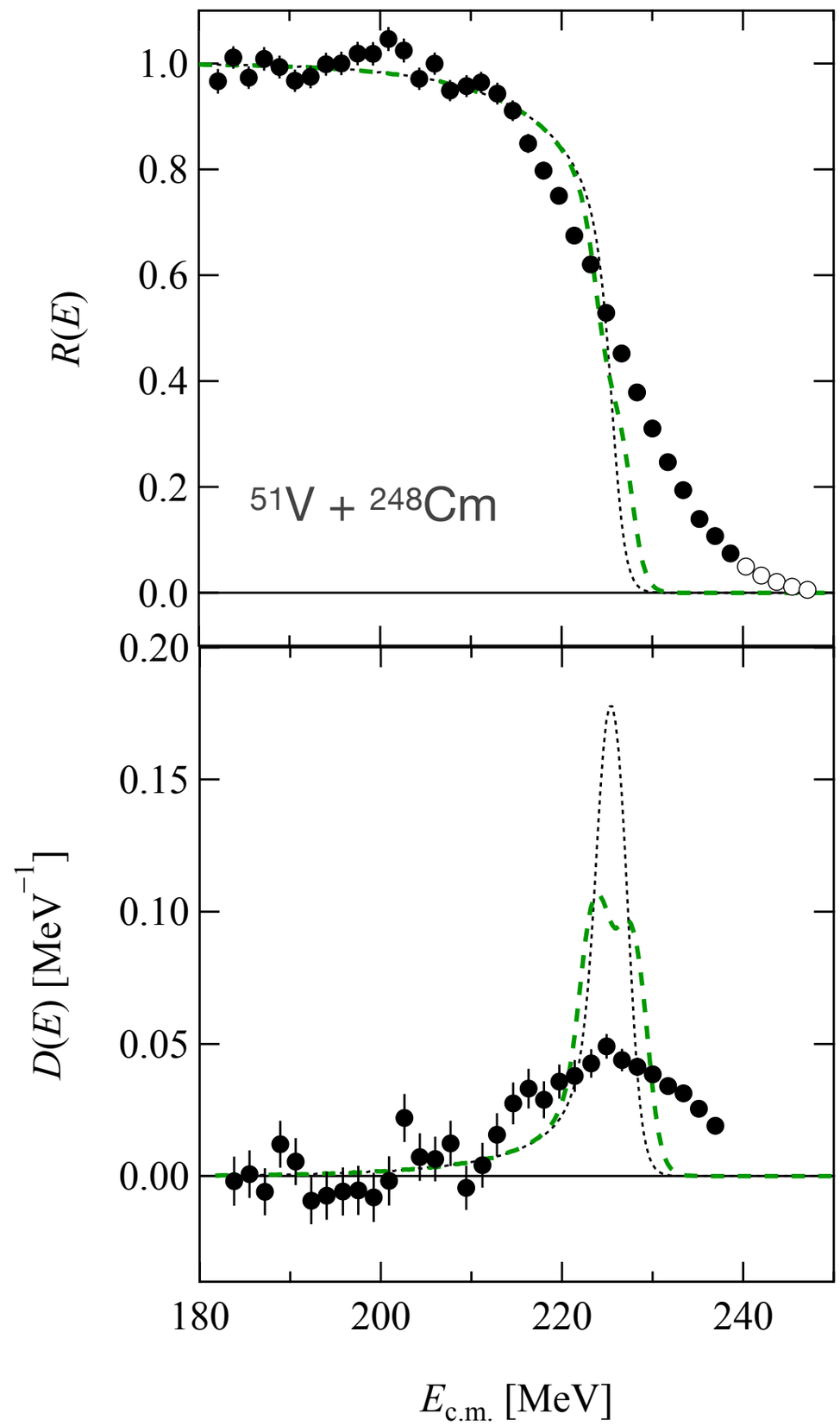
$\beta_2 = 0.11$ (From exp. B(E2))

$E_{1ph} = 0.32$ MeV (From exp. value)

W. Jimin and H. Xiaolong, Nucl. Data Sheets ***144****, 1 (2017).*



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W. Jimin and H. Xiaolong, Nucl. Data Sheets ***144****, 1 (2017).*

+ Rotational coupling of ^{248}Cm

$\beta_2 = 0.286$ (From exp. B(E2))

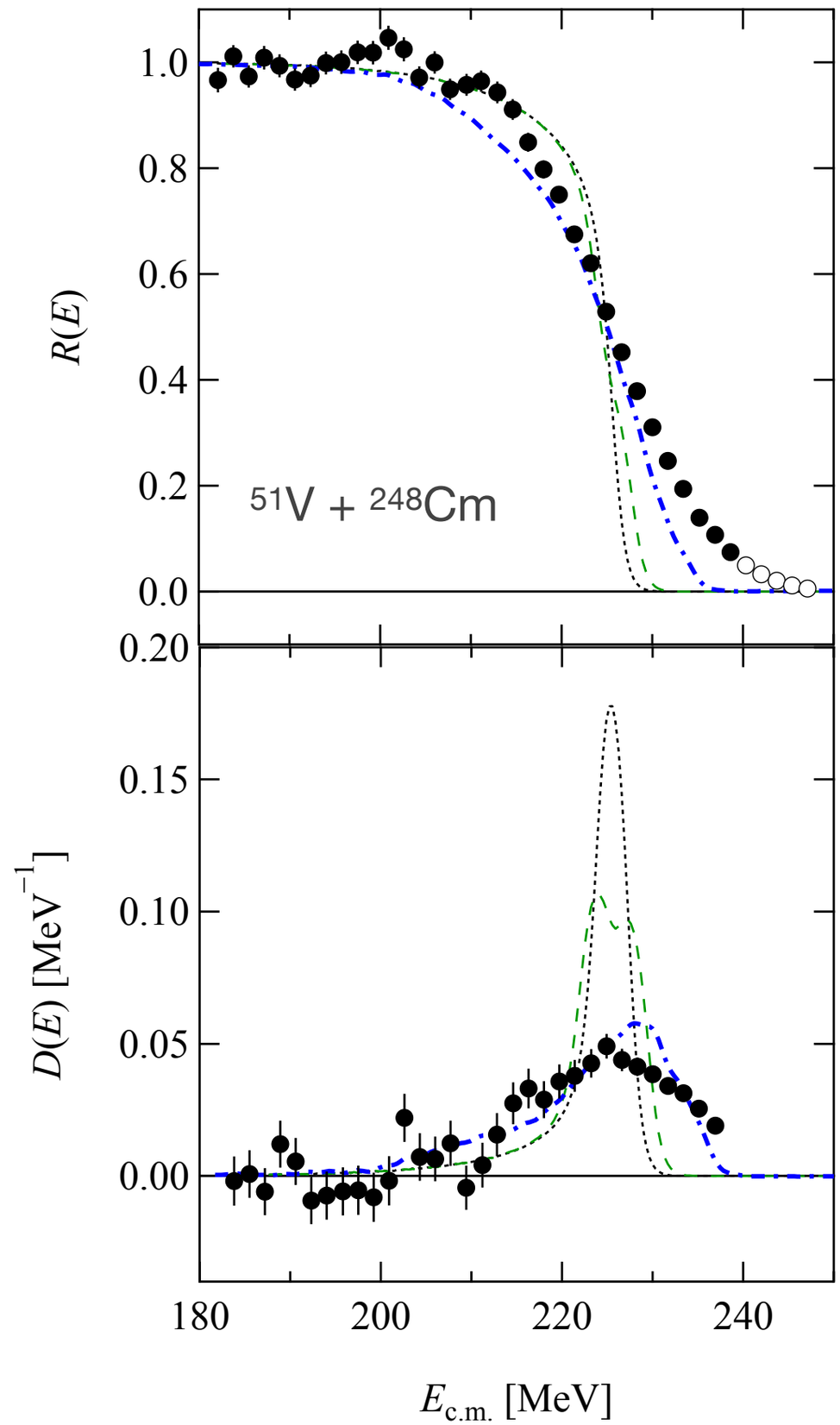
B. Pritychenko et al., Atom. Data and Nucl. Data Tables ***107****, 1 (2016).*

$\beta_4 = 0.039$ (FRDM value)

P. Möller et al., Atom. Data and Nucl. Data Tables ***109-110****, 1 (2016).*

$\beta_6 = 0.030$ (Same value as for previous study)

T. Tanaka et al., PRL ***124****, 052502 (2020).*



Comparison with coupled-channels (CC) calculations

Coupled-channels calc. using CCFULL code

K. Hagino et al., Comput. Phys. Commun. ***123****, 143 (1999).*

Single-channel calculation

Optical potential with empirical parameters

O. Akyüz and A. Winther,
in Proceedings of the International School of Physics "Enrico Fermi," (1979).

+ Vibrational coupling of ^{51}V

$\beta_2 = 0.11$ (From exp. B(E2))

$E_{1ph} = 0.32$ MeV (From exp. value)

W. Jimin and H. Xiaolong, Nucl. Data Sheets ***144****, 1 (2017).*

+ Rotational coupling of ^{248}Cm

$\beta_2 = 0.286$ (From exp. B(E2))

B. Pritychenko et al., Atom. Data and Nucl. Data Tables ***107****, 1 (2016).*

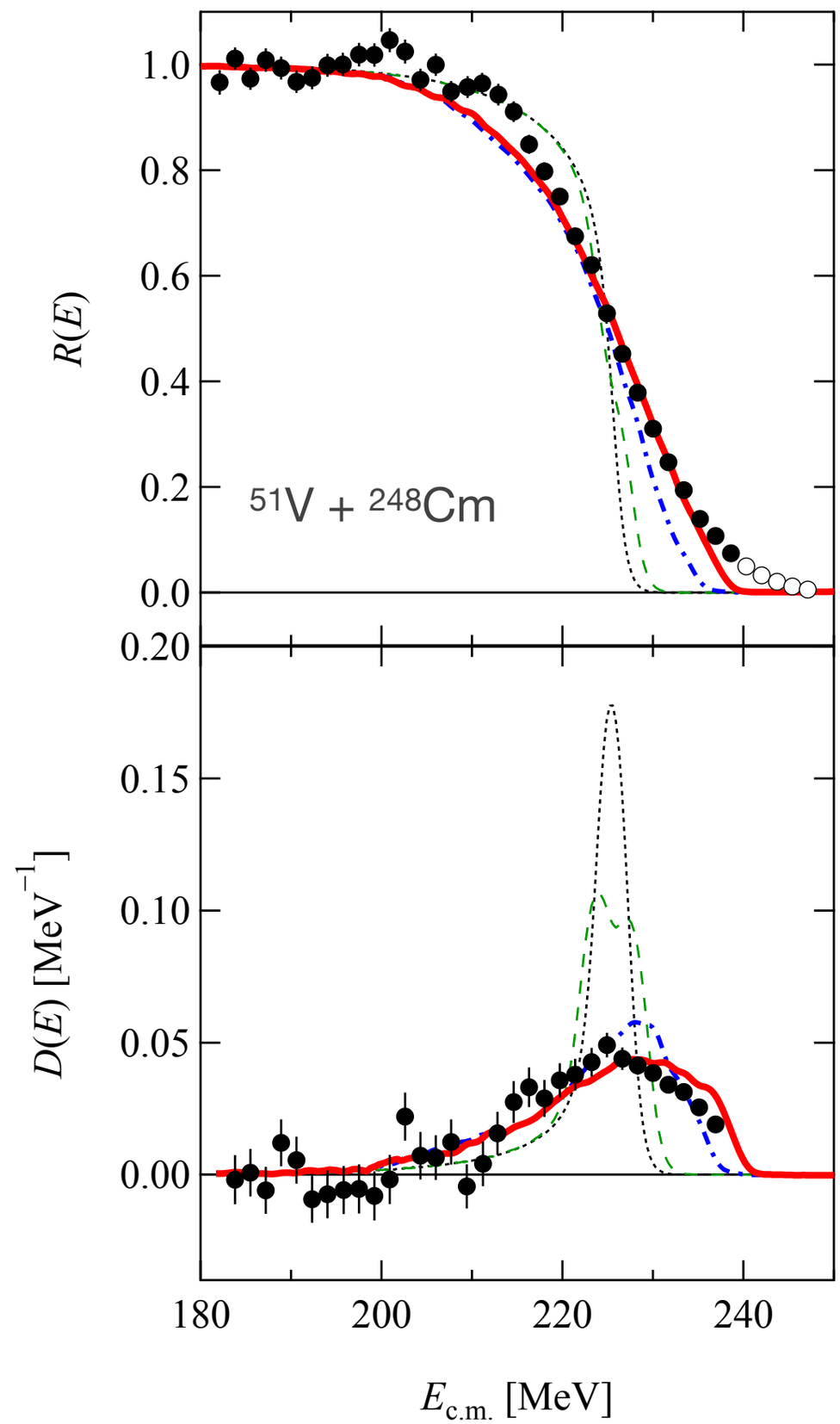
$\beta_4 = 0.039$ (FRDM value)

P. Möller et al., Atom. Data and Nucl. Data Tables ***109-110****, 1 (2016).*

$\beta_6 = 0.030$ (Same value as for previous study)

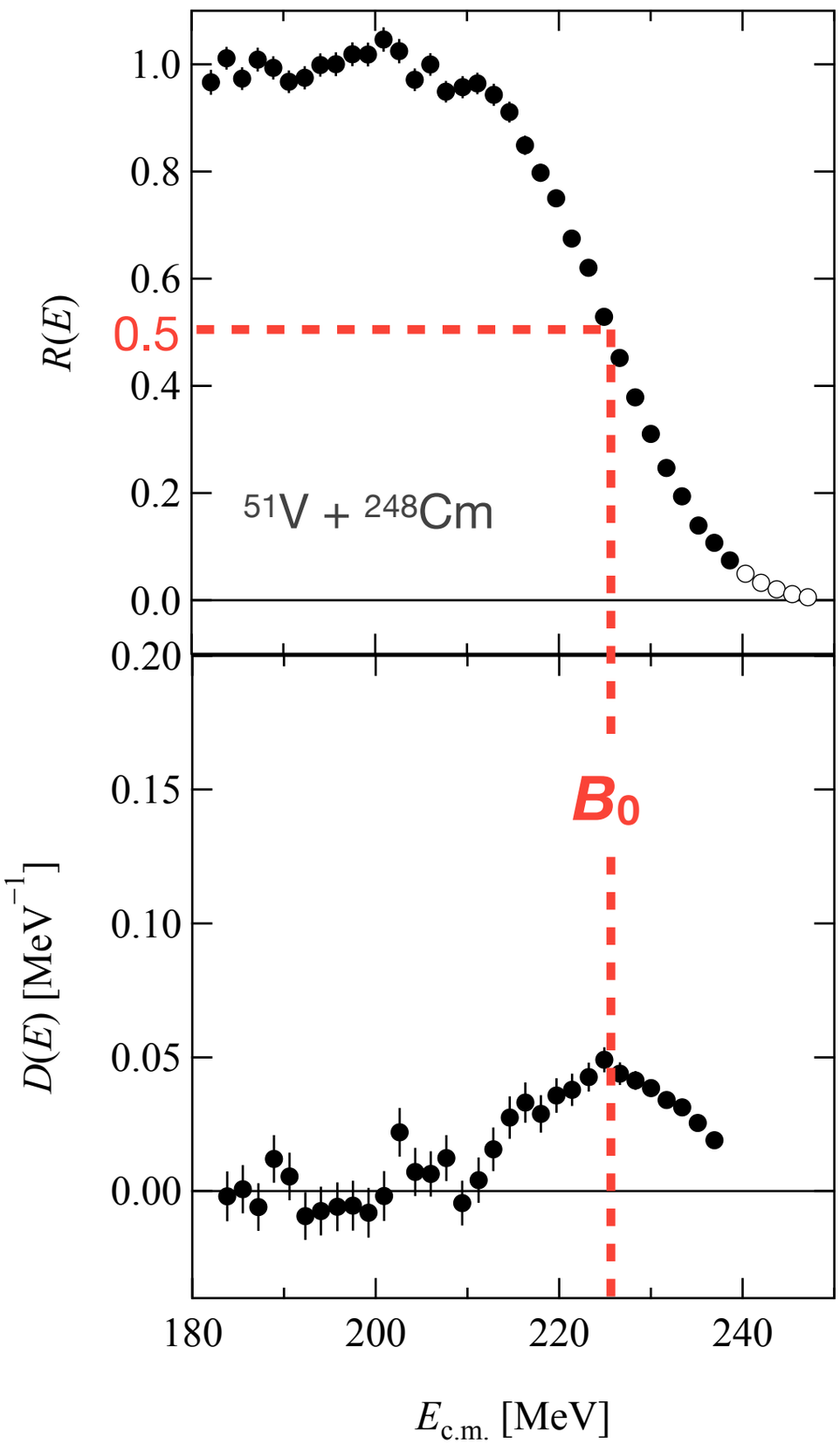
T. Tanaka et al., PRL ***124****, 052502 (2020).*

+ Coupling of 1n transfer reaction



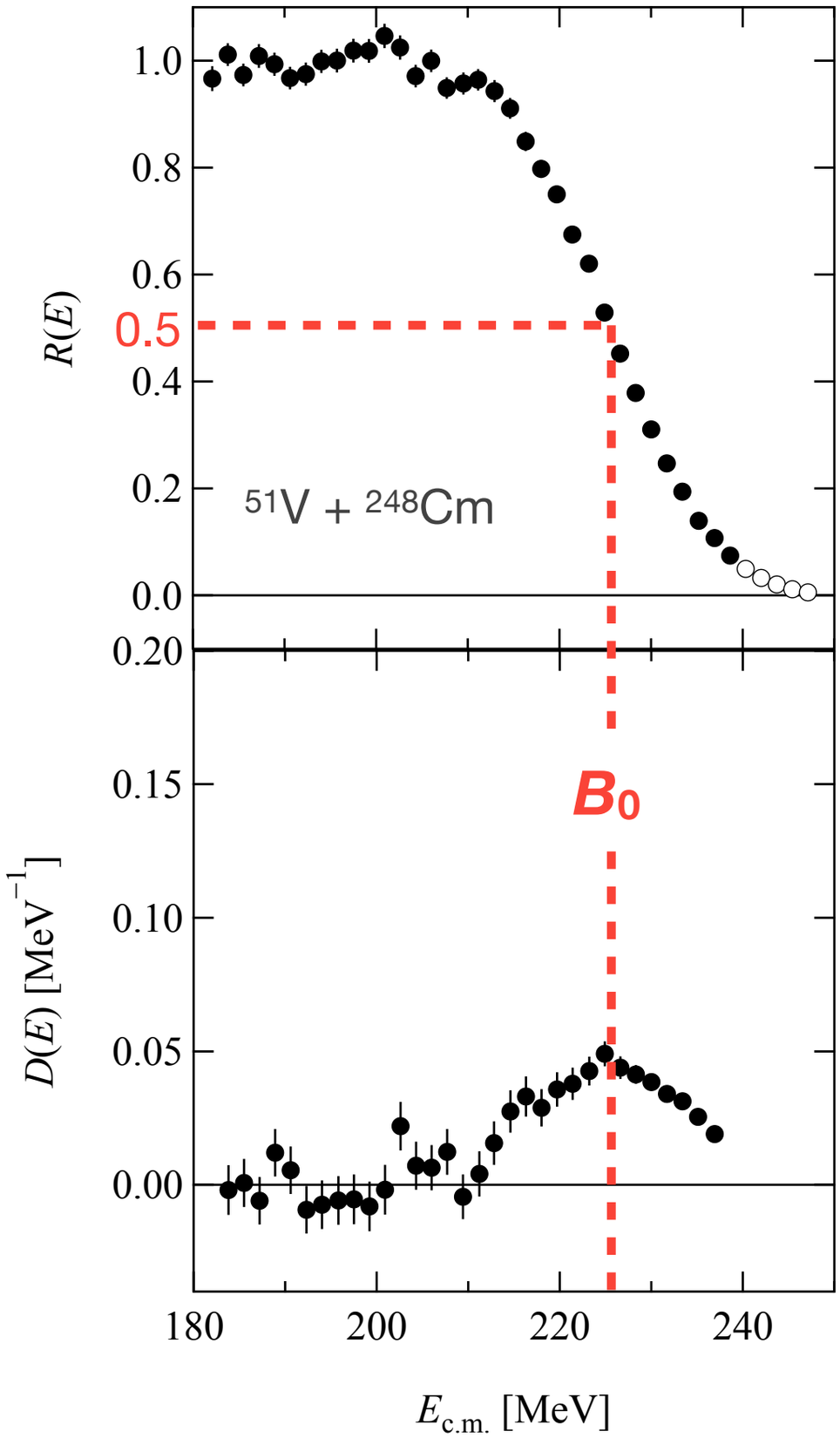
Target deformation significantly affects $D(E)$.

Average Coulomb barrier height B_0 of $^{51}V+^{248}Cm$



$^{51}V + ^{248}Cm$ | B_0 = 225.6 ± 0.2 MeV

Average Coulomb barrier height B_0 of $^{51}V+^{248}Cm$



$^{51}V + ^{248}Cm$ | B_0 = 225.6 ± 0.2 MeV

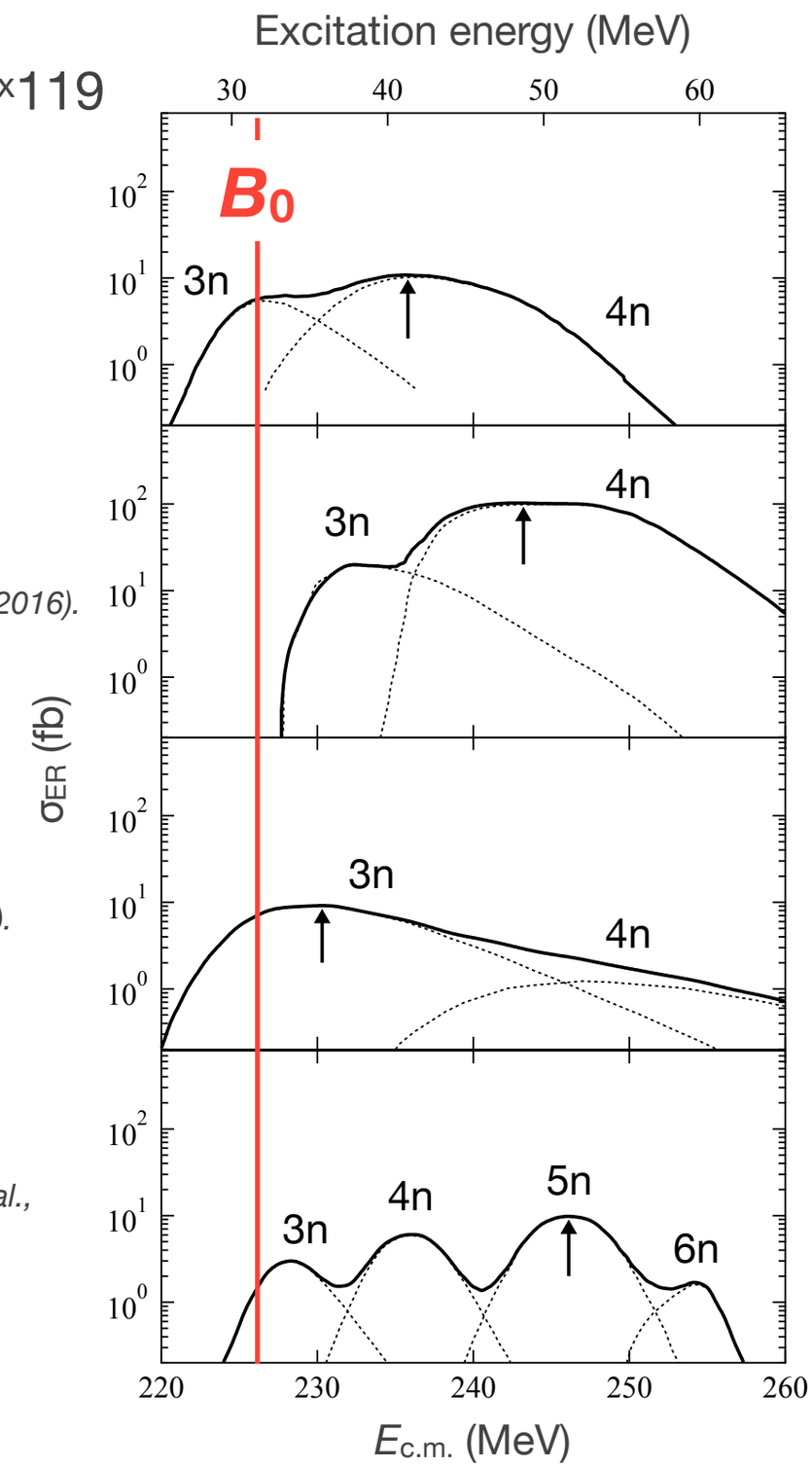
$^{248}Cm(^{51}V, xn)^{299-x}119$

*L. Zhu et al., PRC **89**, 024615 (2014).*

*N. Ghahramany et al., Eur. Phys. J. A **52**, 287 (2016).*

*X.-J. Lv et al., PRC **103**, 064616 (2021).*

*K. Swiek-Wilczyńska et al., PRC **99**, 054603 (2019).*



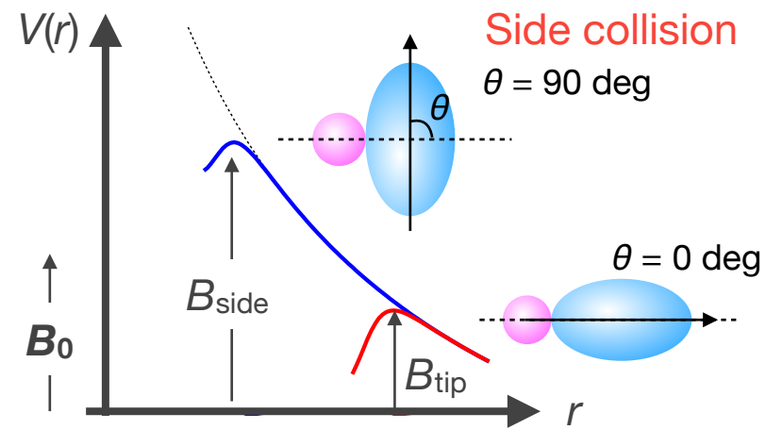
Side-collision energy B_{side} derived from B_0

Side collision in hot-fusion reaction

Actinide target | **Large prolate deformation**
→ **Side collision is favorable** for CN&ER formation.

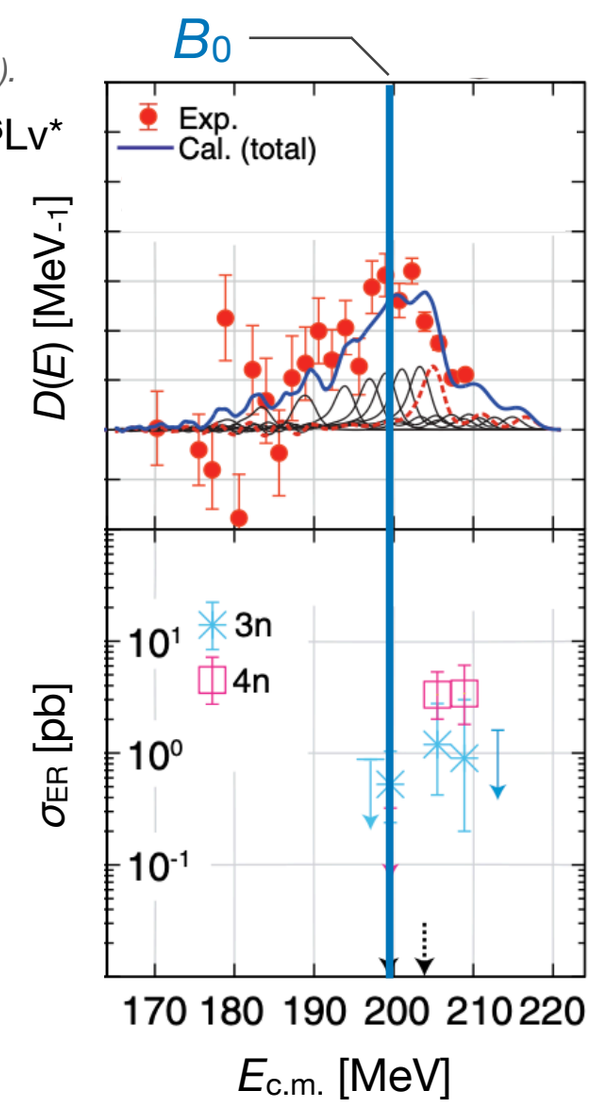
cf.) fusion-fission studies for hot fusion systems.

*D. J. Hinde et al., PRL **74**, 1295 (1995).*
*K. Nishio et al., PRC **62**, 014602 (2000).*



*T. Tanaka et al., PRL **124**, 052502 (2020).*

$^{48}Ca + ^{248}Cm \rightarrow ^{296}Lv^*$



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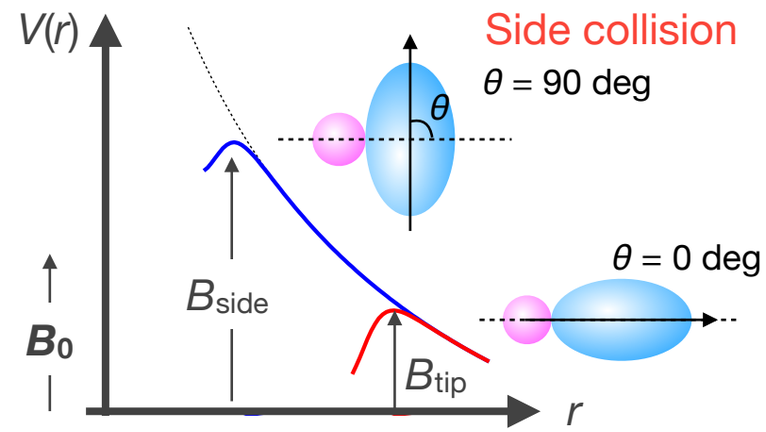
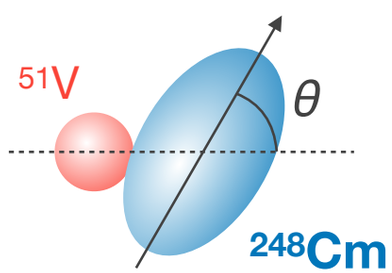


B_0 → B_{side}

Averaged value over orientation angles

*T. Tanaka et al., PRL **124**, 052502 (2020).*
*K. Hagino and N. Takigawa, PTP **128**, 1061 (2012).*

$$B_0 = \int_0^{\pi/2} B(\theta) \cdot \sin\theta d\theta$$



B_{side} = B(90°) is more consistent with peak of $\sigma_{ER}(E)$ than B_0.

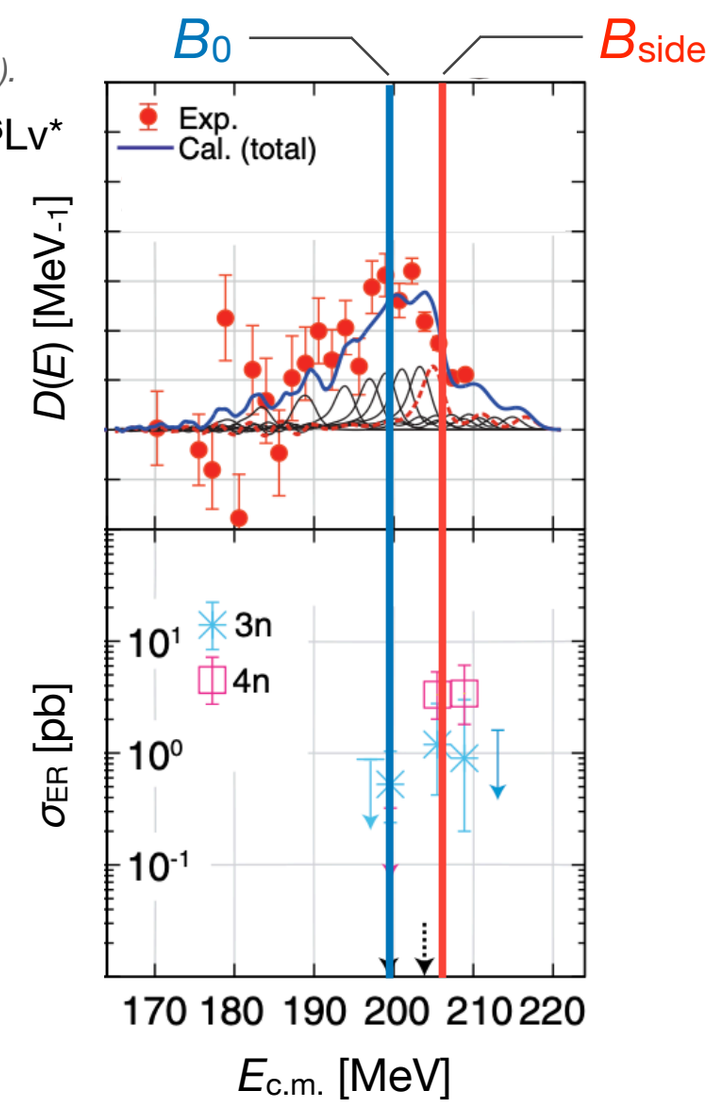
From the same procedure,

^{51}V+^{248}Cm

B_{side} = **233.0** MeV (**B_0** + 7.4 MeV)

*T. Tanaka et al., PRL **124**, 052502 (2020).*

^{48}Ca + ^{248}Cm → ^{296}Lv*



Relation between experimental B_{side} and optimal energy E_{opt}

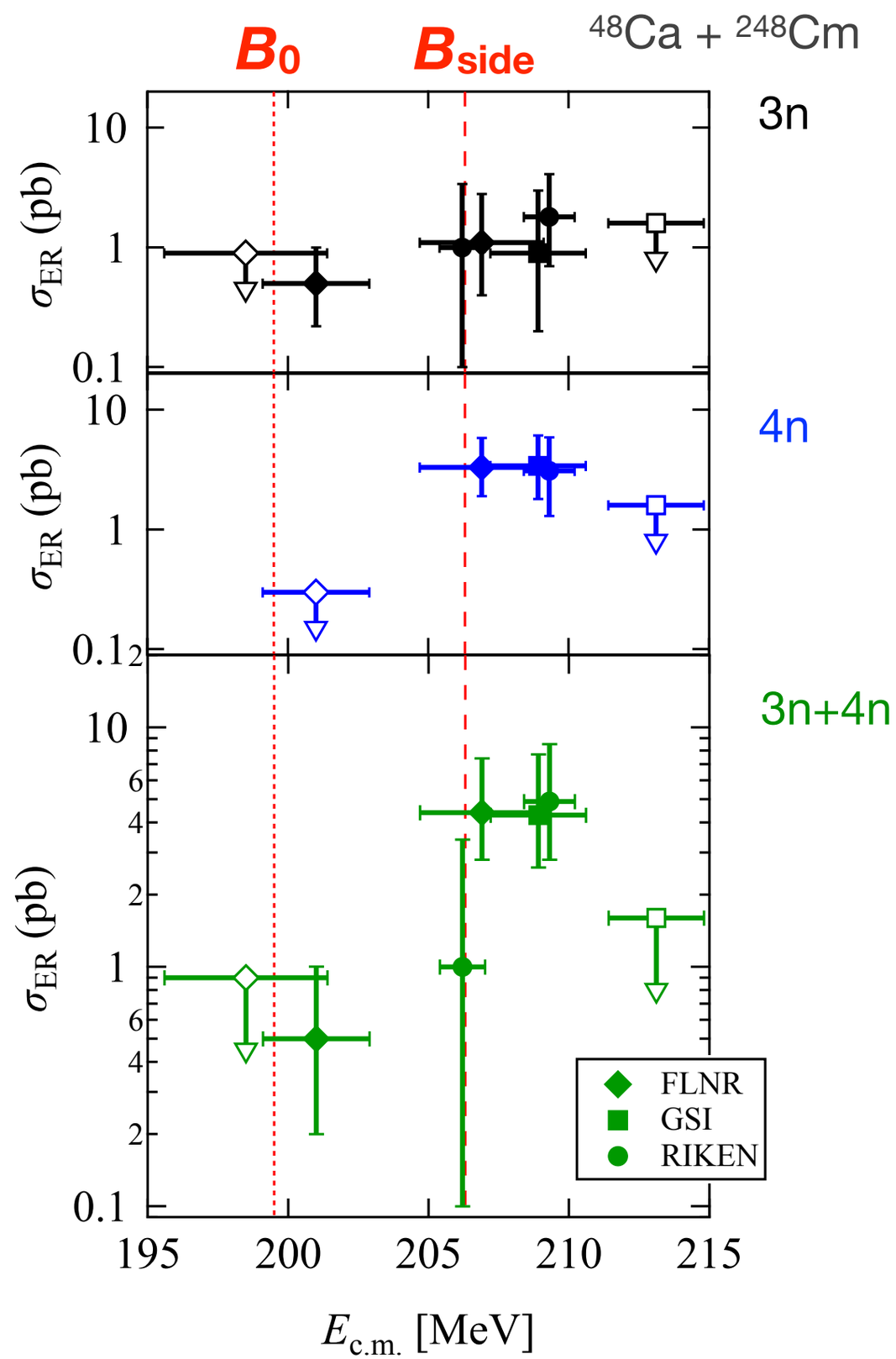
^{48}Ca + ^{248}Cm

- Similar masses to ^{51}V + ^{248}Cm.
- D_{QE} & σ_{ER} data are available.

D_{QE}
*T. Tanaka et al., PRL **124**, 052502 (2020).*

σ_{ER}
FLNR: Yu. Ts. Oganessian *et al.*, PRC **70**, 054609 (2004).
Yu. Ts. Oganessian *et al.*, PRC **63**, 011301(R) (2001).
GSI: S. Hofmann *et al.*, Eur. Phys. J. A **52**, 180 (2016).
RIKEN: D. Kaji et al., J. Phys. Soc. Jpn. **86**, 034201 (2017).

B_{side} is located around maximum of σ_{ER}.



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*T. Tanaka et al., PRL **124**, 052502 (2020).*

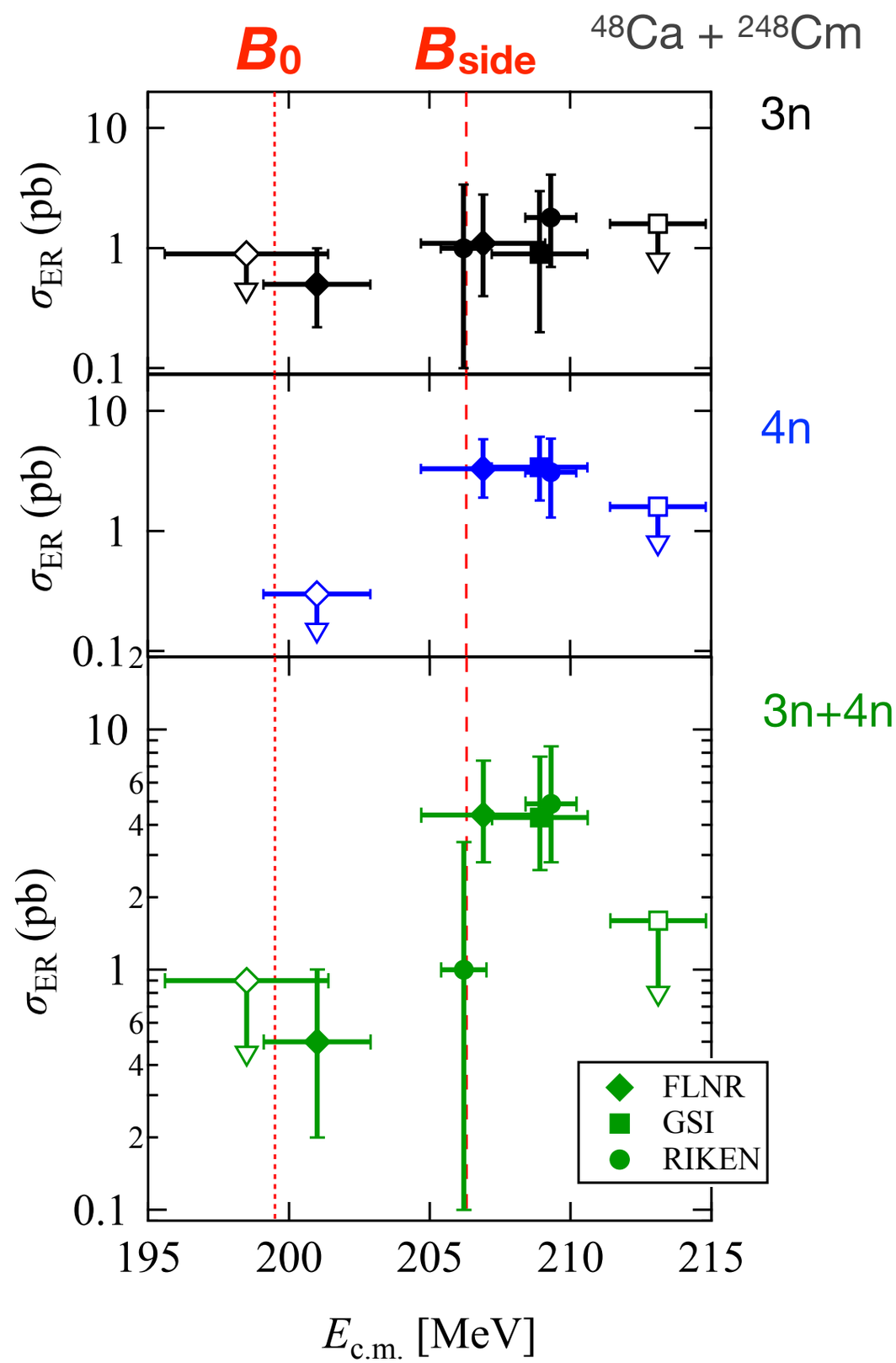
σ_{ER}
FLNR: Yu. Ts. Oganessian *et al.*, PRC **70**, 054609 (2004).
Yu. Ts. Oganessian *et al.*, PRC **63**, 011301(R) (2001).
GSI: S. Hofmann *et al.*, Eur. Phys. J. A **52**, 180 (2016).
RIKEN: D. Kaji et al., J. Phys. Soc. Jpn. **86**, 034201 (2017).

B_{side} is located around maximum of σ_{ER}.

In more detail…

Optimal reaction energy E_{opt} is **slightly higher**??

(*) Pointed out also in theoretical study. (+2-3 MeV in ^{48}Ca+^{248}Cm)
*K. Hagino, PRC **98**, 014607 (2018).*



Relation between experimental B_{side} and optimal energy E_{opt}

^{48}Ca + ^{248}Cm

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- D_{QE} & σ_{ER} data are available.

D_{QE}
*T. Tanaka et al., PRL **124**, 052502 (2020).*

σ_{ER}
FLNR: Yu. Ts. Oganessian *et al.*, PRC **70**, 054609 (2004).
Yu. Ts. Oganessian *et al.*, PRC **63**, 011301(R) (2001).
GSI: S. Hofmann *et al.*, Eur. Phys. J. A **52**, 180 (2016).
RIKEN: D. Kaji et al., J. Phys. Soc. Jpn. **86**, 034201 (2017).

B_{side} is located around maximum of σ_{ER}.

In more detail…

Optimal reaction energy E_{opt} is **slightly higher**??

(*) Pointed out also in theoretical study. (+2-3 MeV in ^{48}Ca+^{248}Cm)
*K. Hagino, PRC **98**, 014607 (2018).*

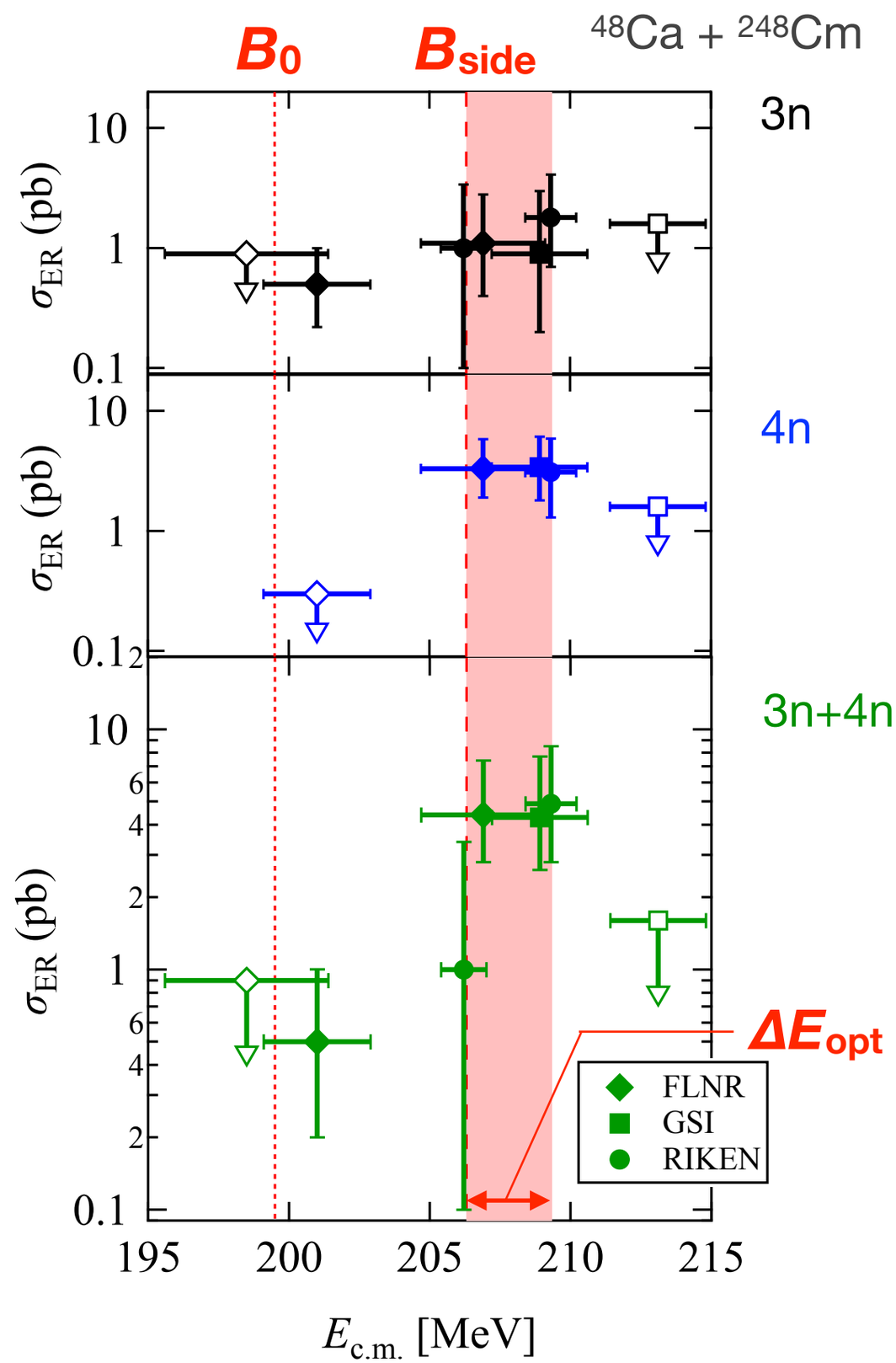
Uncertainty in relation between B_{side} & E_{opt}

ΔE_{opt} = +3.0 MeV (**+1.5% relative to B_{side}**)

Assuming similar situation,

^{51}V+^{248}Cm

ΔE_{opt} = +0.015 x B_{side} = **3.5 MeV**



Deduced optimal energy for ^{248}Cm(^{51}V, xn)$^{299-x}$119

Deduced energies from exp.

- Average barrier height
  B_0 = **225.6(2)** MeV

- Side-collision energy
  B_{side} = **233.0(2)** MeV

- Uncertainty between E_{opt} & B_{side}
  ΔE_{opt} = **+3.5** MeV

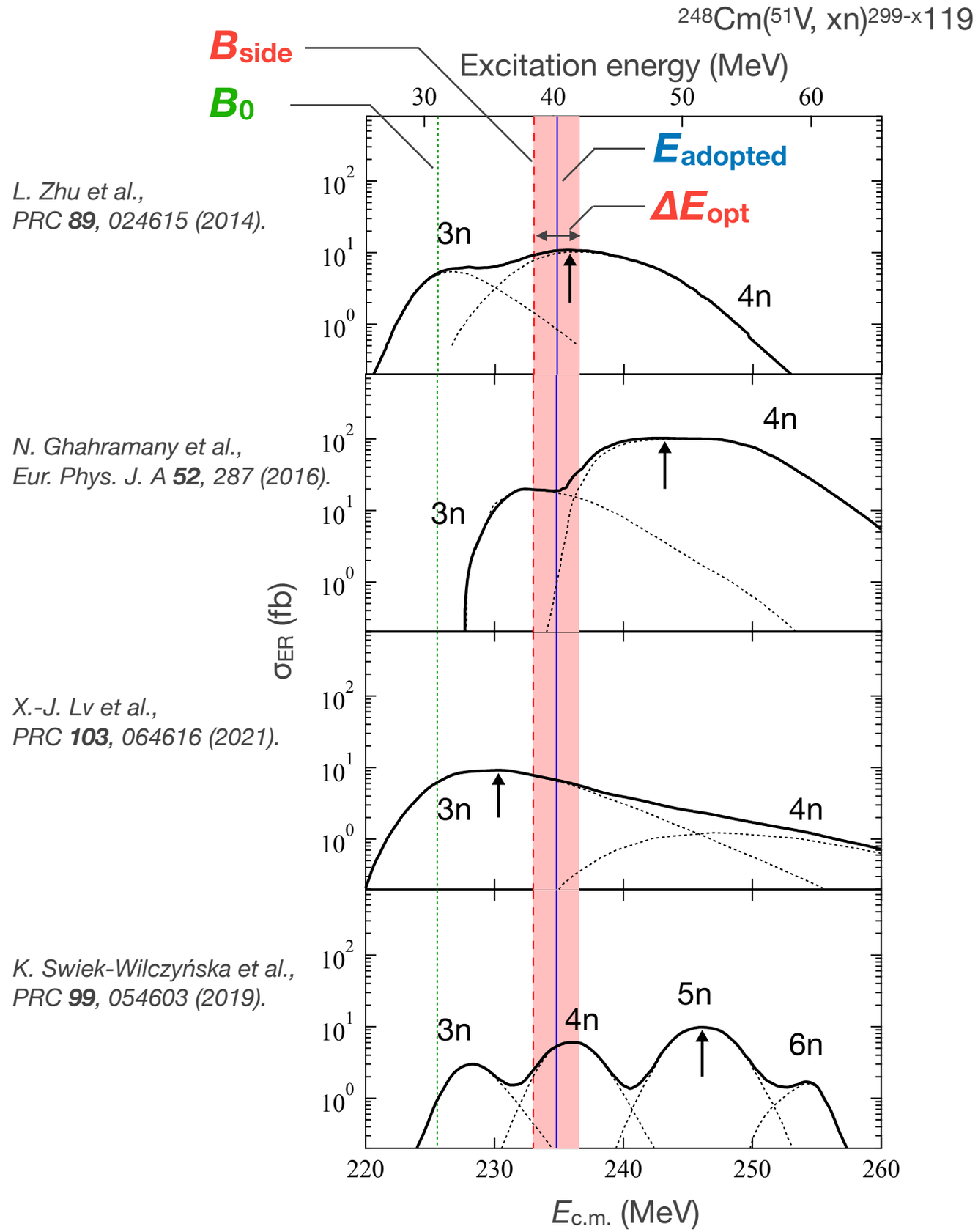
(*) Comparable to
energy spread in typical-thick target (~500 μg/cm²)

- Adopted energy
  for synthesis of element-119 @RIKEN

$E_{adopted} = B_{side} + 1/2 \times \Delta E_{opt}$ = **234.8** MeV

(*) E_{ex}(^{299}119*) = 40.3 MeV

Further theoretical studies based on present experimental B_0 value are strongly desirable.



Summary

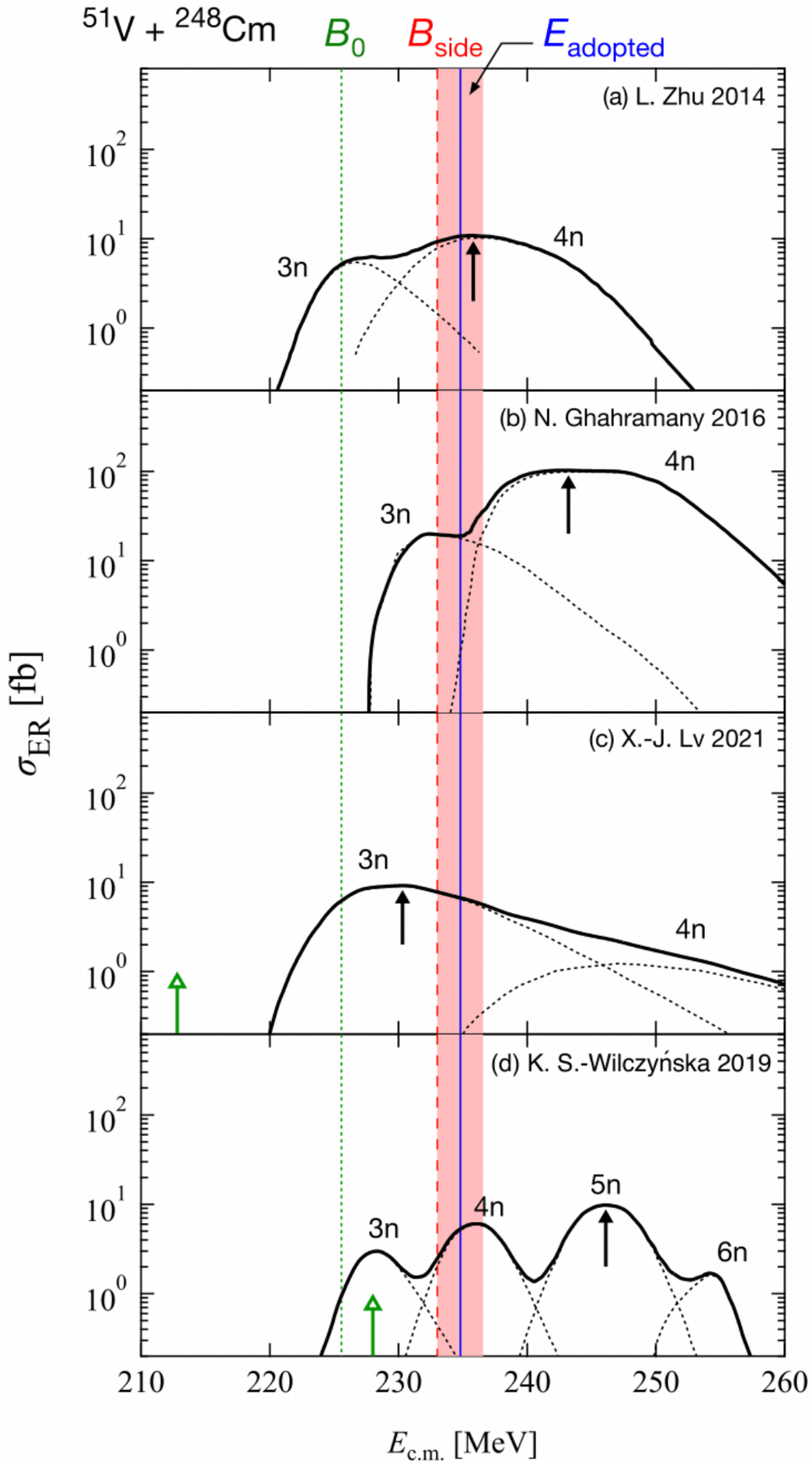
Quasielastic (QE) backscattering of ^{51}V+^{248}Cm was measured in SRILAC, RIKEN.
→ **QE Barrier distribution** was extracted.

Evaluation of **optimal reaction energy for ^{248}Cm(^{51}V,xn)$^{299-x}$119**
based on **experimental information**.

- Average barrier height
  B_0 = **225.6(2)** MeV — **Purely from experimental result**
- Side-collision energy
  B_{side} = **233.0(2)** MeV — **From calculation using experimental barrier distribution**
- Uncertainty between E_{opt} & B_{side}
  ΔE_{opt} = **+3.5** MeV — **Evaluation in ^{48}Ca+^{248}Cm**
- Adopted reaction energy
  $E_{adopted}$ = **234.8** MeV ($E_{ex}[^{299}119^*]$ = 40.3 MeV)

Recently published in Journal of the Physical Society of Japan **91**, 084201 (2022).
M. Tanaka *et al.*,
"Probing Optimal Reaction Energy for Synthesis of Element 119 from 51V+248Cm Reaction with Quasielastic Barrier Distribution Measurement"

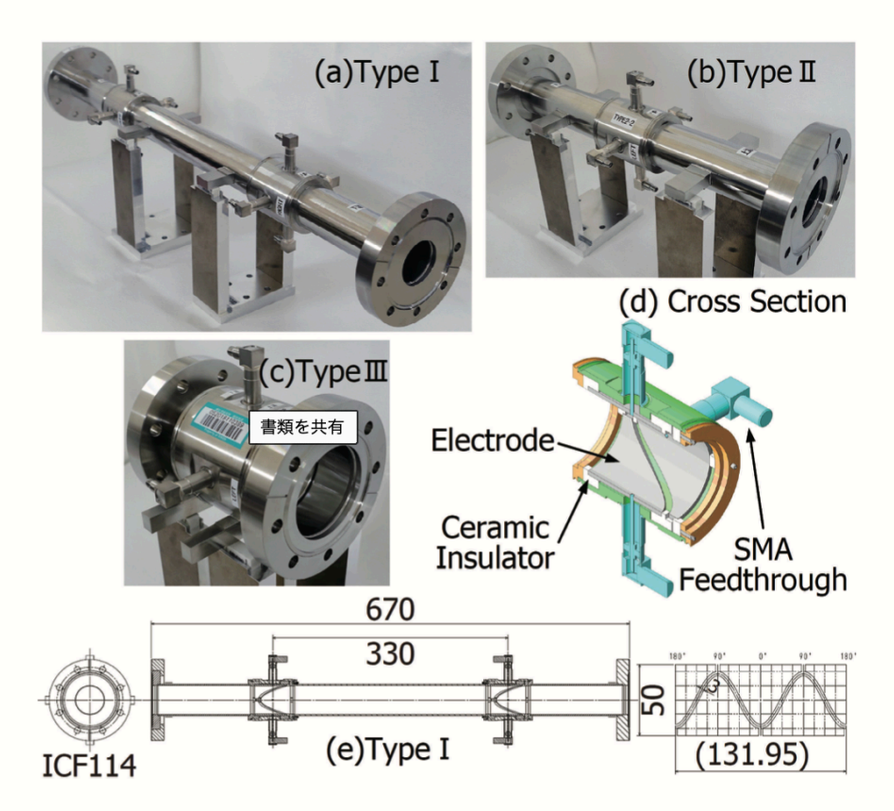
Backup slides


$^{51}V + ^{248}Cm$
B_0
B_{side}
$E_{adopted}$
(a) L. Zhu 2014
(b) N. Ghahramany 2016
(c) X.-J. Lv 2021
(d) K. S.-Wilczyńska 2019
3n
4n
5n
6n
σ_{ER} [fb]
$E_{c.m.}$ [MeV]
210
220
230
240
250
260

TOF device for beam-energy monitor

"First Beam from SRILAC"
RIKEN Accel. Prog. Rep. **54** (2021).

10^{-4} accuracy of energy determination from TOF measurement



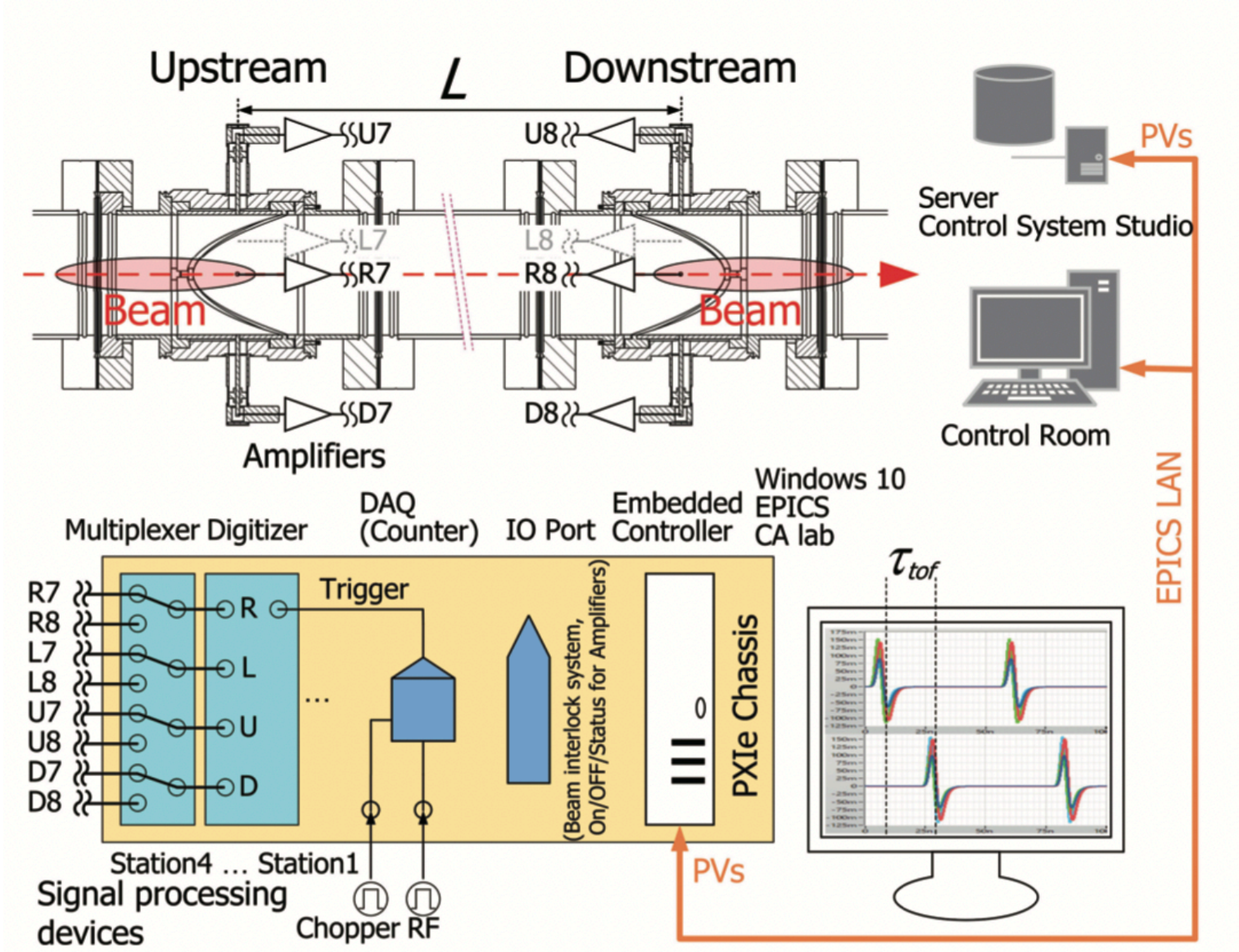


Fig. 11. Block diagram of BEPMs and DAQ system.[27)]

GARIS-III

Nuclear Instruments and Methods in Physics Research B 317 (2013) 311–314

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journal homepage: www.elsevier.com/locate/nimb

Gas-filled recoil ion separator GARIS-II

D. Kaji [a,*], K. Morimoto [a], N. Sato [a,b,1], A. Yoneda [a], K. Morita [a]

[a] Nishina Center for Accelerator Based Science, RIKEN, Wako, Saitama 351-0198, Japan
[b] Department of Physics, Tohoku University, Sendai, Miyagi 980-8578, Japan

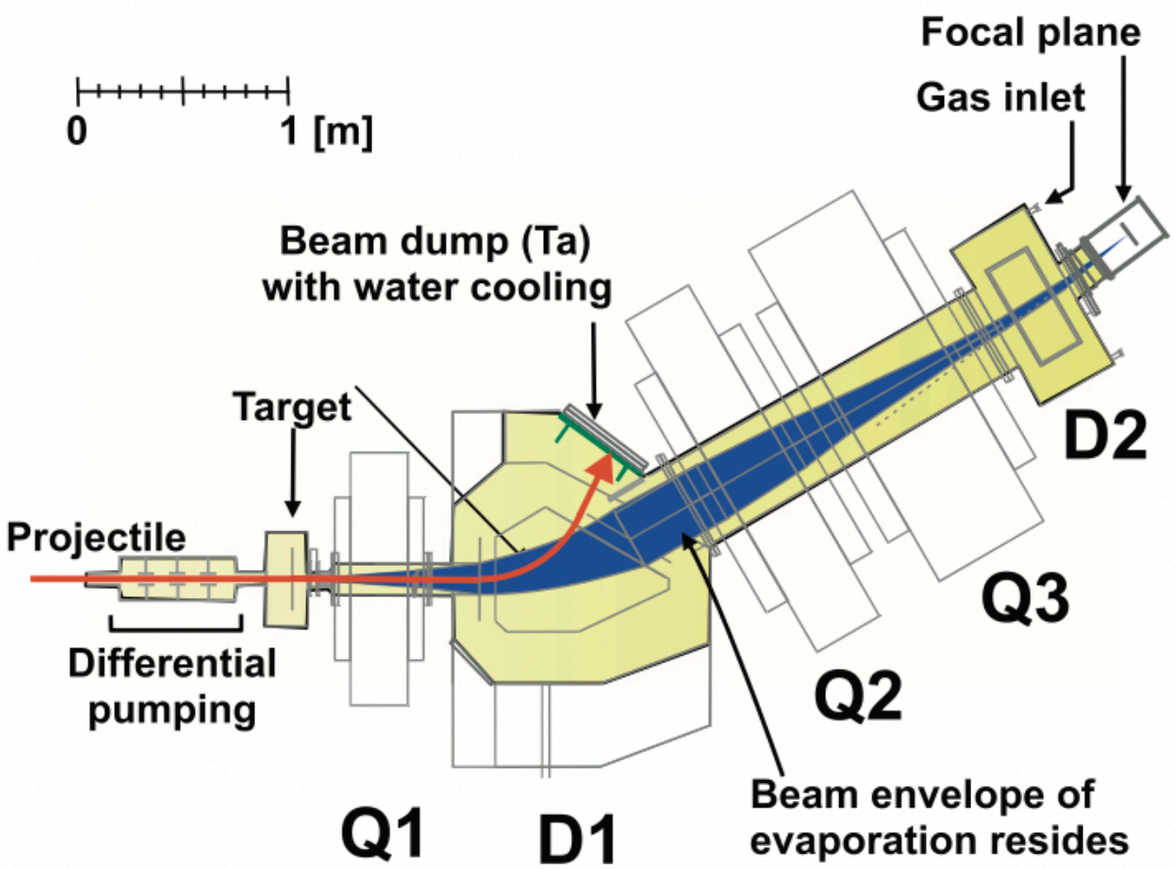
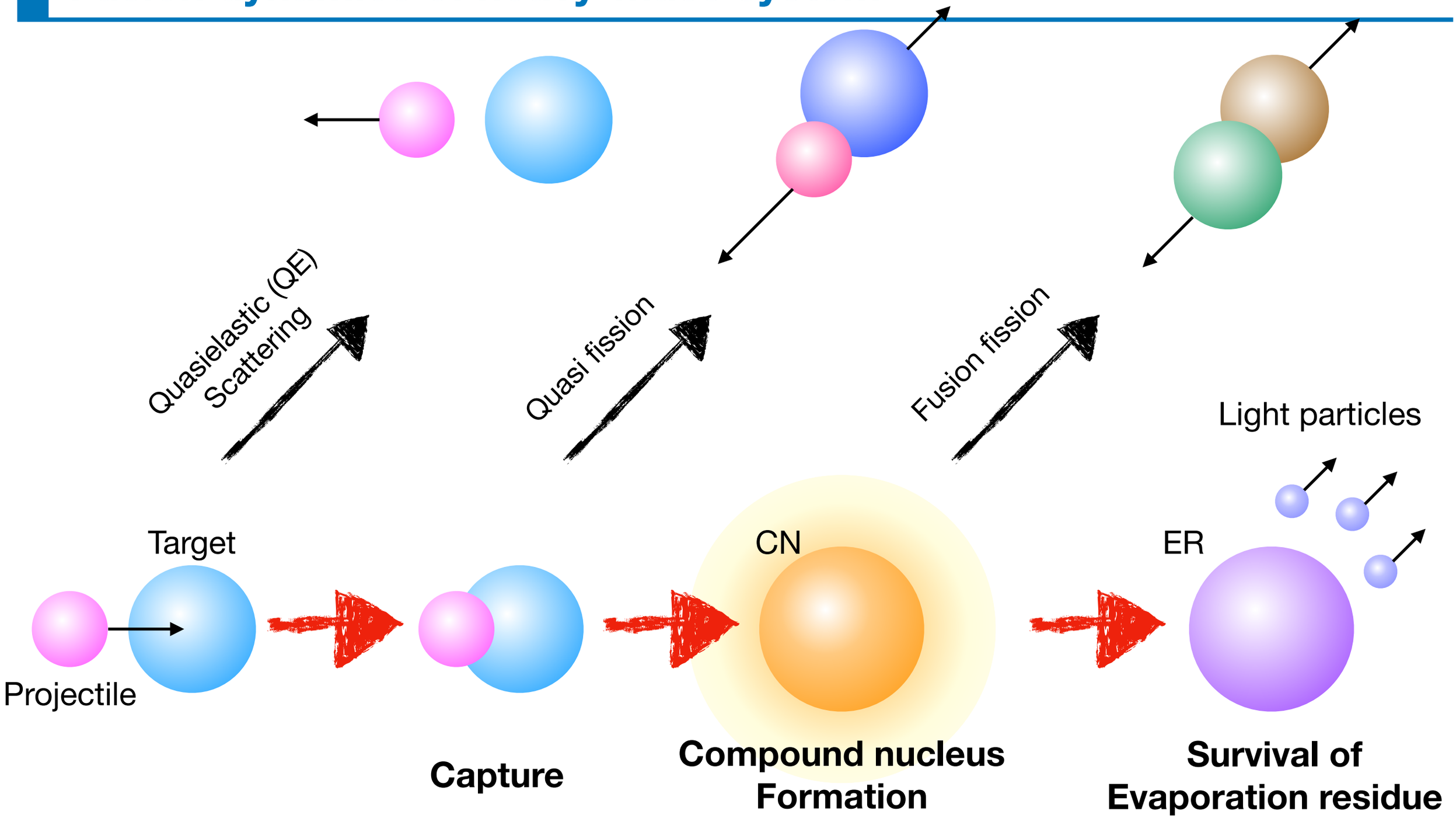


Table 3
Ion optical characteristics of GARIS-II and transmission anticipated for some types of hot fusions.

	GARIS	GARIS-II
Configuration	DQ_vQ_hD	$Q_vDQ_hQ_vD$
Ang. acceptance (X) (mrad)	±61	±47
Ang. acceptance (Y) (mrad)	±57	±110
Solid angle (msr)	12.2	18.5
Total path length (m)	5.76	5.06
Maximum $B\rho$ (Tm)	2.16	2.43
Dispersion (mm/%)	9.7	19.3

Fusion dynamics of heavy-mass system



$$\sigma_{ER} = \sigma_{cap} \times P_{CN} \times P_{Surv}$$

New superheavy element search

Cold fusion w/ ^{208}Pb or ^{209}Bi target

Hot fusion w/ ^{48}**Ca** beam

Fr	Ra	Ac/Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
119	**120**																

- ^{249}**Cf** + ^{48}Ca → ^{294}Og + 3n

Heaviest target material

Projectile beam **heavier than ^{48}Ca @ *Z* > 118**

- ^{244}Pu + ^{58}**Fe** → $^{302-x}$120 + xn
  *Yu. Ts. Oganessian et al., PRC **79**, 024603 (2009).*
- ^{238}U + ^{64}**Ni** → $^{302-x}$120 + xn
  *S. Hofmann et al., GSI Report **2008**, 131 (2009).*
- ^{248}Cm + ^{54}**Cr** → $^{302-x}$120 + xn
  *S. Hofmann et al., EPJ A **52**, 180 (2016).*
- ^{249}Bk + ^{50}**Ti** → $^{299-x}$119 + xn
  *J. Khuyagbaatar et al., PRC **102**, 064602 (2020).*
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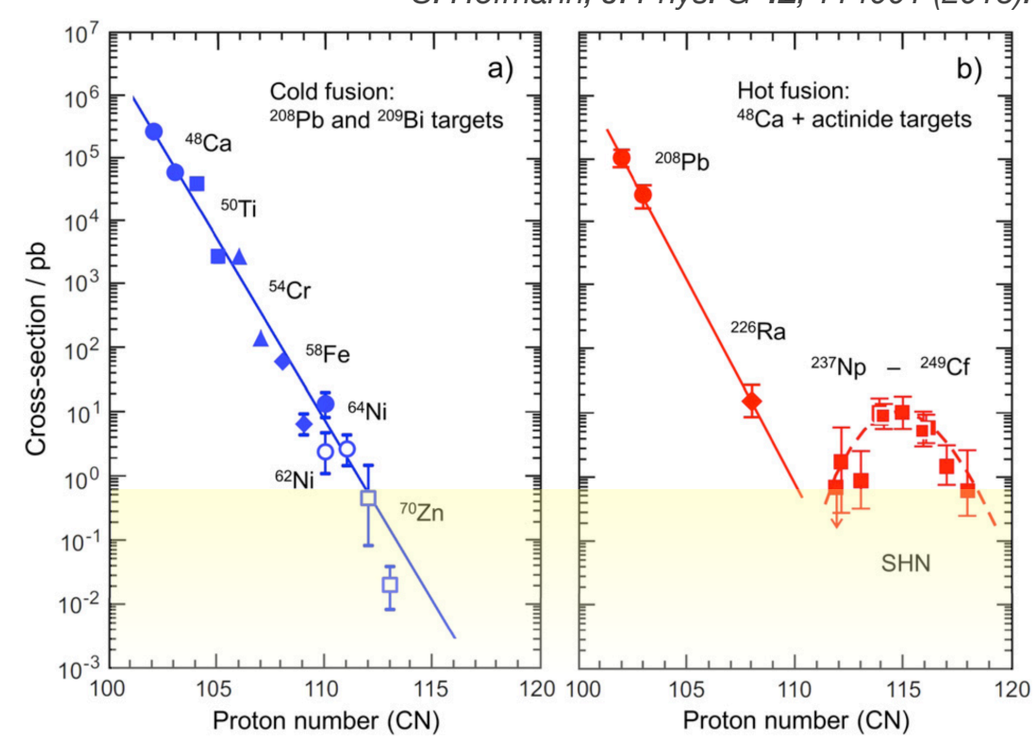
Fr	Ra	Ac/Lr	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Cn	Nh	Fl	Mc	Lv	Ts	Og
119	**120**																

- ^{249}**Cf** + ^{48}Ca → ^{294}Og + 3n Heaviest target material

Projectile beam **heavier than ^{48}Ca @ *Z* > 118**

- ^{244}Pu + ^{58}**Fe** → $^{302-x}$120 + xn σ_{ER} < 400 fb
  *Yu. Ts. Oganessian et al., PRC **79**, 024603 (2009).*
- ^{238}U + ^{64}**Ni** → $^{302-x}$120 + xn σ_{ER} < 90 fb
  *S. Hofmann et al., GSI Report **2008**, 131 (2009).*
- ^{248}Cm + ^{54}**Cr** → $^{302-x}$120 + xn σ_{ER} < 580 fb
  *S. Hofmann et al., EPJ A **52**, 180 (2016).*
- ^{249}Bk + ^{50}**Ti** → $^{299-x}$119 + xn σ_{ER} < 65 fb
  *J. Khuyagbaatar et al., PRC **102**, 064602 (2020).*
- ^{249}Cf + ^{50}**Ti** → $^{299-x}$120 + xn σ_{ER} < 280 fb
  *J. Khuyagbaatar et al., PRC **102**, 064602 (2020).*

*S. Hofmann, J. Phys. G **42**, 114001 (2015).*



Example of PID for target-like events

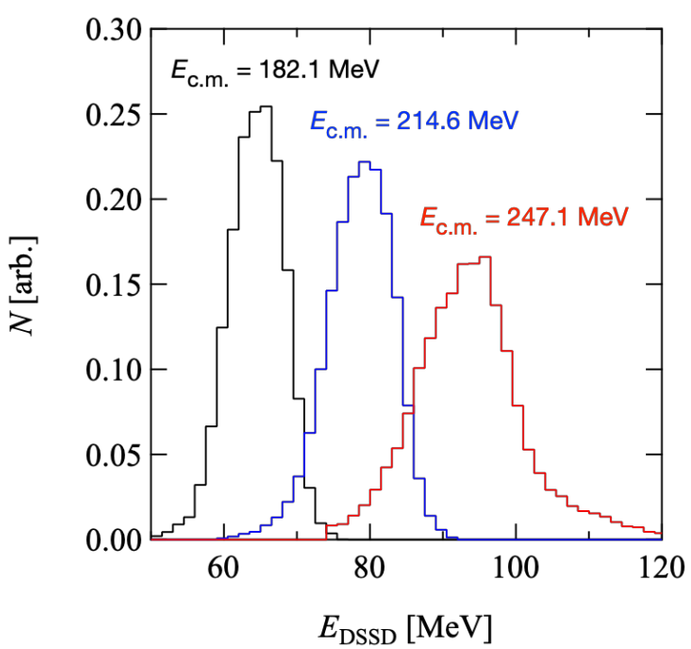
Target-like events were clearly identified.

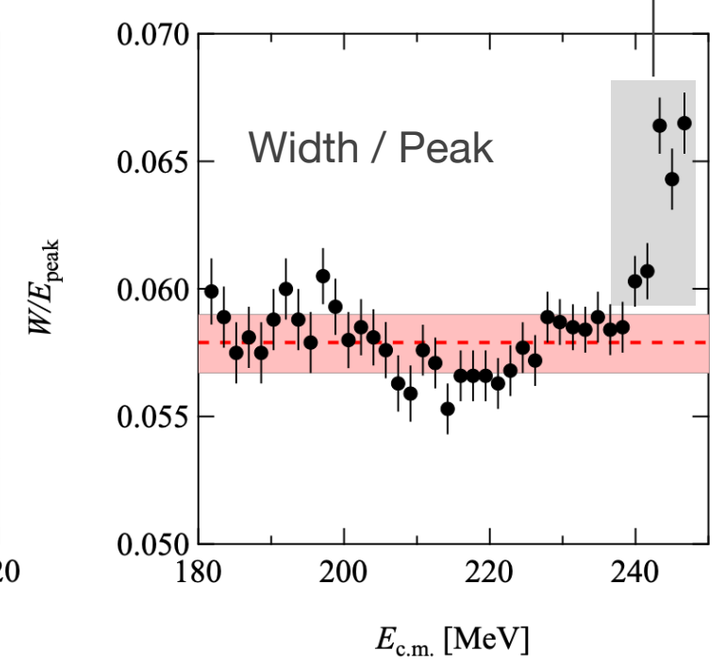
E_{DSSD} spectrum broadened @ $E_{c.m.} \geqq 240.3$ MeV
→ some B.G. contaminants
ex.) deep-inelastic scattering events

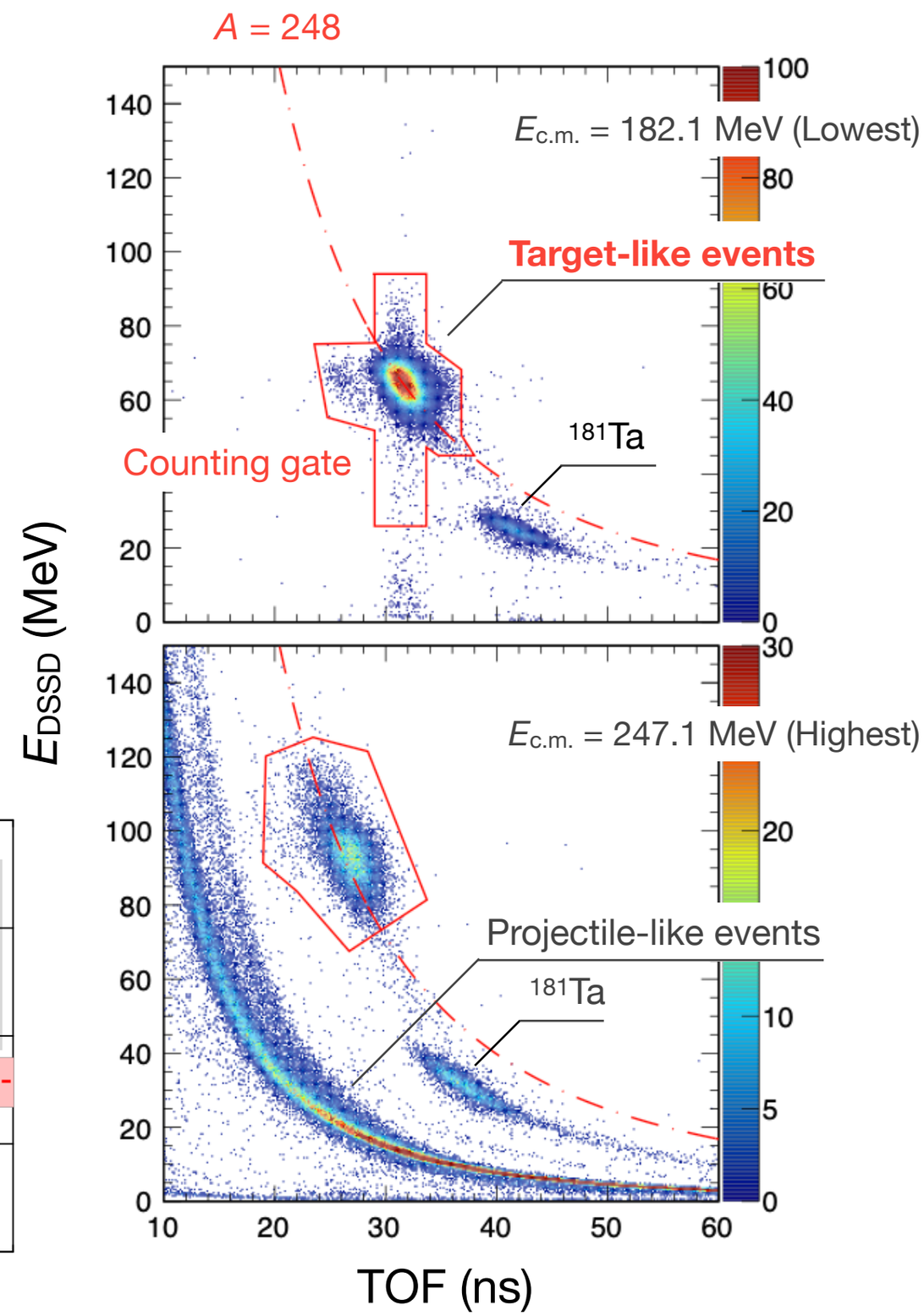
*S. Mitsuoka et al., PRL **99**, 182701 (2007).*
*T. Tanaka et al., J. Phys. Soc. Jpn. **87**, 014201 (2018).*
*T. Niwase et al., JPS Conf Proc. **32**, 010022 (2020).*
*T. Tanaka et al., PRL **124**, 052502 (2020).*

The data @ $E_{c.m.} \geqq 240.3$ MeV (5 points)
were treated as upper limit of $d\sigma_{QE} / d\sigma_{Ruth.}$

Energy spectra of DSSD





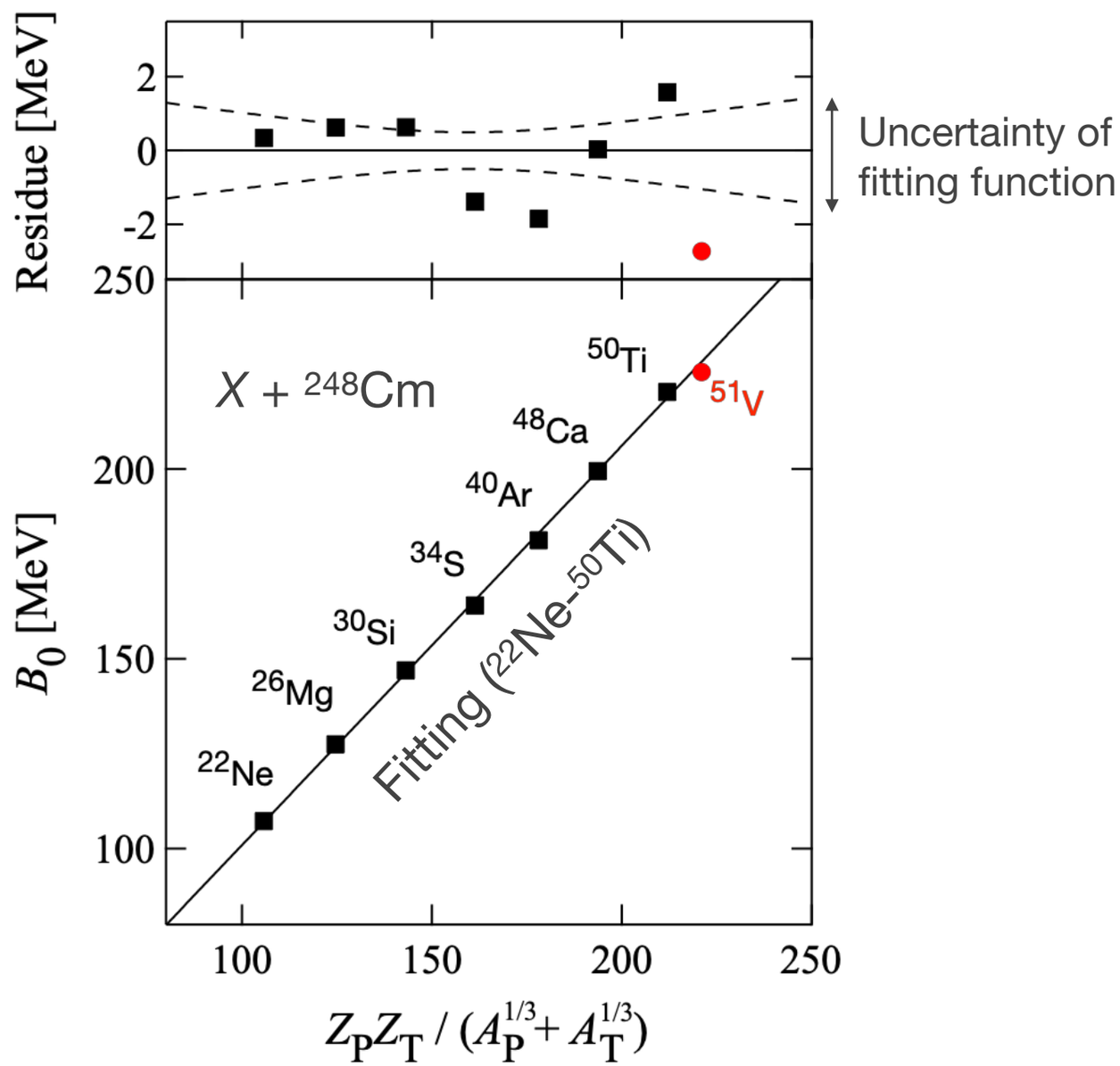


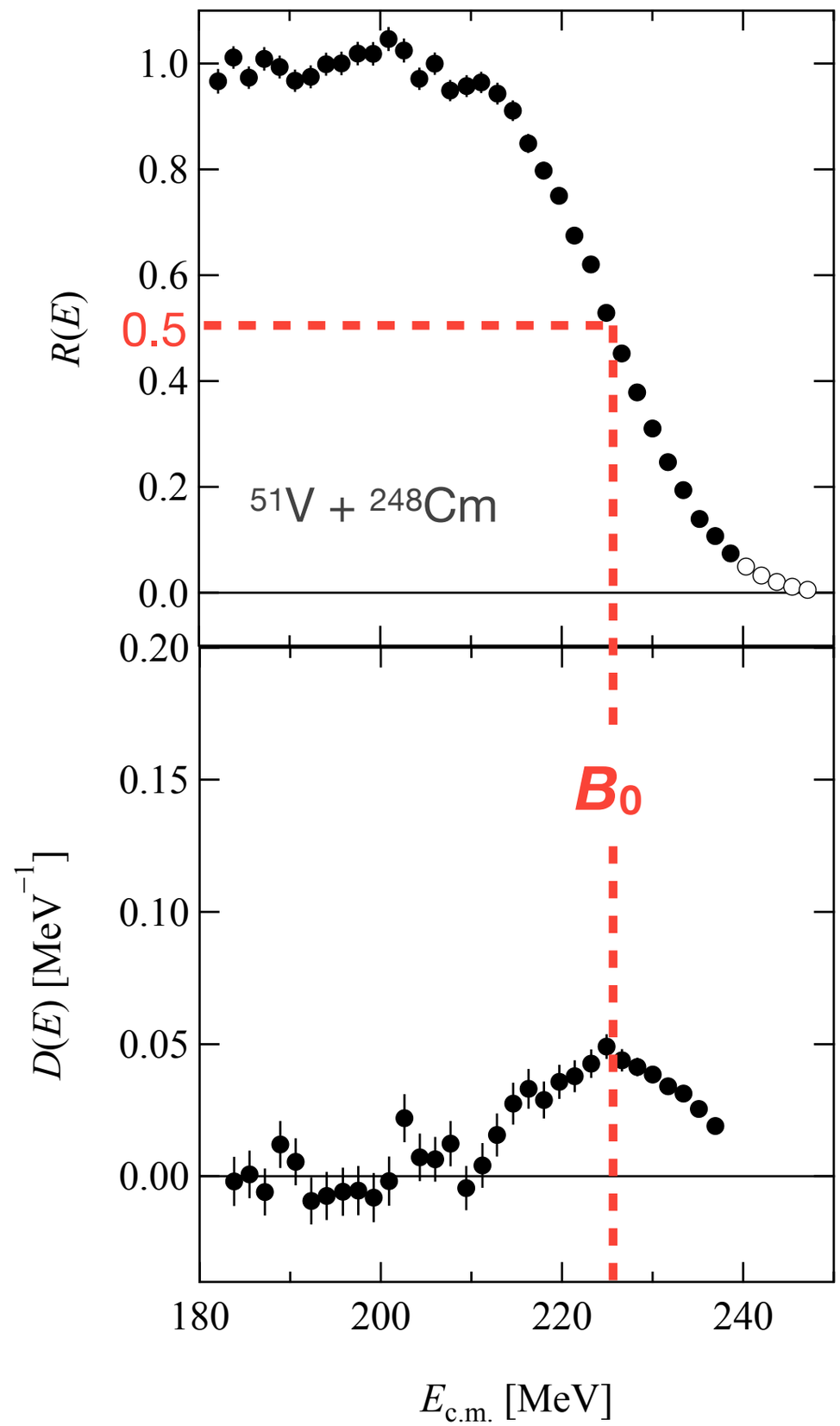
Average Coulomb barrier height B_0

$^{51}V + ^{248}Cm$ | **B_0 = 225.6 ± 0.2 MeV**

Roughly consistent with
B_0 values of other reaction systems with ^{248}Cm.

T. Tanaka, Doctoral thesis, Kyushu University (2019).





Relation between experimental B_{side} and optimal energy E_{opt}

^{48}Ca + ^{248}Cm

- Similar masses to ^{51}V + ^{248}Cm.
- D_{QE} & σ_{ER} data are available.

D_{QE}
*T. Tanaka et al., PRL **124**, 052502 (2020).*

σ_{ER}
FLNR: Yu. Ts. Oganessian *et al.*, PRC **70**, 054609 (2004).
Yu. Ts. Oganessian *et al.*, PRC **63**, 011301(R) (2001).
GSI: S. Hofmann *et al.*, Eur. Phys. J. A **52**, 180 (2016).
RIKEN: D. Kaji et al., J. Phys. Soc. Jpn. **86**, 034201 (2017).

B_{side} is located around maximum of σ_{ER}.

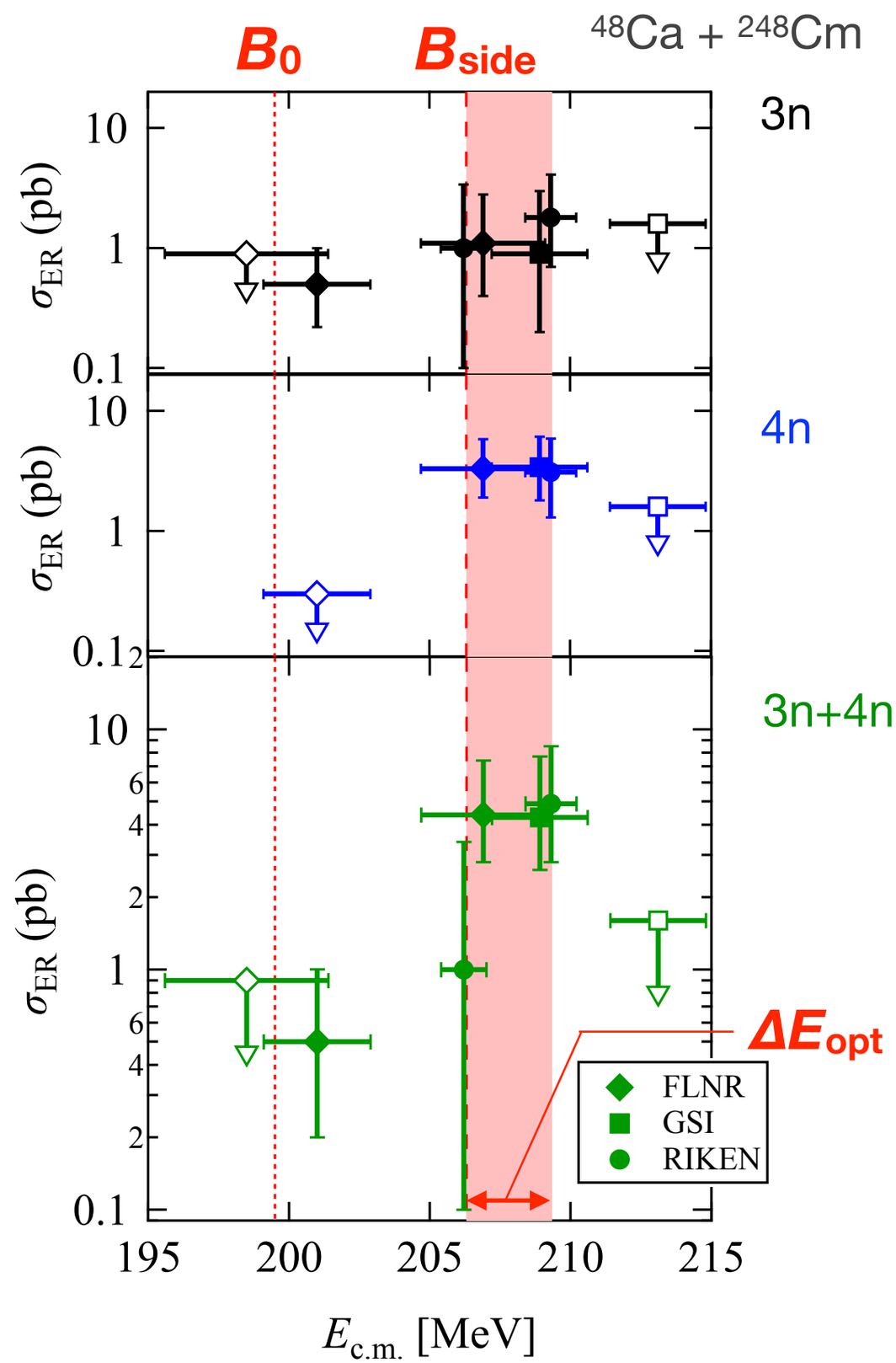
In more detail…

Optimal reaction energy E_{opt} is **slightly higher**??

(*) Pointed out also in theoretical study. (+2-3 MeV in ^{48}Ca+^{248}Cm)
*K. Hagino, PRC **98**, 014607 (2018).*

Uncertainty in relation between B_{side} & E_{opt}

ΔE_{opt} = +3.0 MeV (**+1.5% relative to B_{side}**)



Deduced optimal energy for $^{248}Cm(^{51}V, xn)^{299-x}119$

Deduced energies from exp.

- Average barrier height
  B_0 = **225.6(2)** MeV

- Side-collision energy
  B_{side} = **233.0(2)** MeV

- Uncertainty between E_{opt} & B_{side}
  ΔE_{opt} = **+3.5** MeV

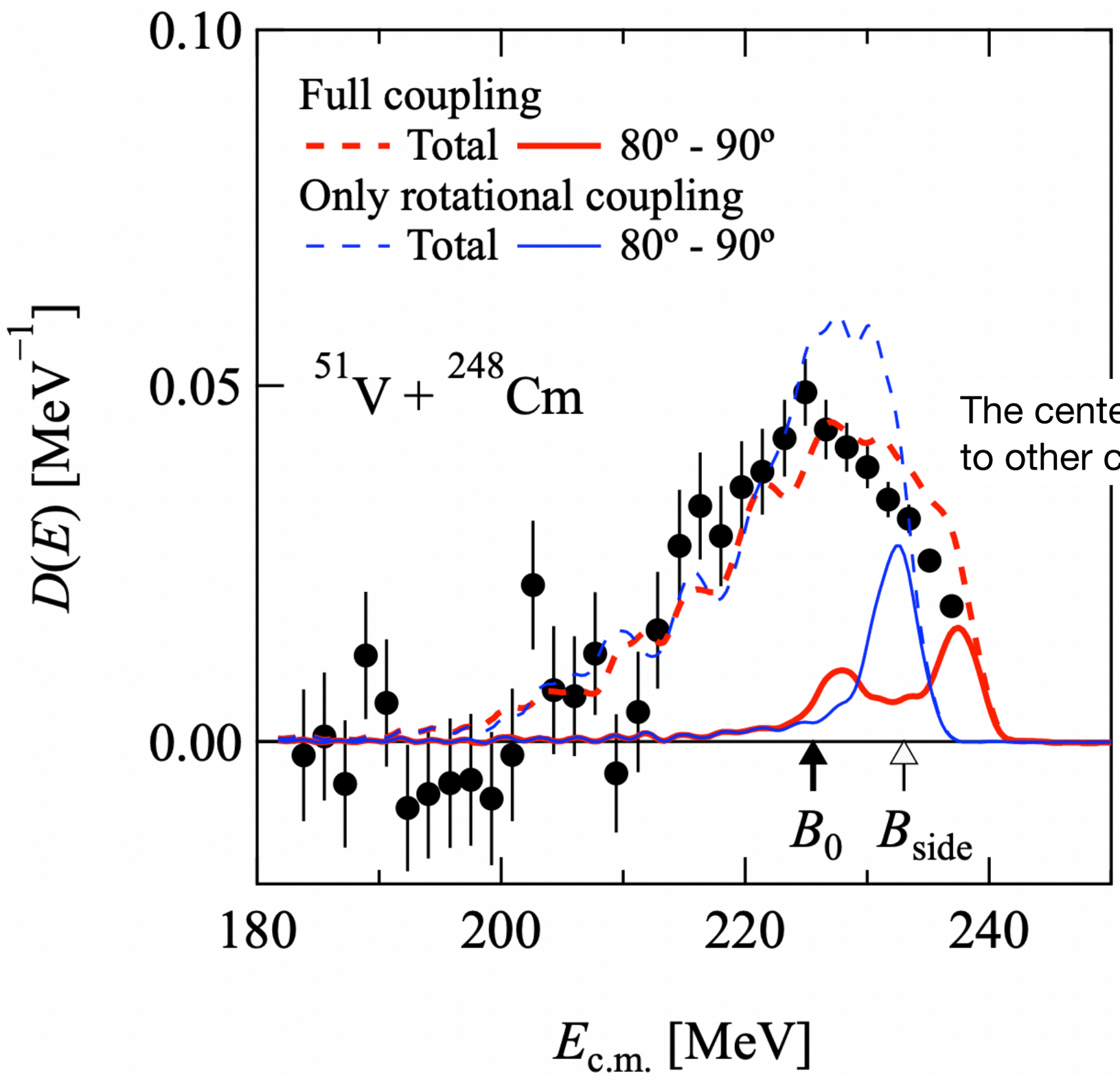
(*) Comparable to
energy spread in typical-thick target (~500 μg/cm²)

- Adopted energy
  for synthesis of element-119 @RIKEN

$E_{adopted} = B_{side} + 1/2 \times \Delta E_{opt} = 234.8$ MeV

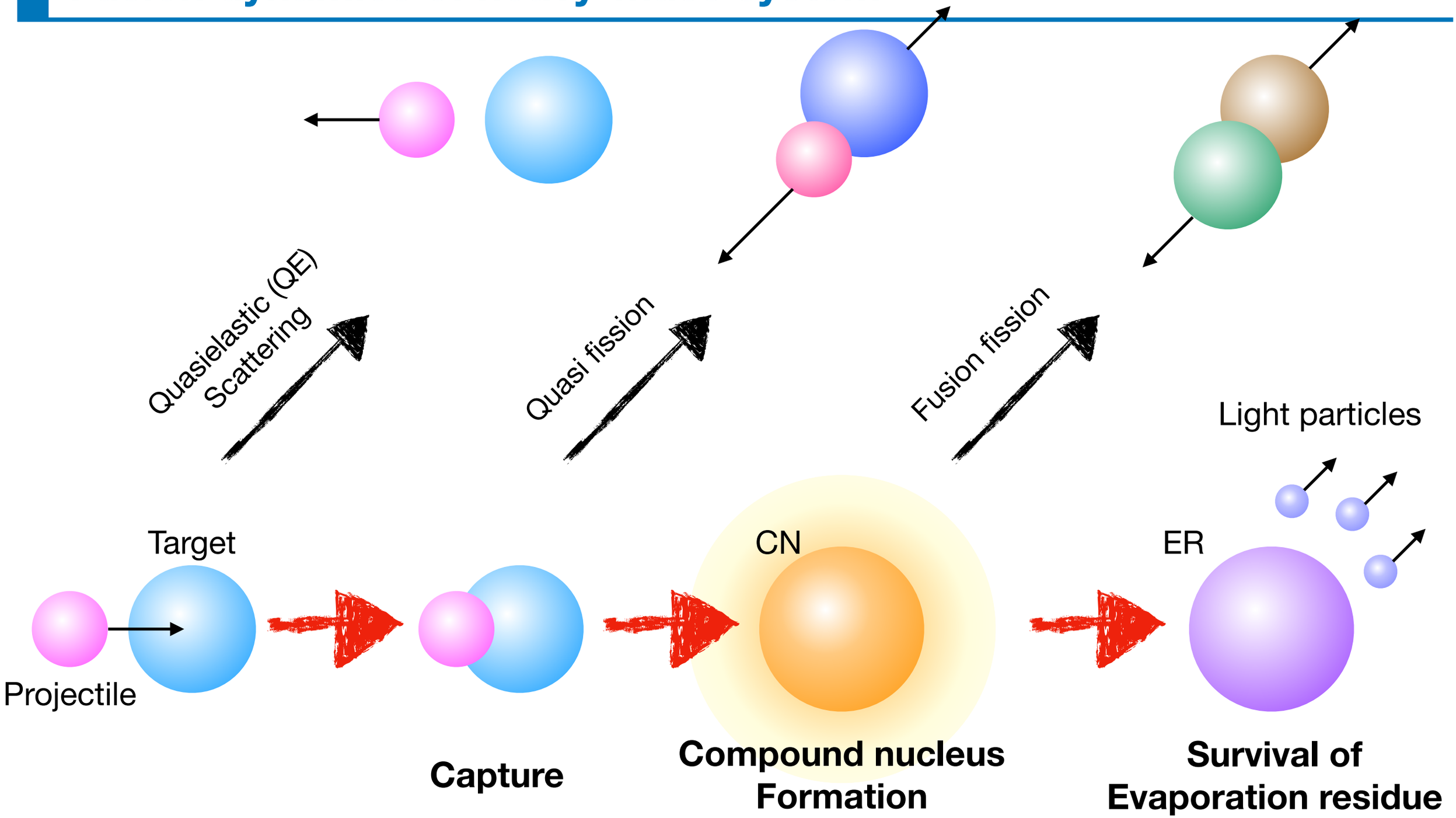
(*) $E_{ex}(^{299}119^*)$ = 40.3 MeV

Relation of side-collision energy and CC calculation



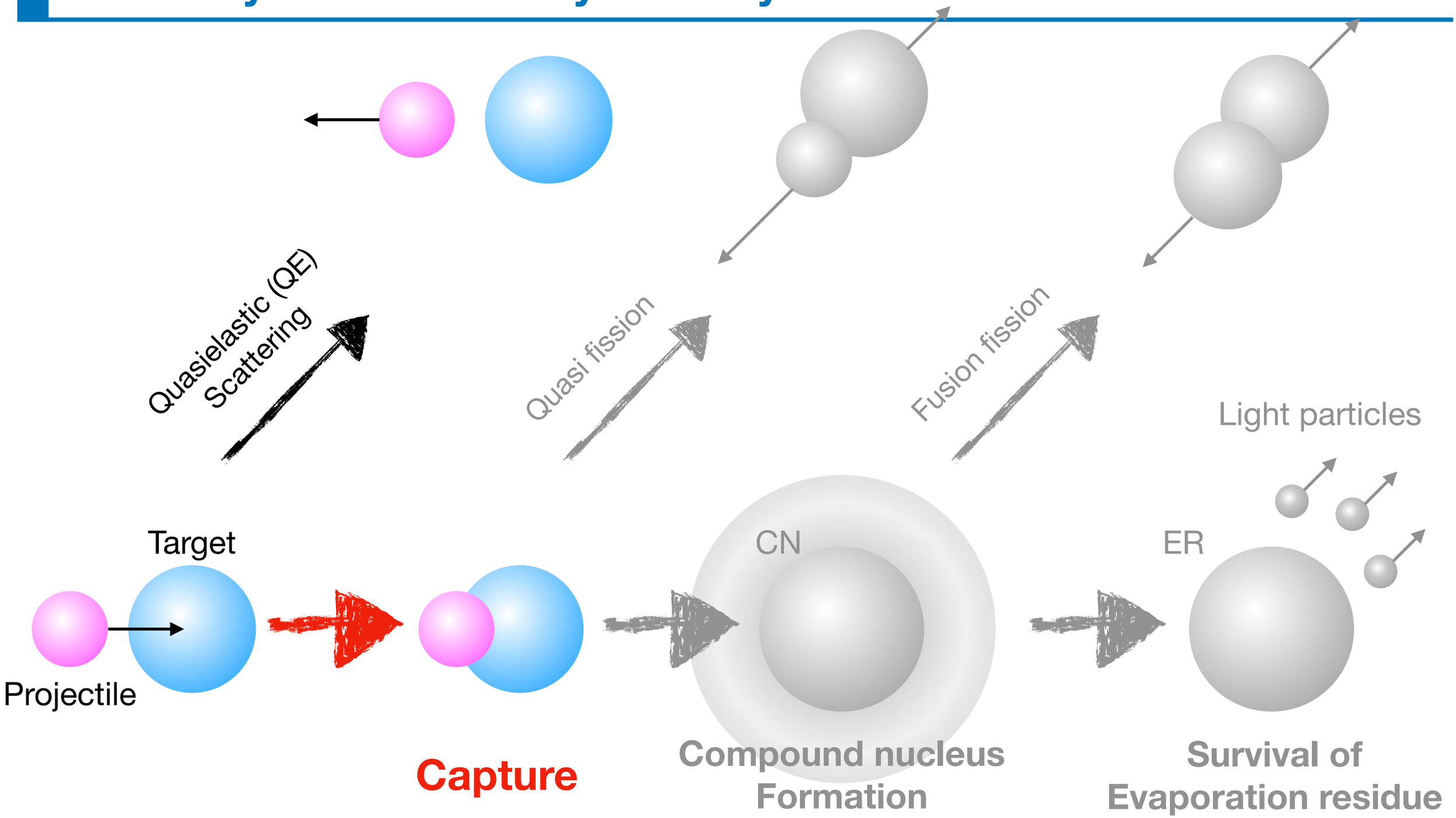
The center of the distribution is insensitive to other coupling effect.

Fusion dynamics of heavy-mass system



$$\sigma_{ER} = \sigma_{cap} \times P_{CN} \times P_{Surv}$$

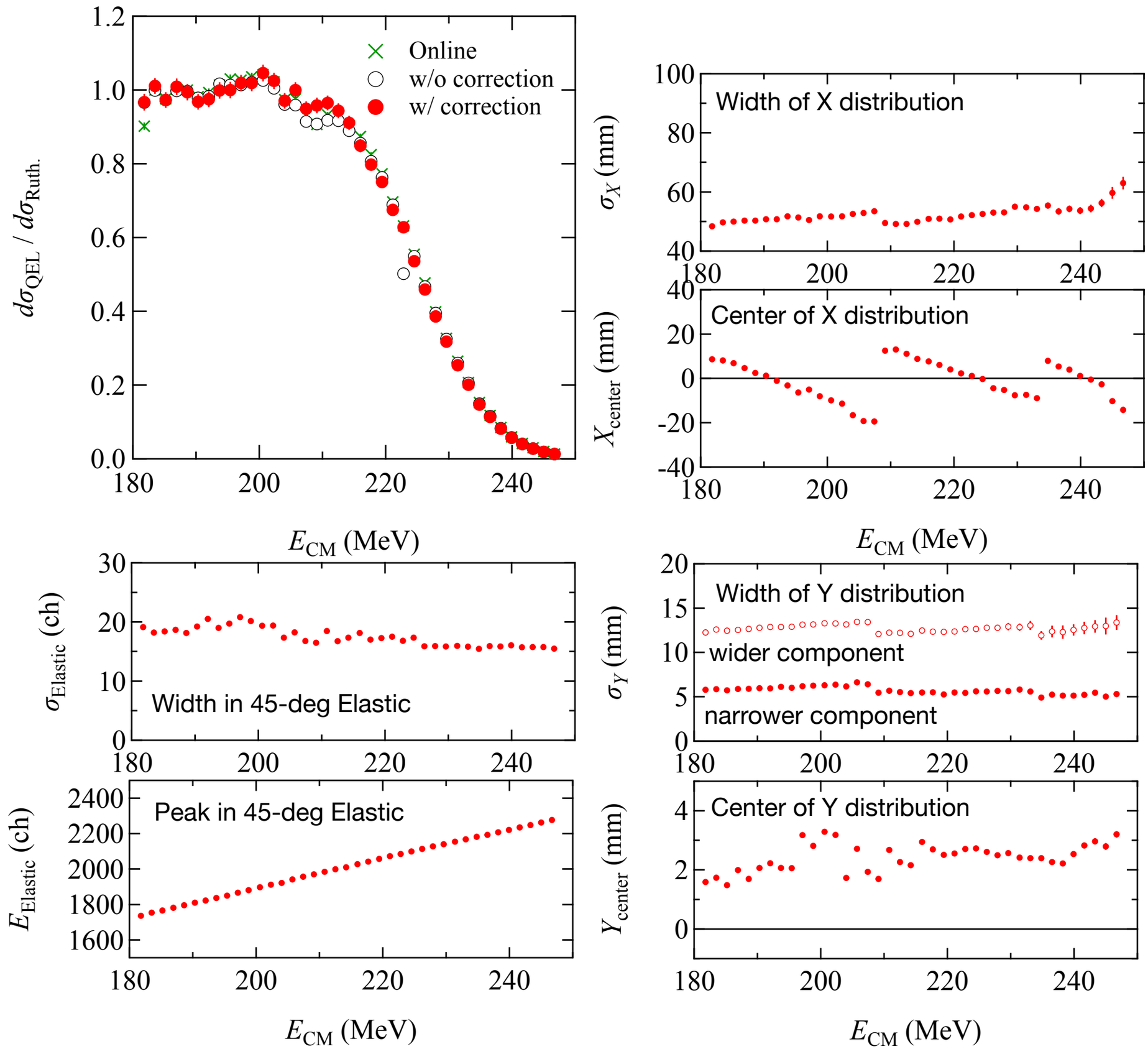
Fusion dynamics of heavy-mass system



$$\sigma_{ER} = \sigma_{cap} \times P_{CN} \times P_{Surv}$$

This study: Probed by **Quasielastic backscattering measurement**

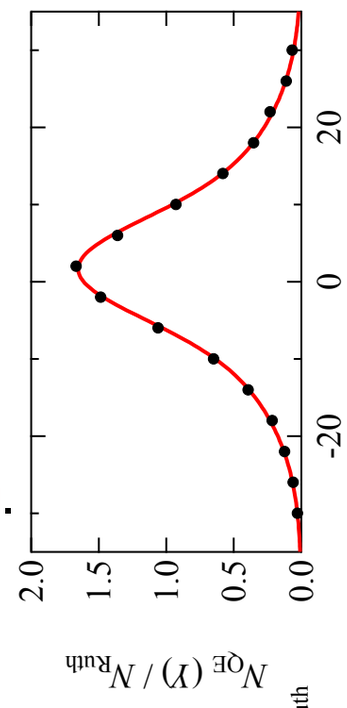
Summary of experimental trend

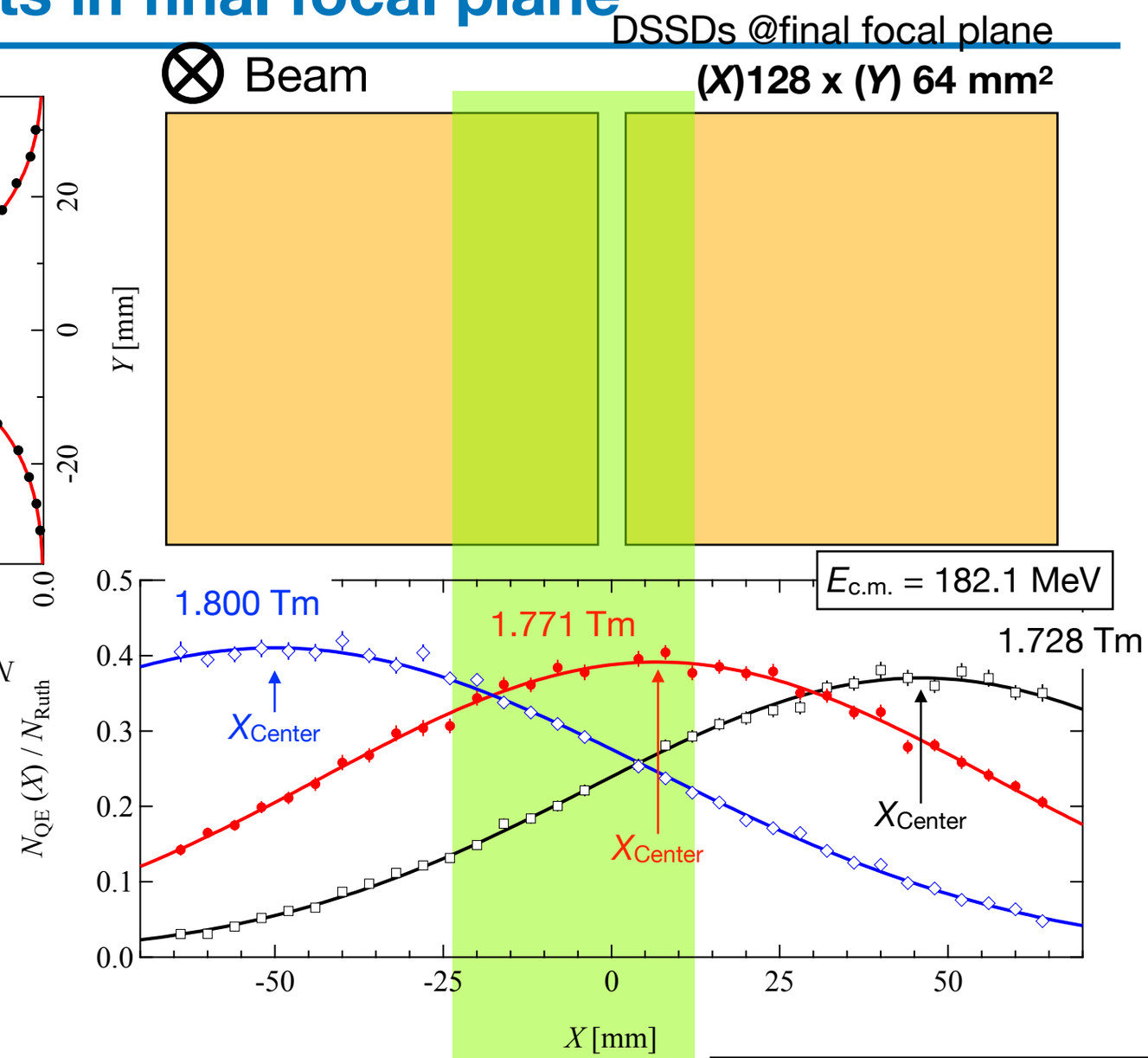


Acceptance of target-like events in final focal plane

- ***Y***
  FWHM : 12 mm
  Much smaller than detector (64 mm)

- ***X***
  FWHM : 80 mm
  Comparable to detector (128 mm)
  → Potentially influenced by ***Bρ* setting**.



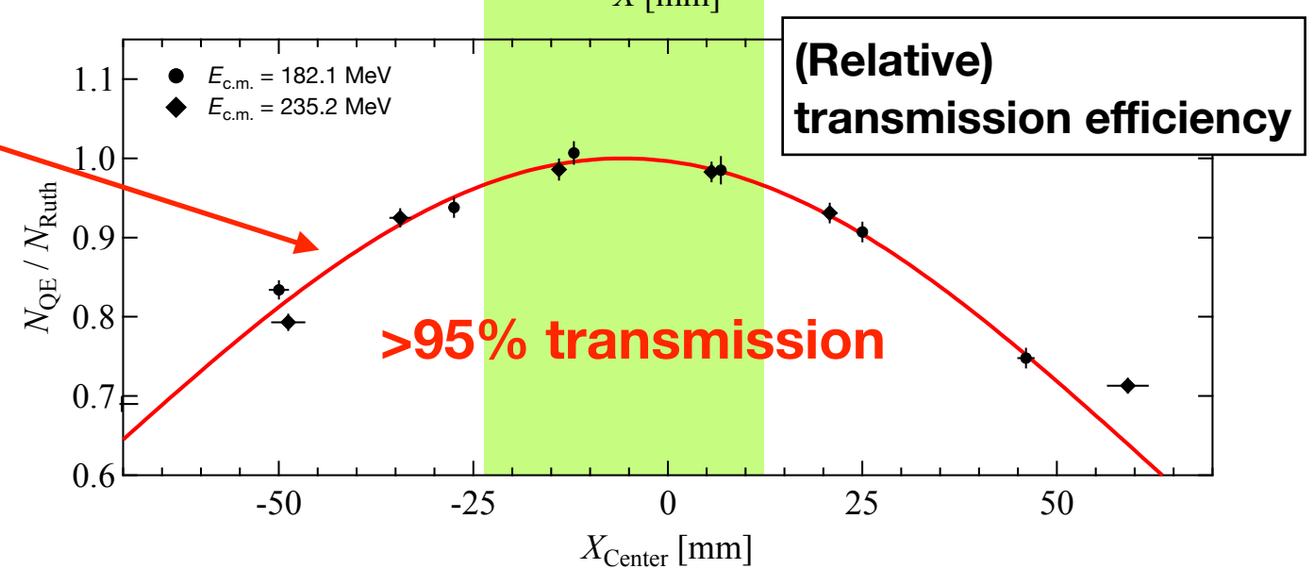


- *Bρ* value was adjusted so that X_{Center} was located **within green region**.

- + Slight loss (<5%) was corrected using fitting function.

Systematic uncertainty: 1.3%
(≒ Statistical uncertainty: 1%)

This condition was satisfied in all data points.



Experimental result

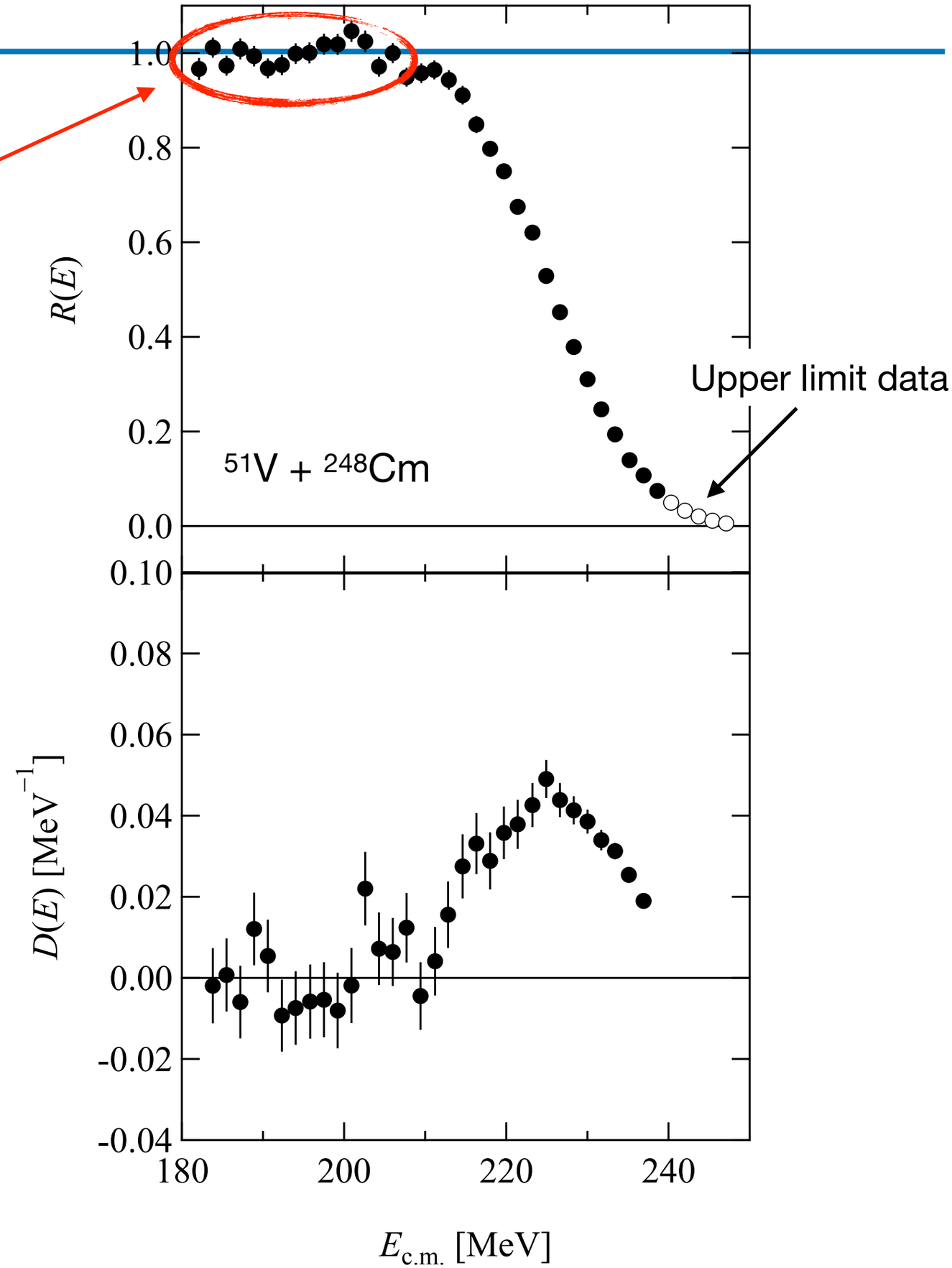
Reflection probability: *R*(*E*)

$$R(E) = \frac{d\sigma_{\mathrm{QE}}}{d\sigma_{\mathrm{Ruth}}} = C \cdot \frac{N_{\mathrm{QE}}[^{248}\mathrm{Cm}]}{N_{\mathrm{Ruth}}[^{51}\mathrm{V}]}$$

QE barrier distribution: *D*(*E*)

$$D(E_i) = \frac{R(E_{i+1}) - R(E_{i-1})}{E_{i+1} - E_{i-1}}$$

3.4 MeV

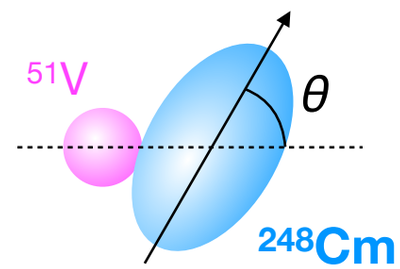


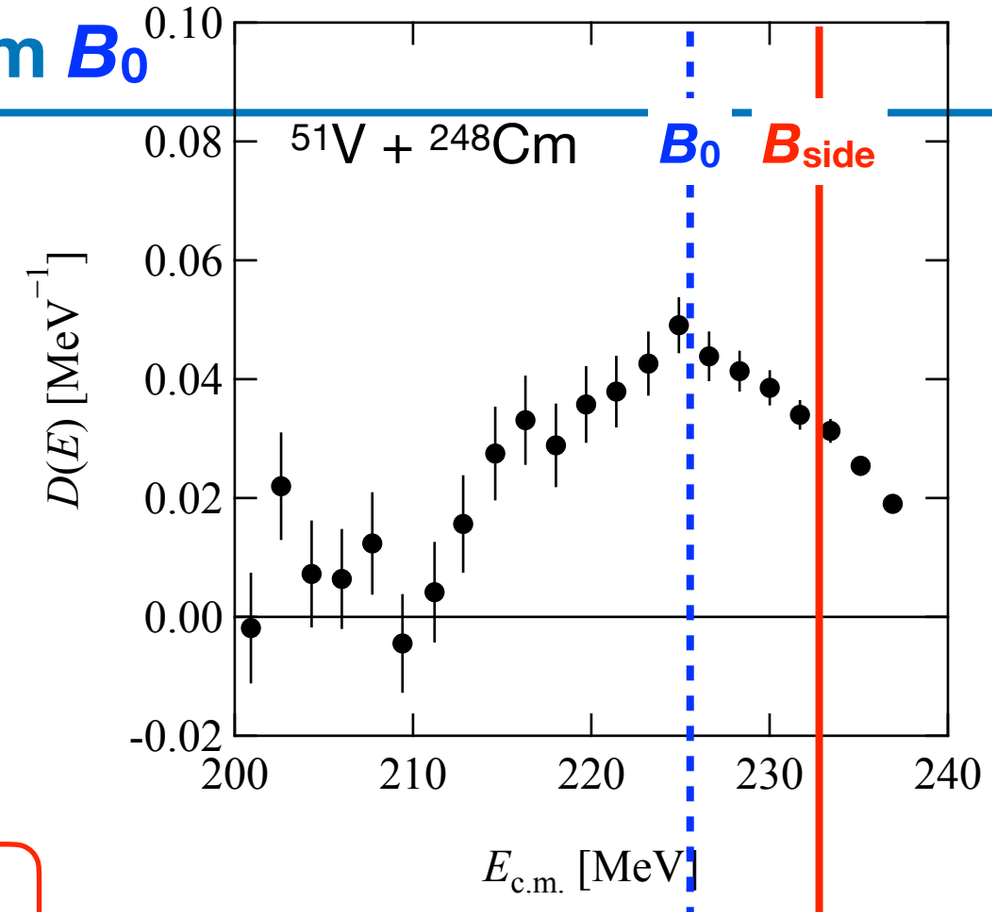
Side-collision energy B_{side} derived from B_0

Experimental B_0 of $^{51}V+^{248}Cm$

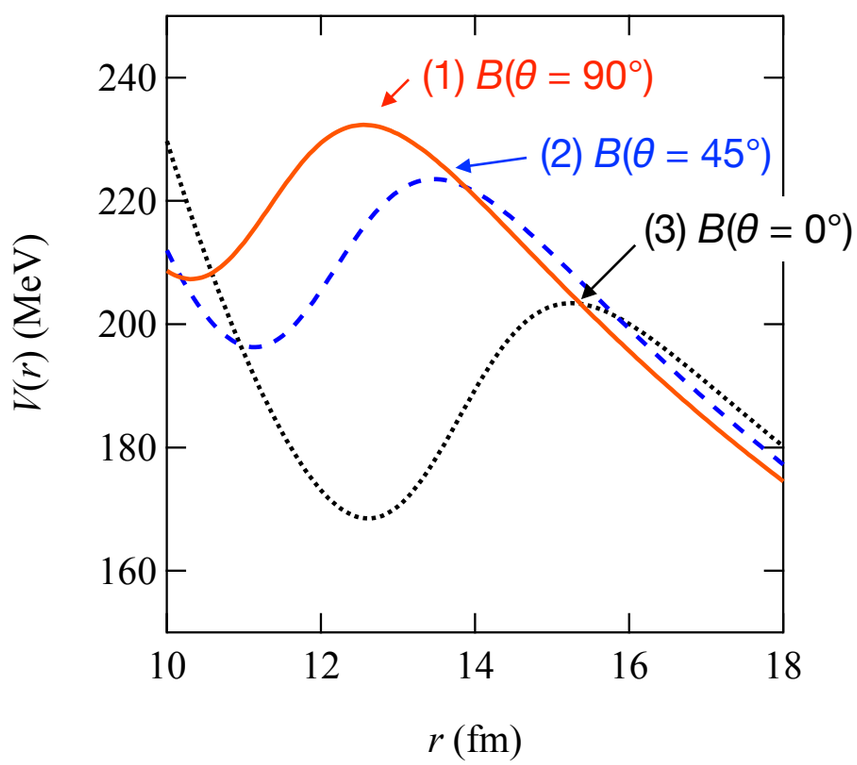
Averaged value over orientation angles

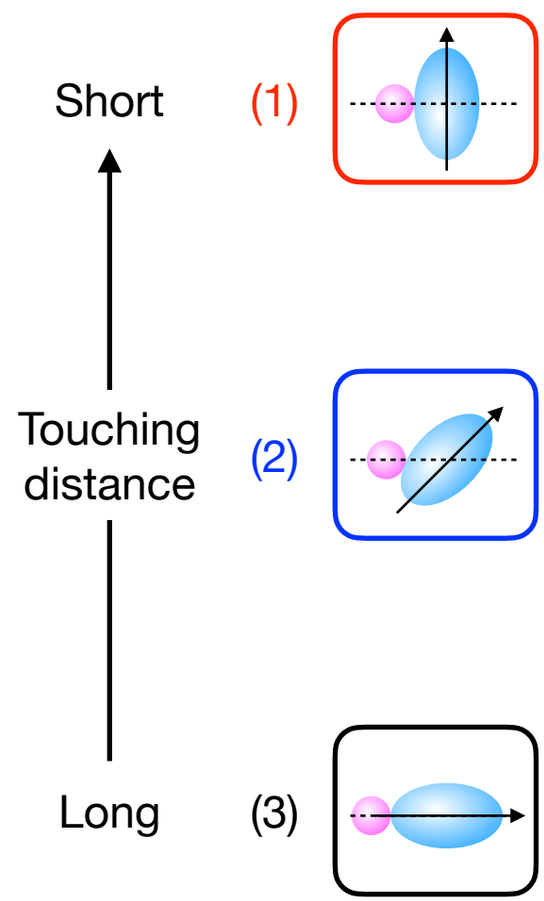
$$B_0 = \int_0^{\pi/2} B(\theta) \cdot \sin\theta d\theta$$

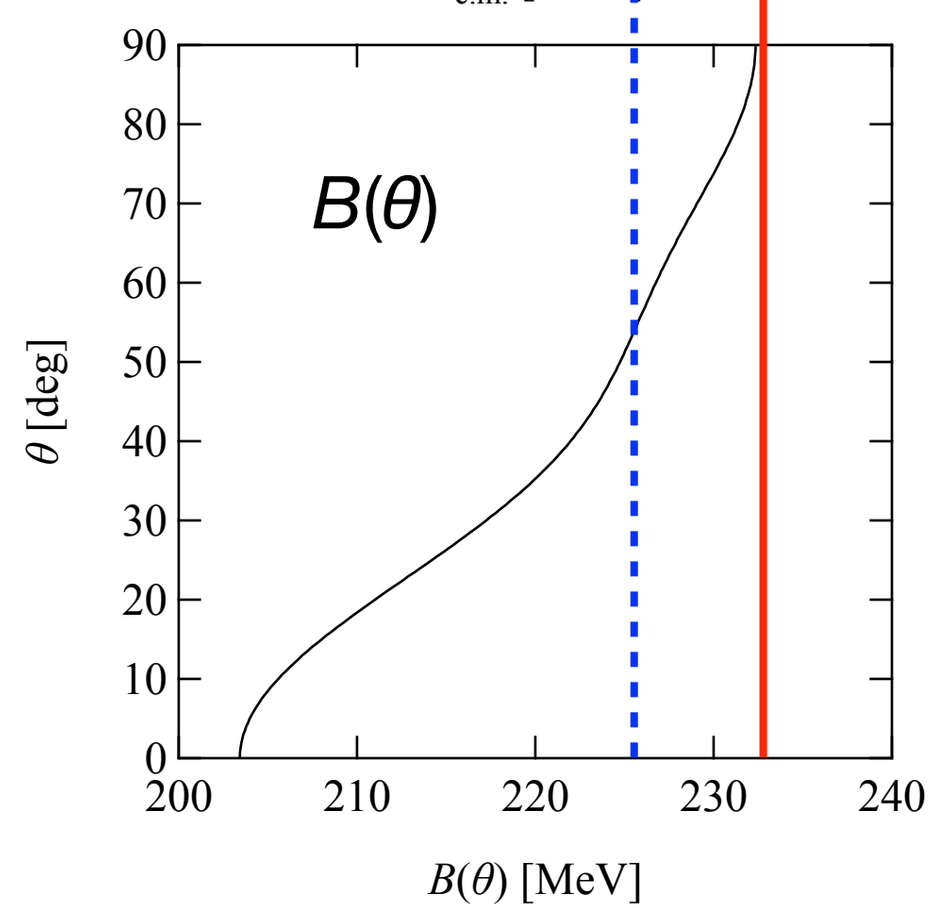




Optical potential $V(r,\theta)$ used in CC calculation.
(Satisfy **B_0 = 225.6 MeV**)







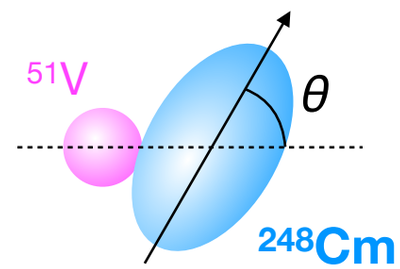
B_{side} = 233.0 MeV (**B_0** + 7.4 MeV)

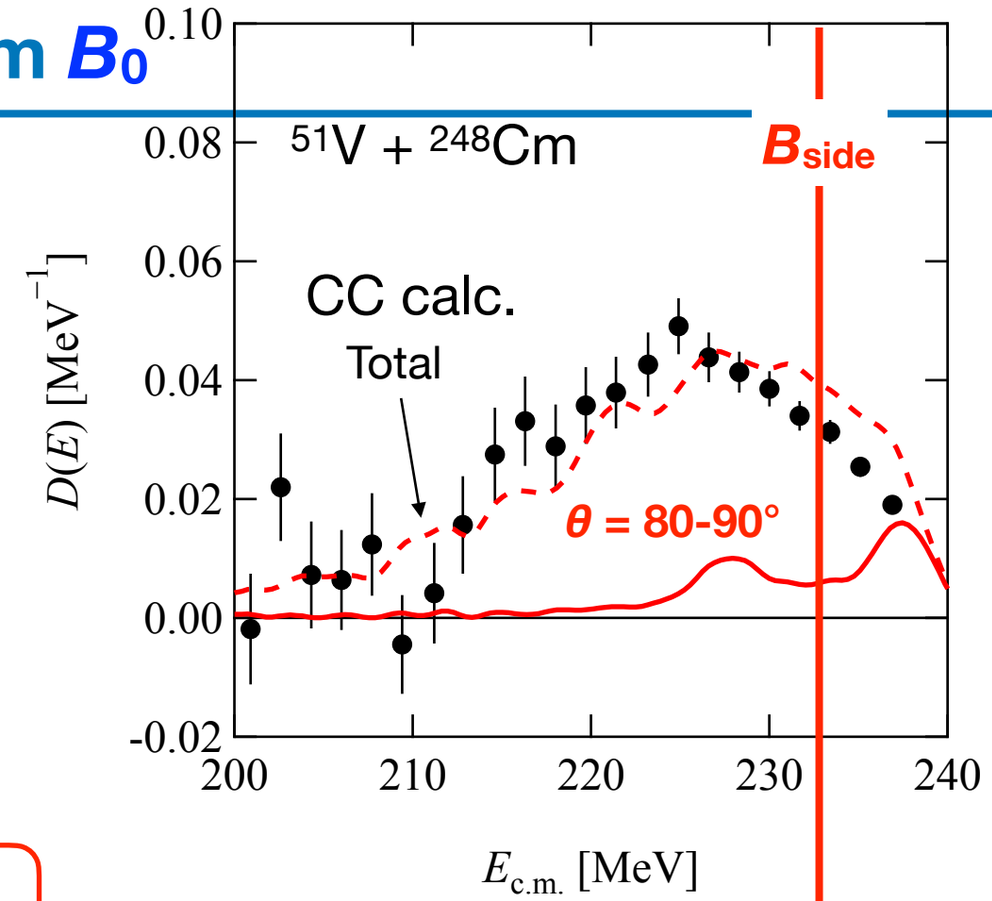
Side-collision energy B_{side} derived from B_0

Experimental B_0 of $^{51}V+^{248}Cm$

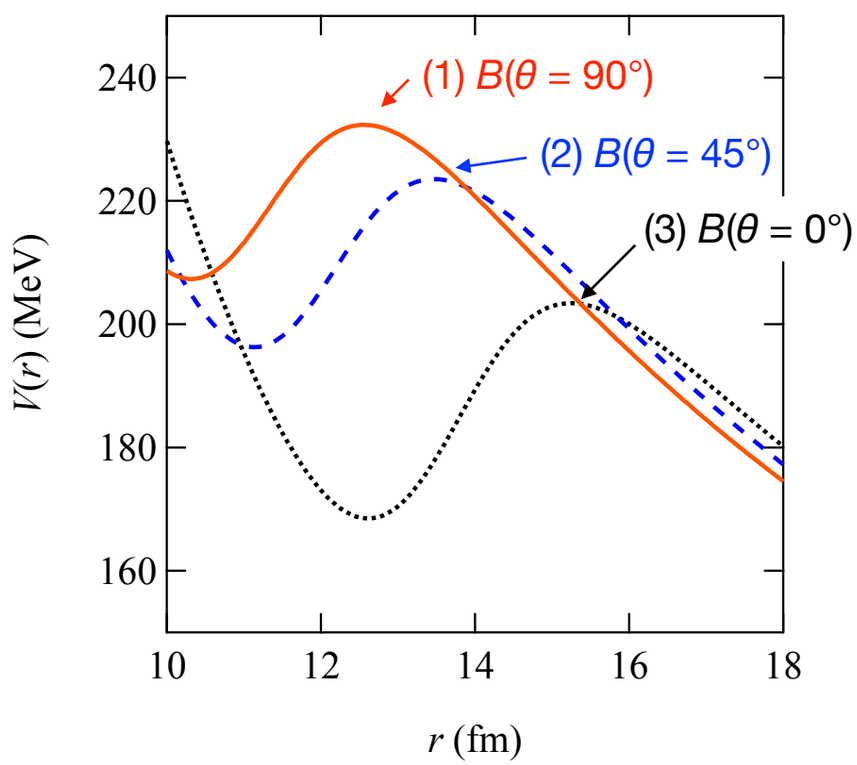
Averaged value over orientation angles

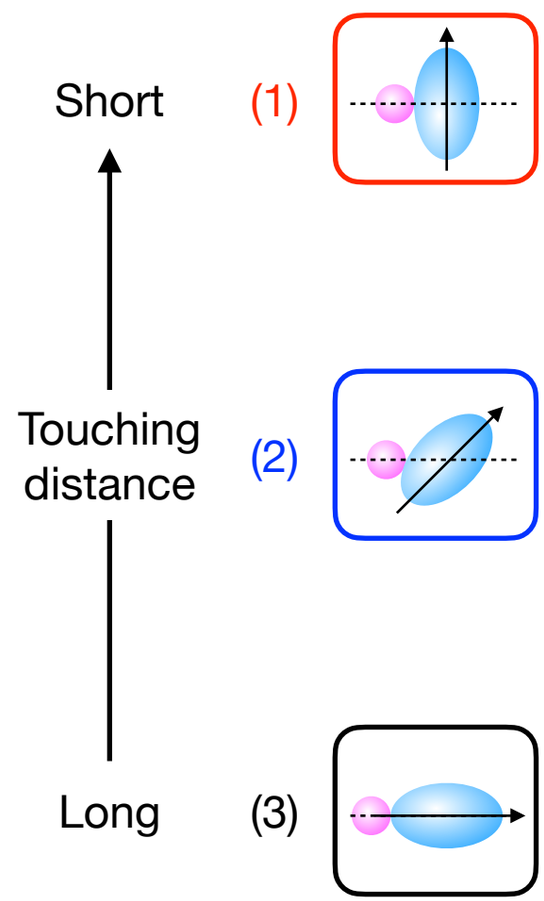
$$B_0 = \int_0^{\pi/2} B(\theta) \cdot \sin\theta d\theta$$

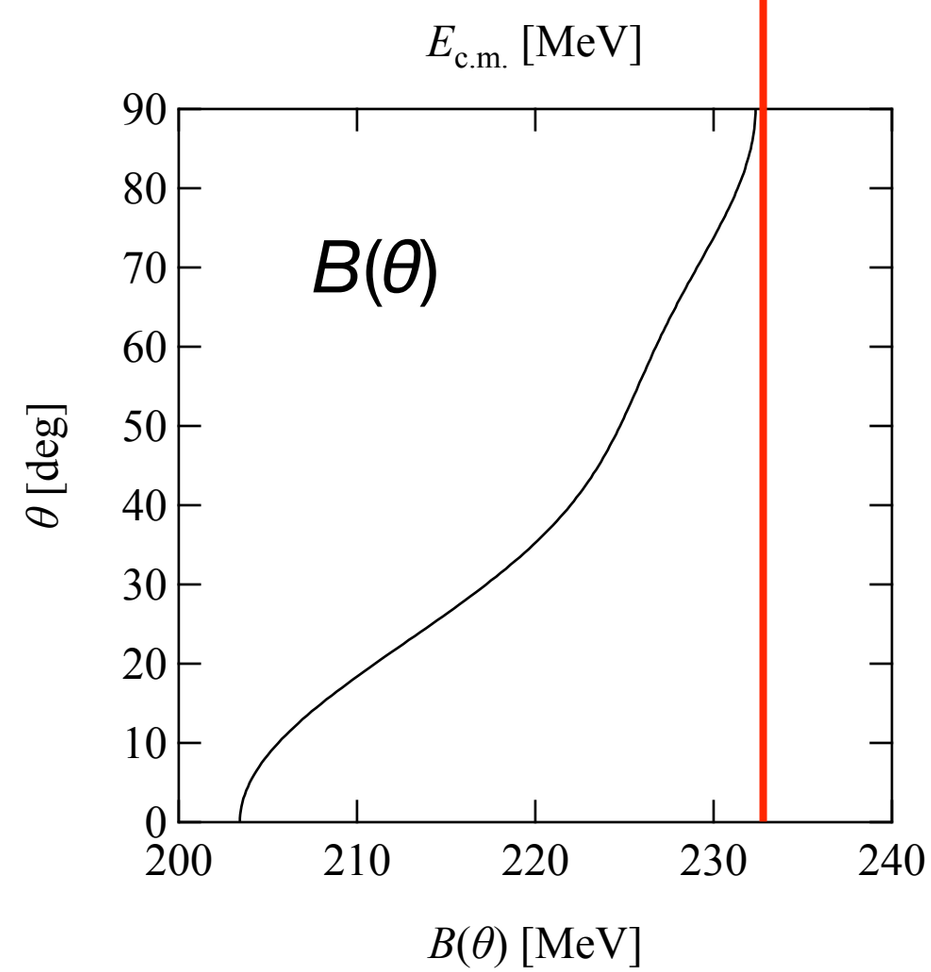




Optical potential $V(r,\theta)$ used in CC calculation.
(Satisfy B_0 = 225.6 MeV)







B_{side} = 233.0 MeV (B_0 + 7.4 MeV)