Fusion and fission reactions at near- and sub-barrier energies

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- Near- and sub-barrier fusion enhancement
- Fusion and fission study for $^{32}S+^{170}Er$ and $^{28}Si+^{174}Yb$
- The recent experiment for $^{7}Li+^{238}U$ reaction mechanism
- To study the deformation of ^{254}Es by using backward QEL
- Summary

The near-barrier reaction mechanism of heavy-ions is important, but it is still not known well up to now.

● Near-barrier fusion of heavy-ions involves the basic quantual tunneling mechanism and the coupled-channels effect.

The reaction mechanisms, such as the sub-barrier fusion enhancement correlated with x*n*-transfer channels and transfer/breakup-induced InComplete Fusion (ICF) are still current hot-topics.

c.f. ^{7}Li+^{209}Bi, K.J. Cook *et al*., PRL 122, 102501 (2019).

● Nuclear fission is a complex process which involves the large mass rearrangement.

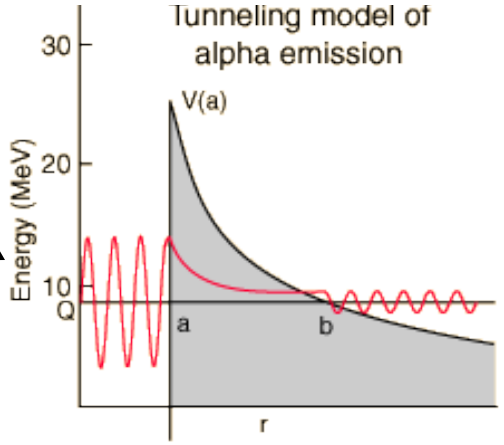
Quasi-Fission (QF) competes with fusion-fission (FF) for heavy systems and the QF has attracted much attention. The signature of QF is the larger angular anisotropy, the bigger mass asymmetry, the strong correlation of fragment mass distribution with angle.

Some talks in this workshop.

Near- and sub-barrier fusion enhancement

The (part) history of fusion (smaller $Z_P Z_T$)

- **The foremost theory base**: @1928 by George Gamow, also by Ronald Wilfrid Gurney & Edward Uhler Condon.

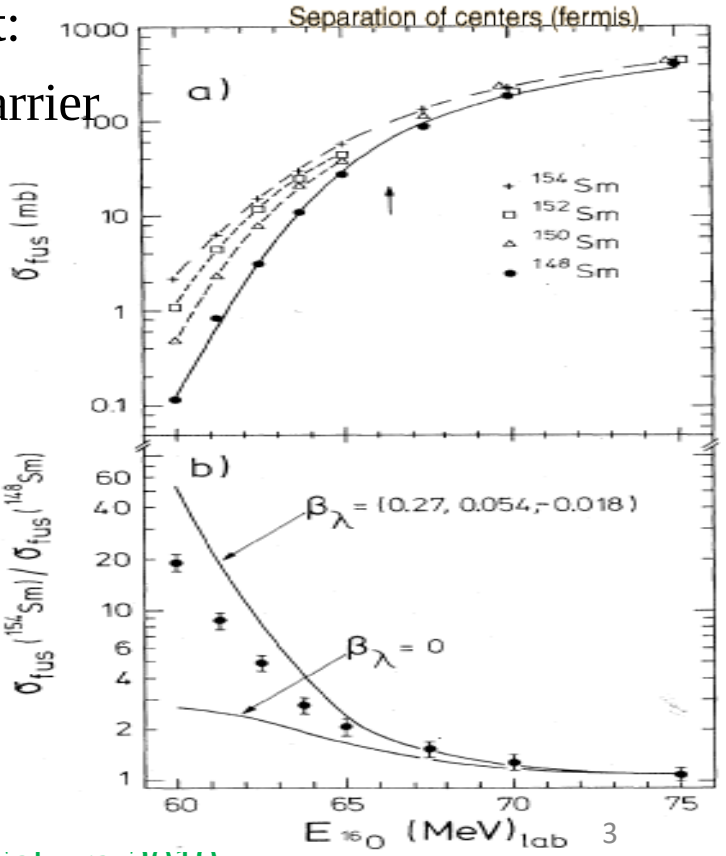


- **The 1st fusion-evaporation experiment**:

J.F. Miller et al., PR 81, 288 (1951)

- **Discovery of the sub-barrier fusion enhancement**:

The anomalous isotopic dependence of the sub-barrier fusion cross sections.
R.G. Stokstad et al., PRL 41, 465 (1978);
M. Beckerman et al., PRL 45, 1472 (1980);
W. Reisdorf et al., PRL 49, 1811 (1982);



- **Fusion barrier distribution (BD):**

N. Rowley *et al.*, Phys. Lett. **B254**, 25 (1991)

- **Many Explanations--Coupling effects:**

Nuclear structure (inelastic excitations)

Reaction dynamics (transfer/breakup reactions)

Near- and sub-barrier fusion enhancement

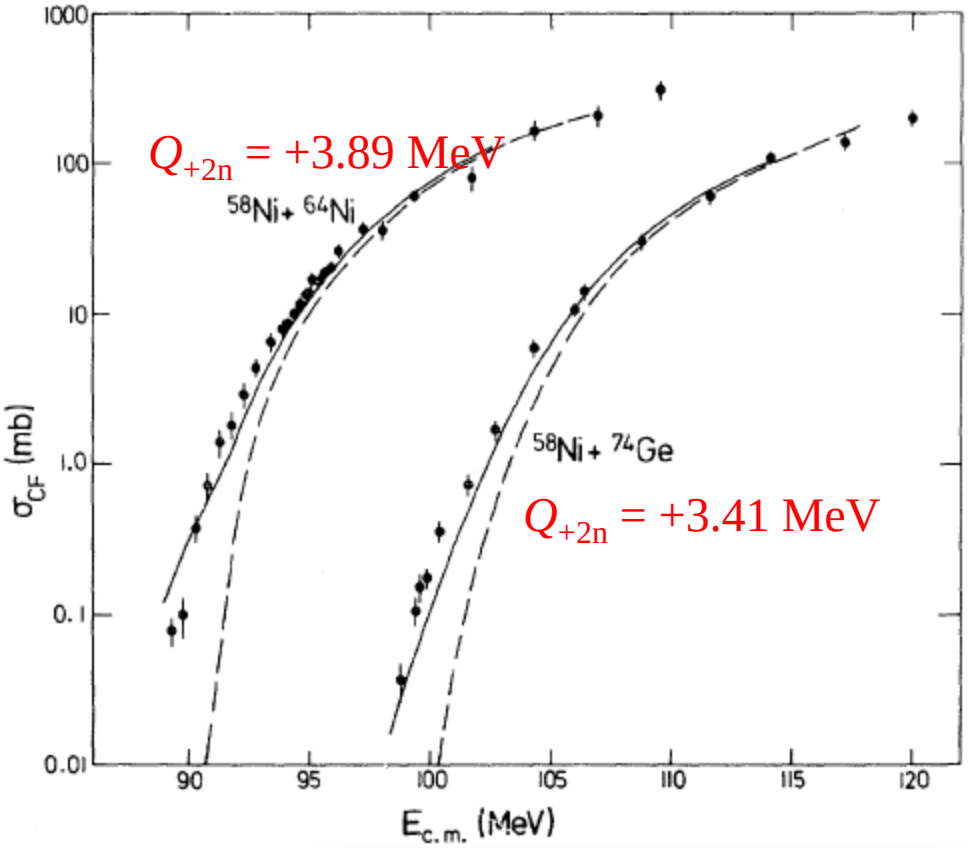
The collective excitation effect can be well described by the coupled-channel theory. But the neutron transfer effect is still a problem.

● **Discovery:** ^{58,64}Ni+^{58,64}Ni, M. Beckerman *et al.*, PRL 45, 1472 (1980).

● **…the Positive *Q*-value Neutron Transfers (PQNT) effect:**

…key idea: …the increased kinetic energy after +*Q*-value neutron transfer channel enhances the transmission probability.

Cf. Broglia et al., PLB 133, 34 (1983); PRC 27, R2433 (1983).



$$\sigma_m(E) = [1 - P(E)]\sigma_0(E) + P(E)\sigma_1(E + Q + \Delta E^C)$$

Based on a two-step picture,

Also for V.I. Zagrebaev, PRC 67, 061601 (2003).

Near- and sub-barrier fusion enhancement

Substantial (additional) near- and sub-barrier fusion enhancement for the +*Q*-value x*n*-**pickup** channels.

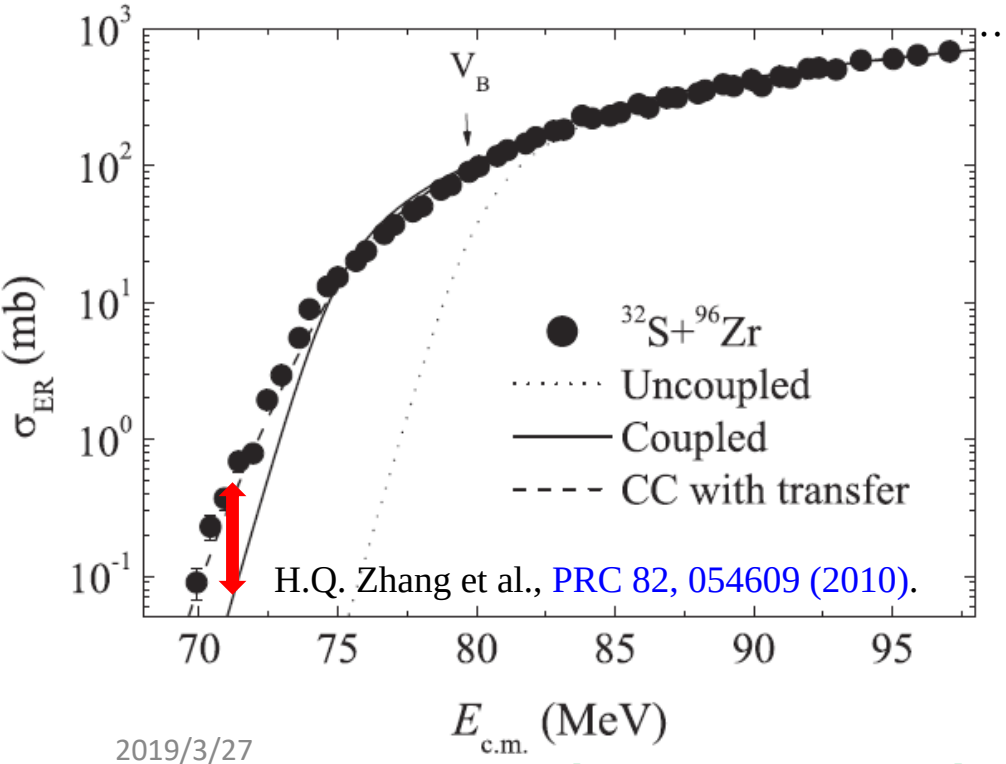
- ^{40}Ca+^{48}Ca, H.A. Aljuwair et al., PRC **30**, 1223 (1984).
- ^{58}Ni+^{64}Ni, M. Beckerman *et al.*, PRL **45**, 1472 (1980).
- ^{40}Ca+^{96}Zr, H. Timmers *et al.*, NPA **633**, 421 (1998).

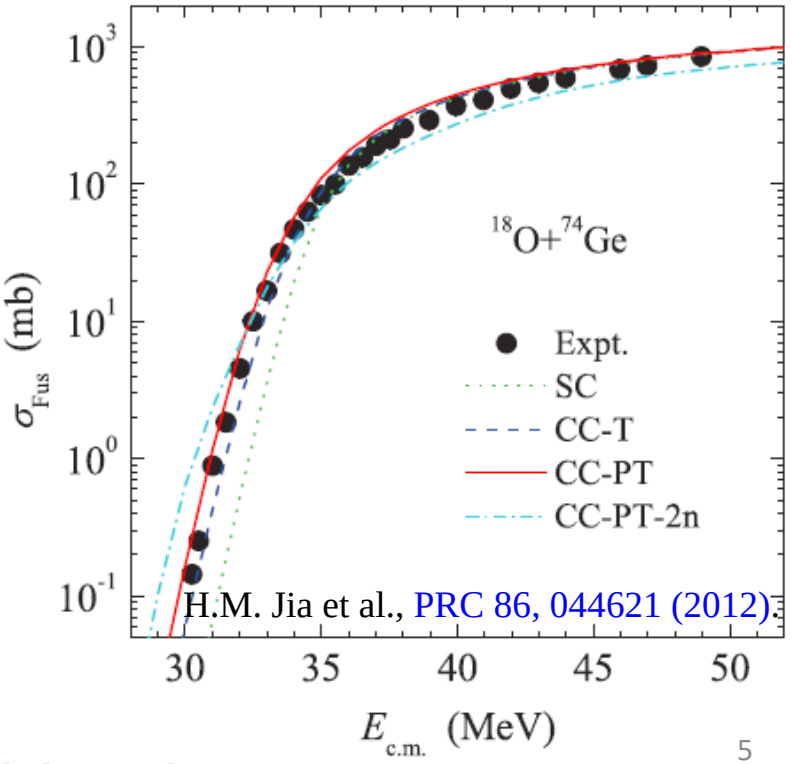
…

No substantial (additional) near- and sub-barrier fusion enhancement for the +*Q*-value 2*n*-**stripping** channel.

- ^{30}Si+^{58}Ni, A.M. Stefanini *et al.*, PRC **30**, 2088 (1984). (Kinematic mismatch)
- ^{18}O+^{A}Sn, P. Jacibs *et al.*, PLB **175**, 271 (1986).
- ^{6}He+^{238}U, R. Raabe et al., Nature **431**, 823 (2004).

…

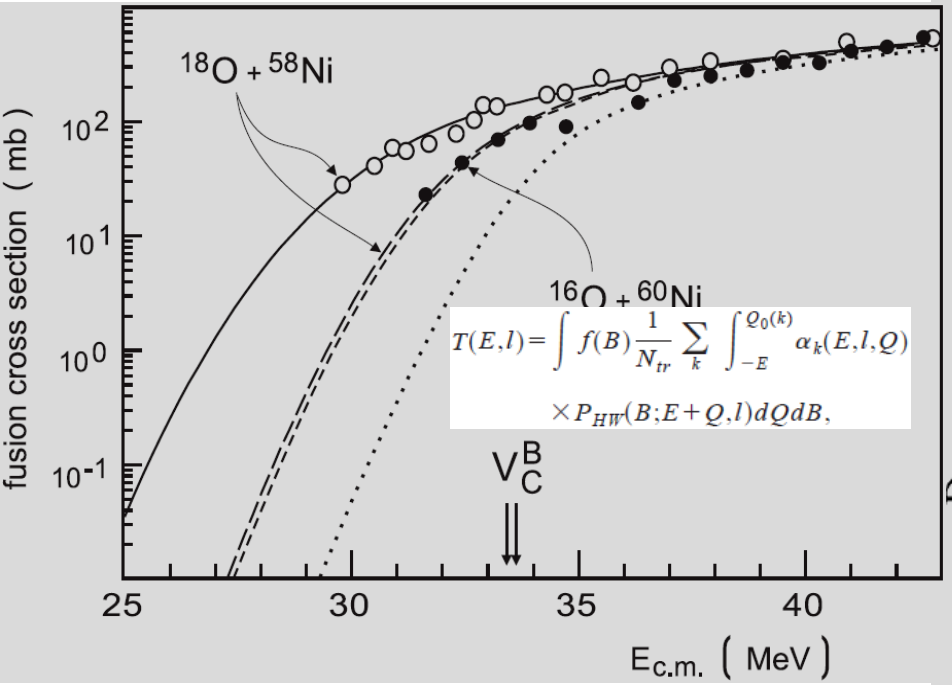


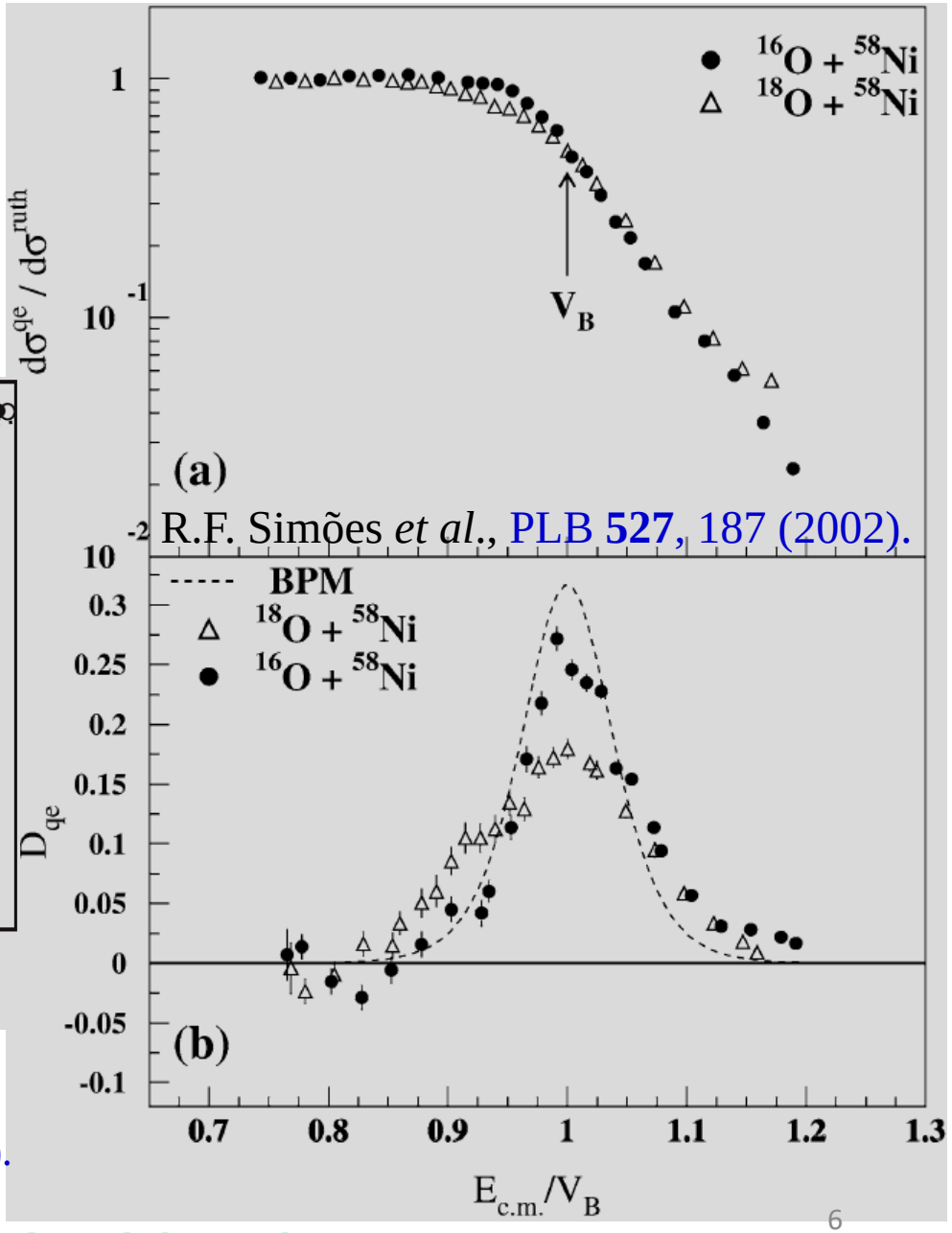


Near- and sub-barrier fusion enhancement

A special case:

Only $^{18}O + ^{58}Ni$ (Q_{-2n} = +8.20 MeV) was claimed to show big enhancement due to the positive Q-value $2n$-stripping channel.





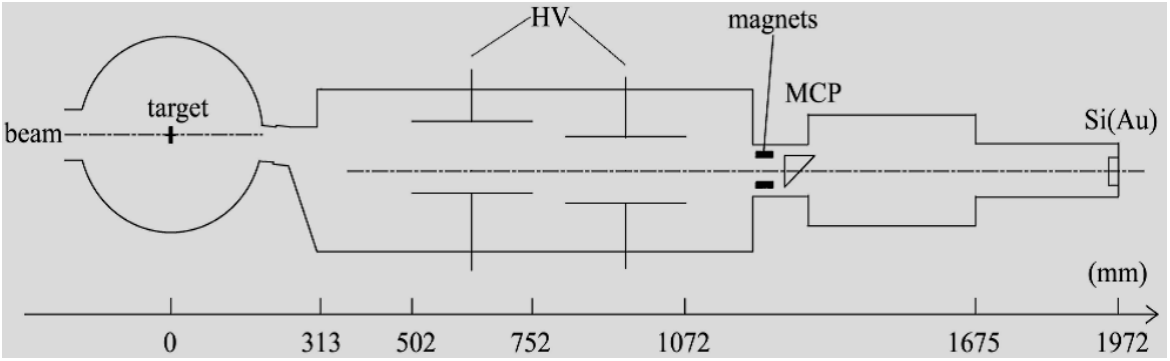
V.I. Zagrebaev, PRC **67**, 061601(R) (2003).
Expt. data : A.M. Borges *et al.*, PRC **46**, 2360 (1992).

Near- and sub-barrier fusion enhancement

Experiment and result

- ♠ Electrostatic deflector
- ♠ HI-13 tandem accelerator at CIAE

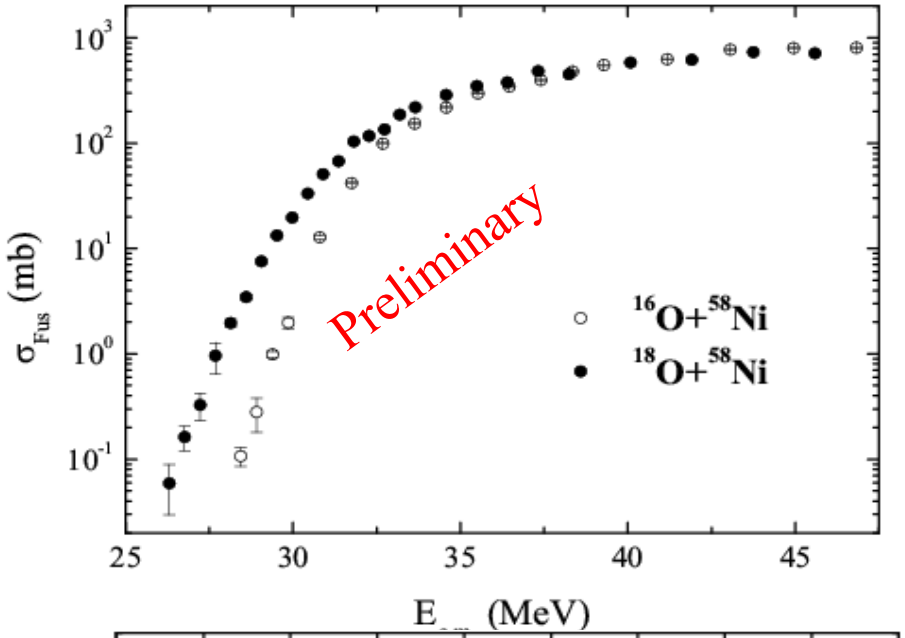
- ♠ Separation:
  - electrical rigidity $\eta = E/q$;
  - Optimal high voltage;
- ♠ Identification:
  - TOF-*E* (MCP + QSD);
- ♠ Angular distribution;
- ♠ Transmission efficiency.

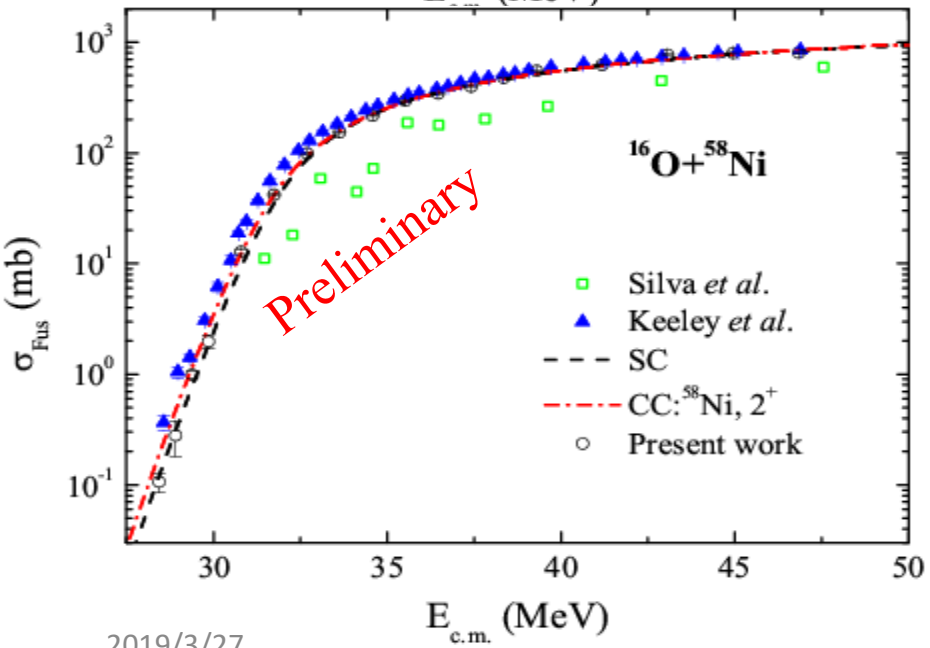


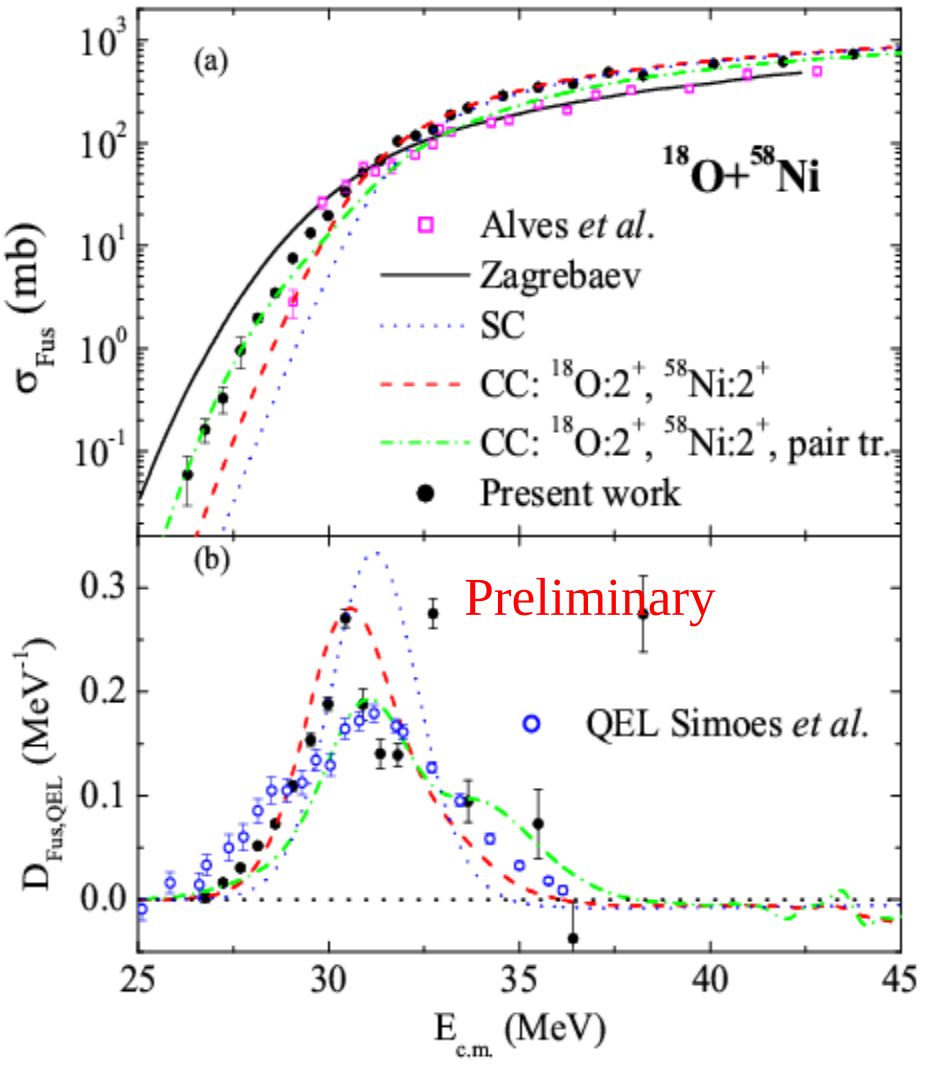
- ♠ Beam: ^{16,18}O, 2-20 pnA, 31.8 – 60.0 MeV, energy step 2.4/1.2/0.6 MeV.
- ♠ Target: ^{58}Ni, 99.80% isotope enrichment, thin, C backing.
- ♠ Beam monitors: 4 Si detectors at $\theta_{lab.} = 17^\circ$.

H.Q. Zhang *et al.*, Chin. Phys. C **34**, 1628 (2010).

Near- and sub-barrier fusion enhancement







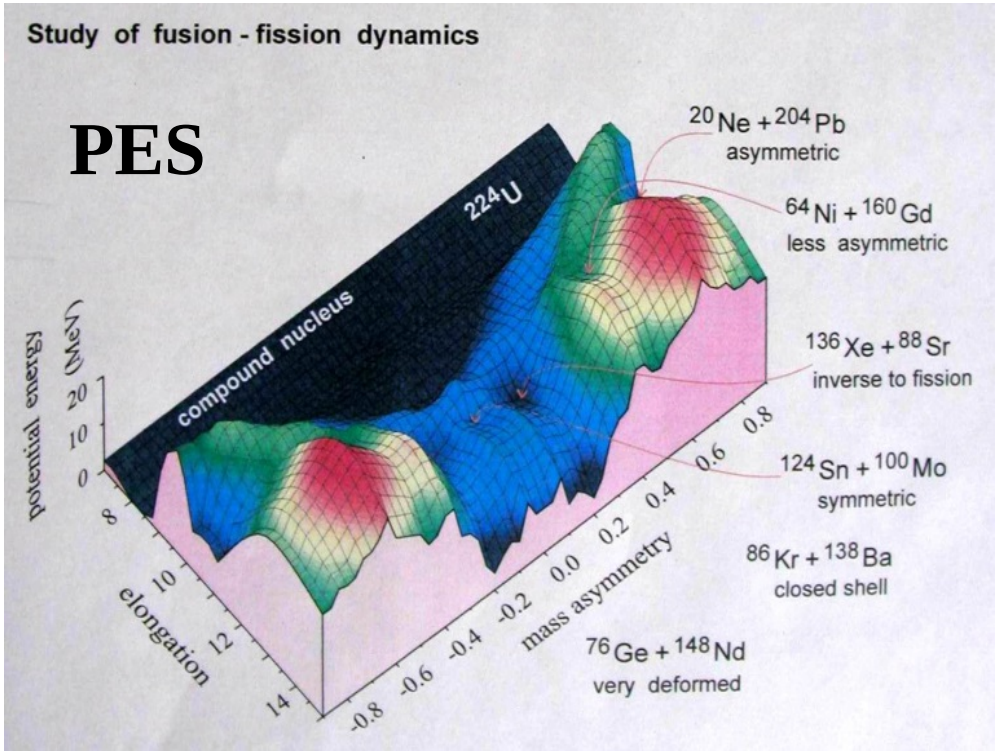
Only modest enhancement for the system with positive *Q*-value 2*n*-stipping channel, compared to the pickup channel.

Fusion-fission Dynamics

Fission modes:

- **Complete Fusion-fission**
  CN is formed with all D.o.F. achieving equilibrium.
- **Pre-equilibrium Fission**
  Mass is equilibrated, but *K* is not.
- **Quasi-fission**
  Both Mass and *K* are not equilibrated.
- **Fast-fission**
  No fission barrier.

Different fission mechanisms may appear in the fission process.



Potential energy surface (PES) plays a key role in understanding the evolution of the di-nuclear systems (DNS)

Fusion and fission study for $^{32}S+^{170}Er$ and $^{28}Si+^{174}Yb$

Systems: $^{32}S+^{170}Er$ & $^{28}Si+^{174}Yb$

- Both target nuclei have similar quadrupole deformation parameters (β_2~0.32).

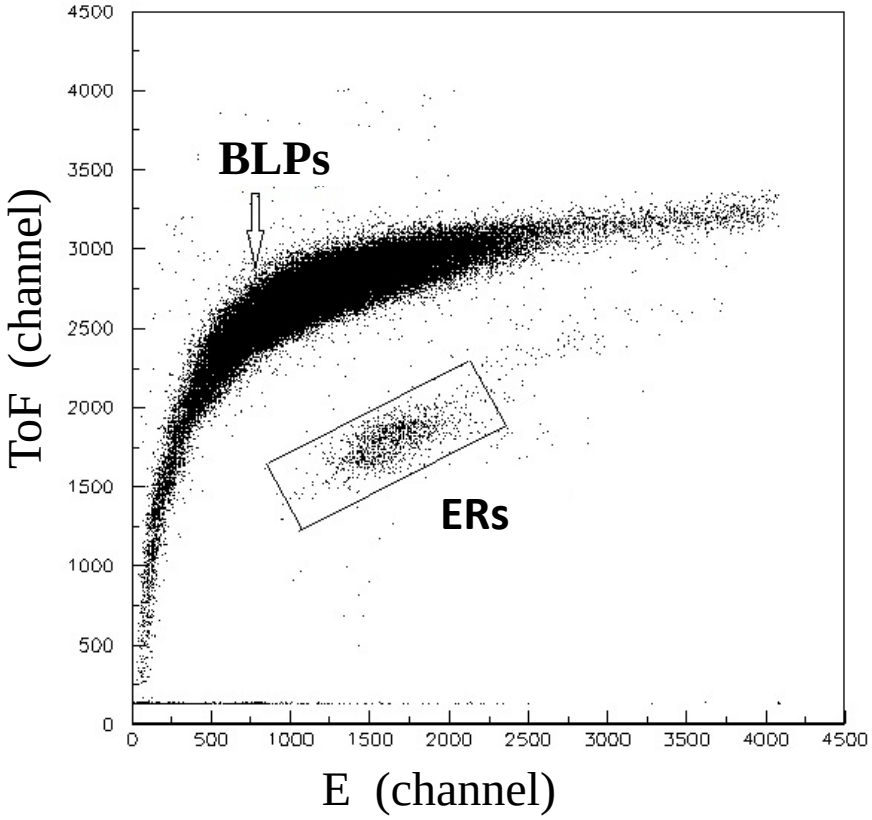
  They form the same CN and thus facilitate studying the entrance channel effect.

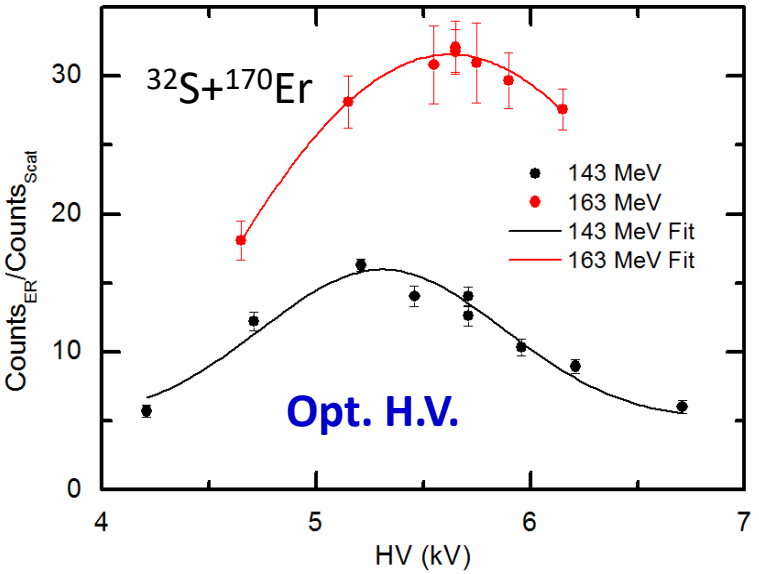
- Their charge products are both ~1000, which locate at the region where QF starts to occur.

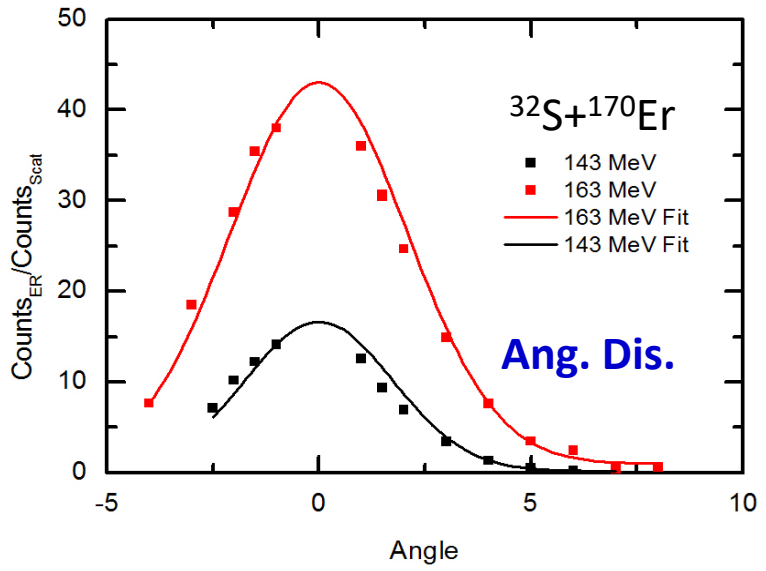
- Both systems have comparable fusion-evaporation and fusion-fission probability, so both processes can be measured, thus providing a good case to explore the potential energy surface (PES) and to strictly test the models.

Fusion and fission study for $^{32}S+^{170}Er$ and $^{28}Si+^{174}Yb$

Fusion-evaporation measurement



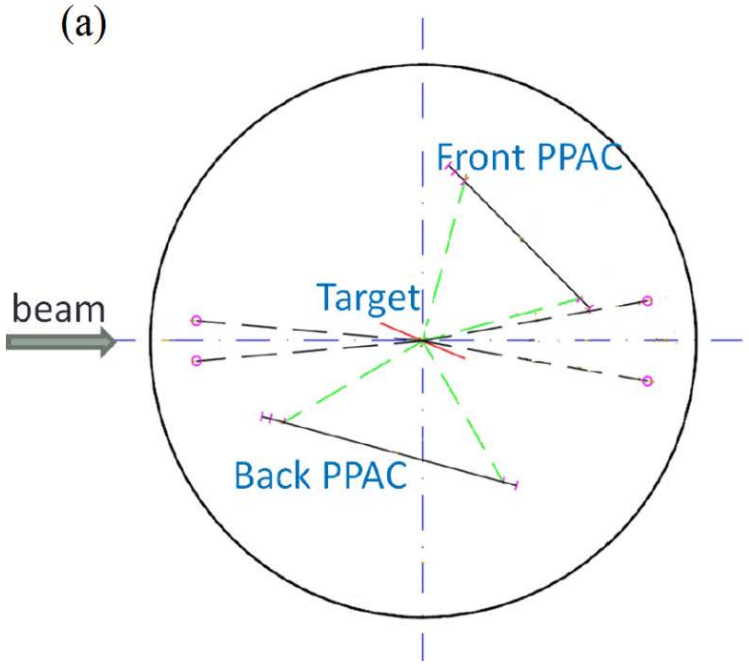


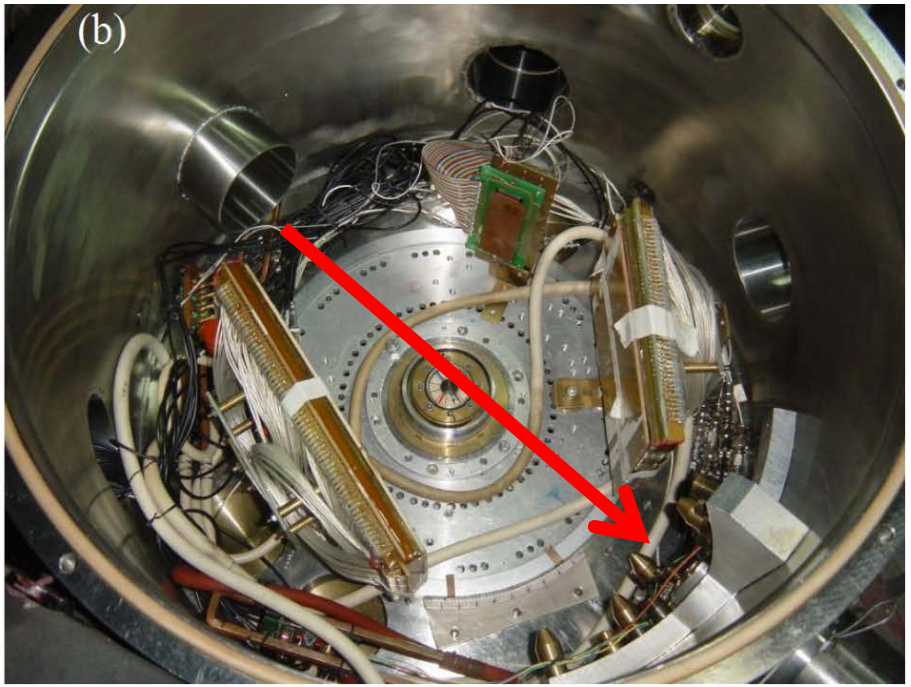


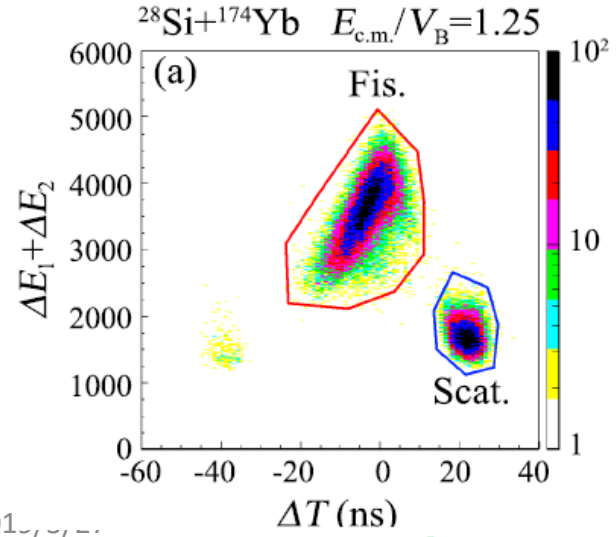
- Measured at 2°
- Integration to get total fusion evaporation cross section.

Fusion and fission study for $^{32}S+^{170}Er$ and $^{28}Si+^{174}Yb$

Fission measurement







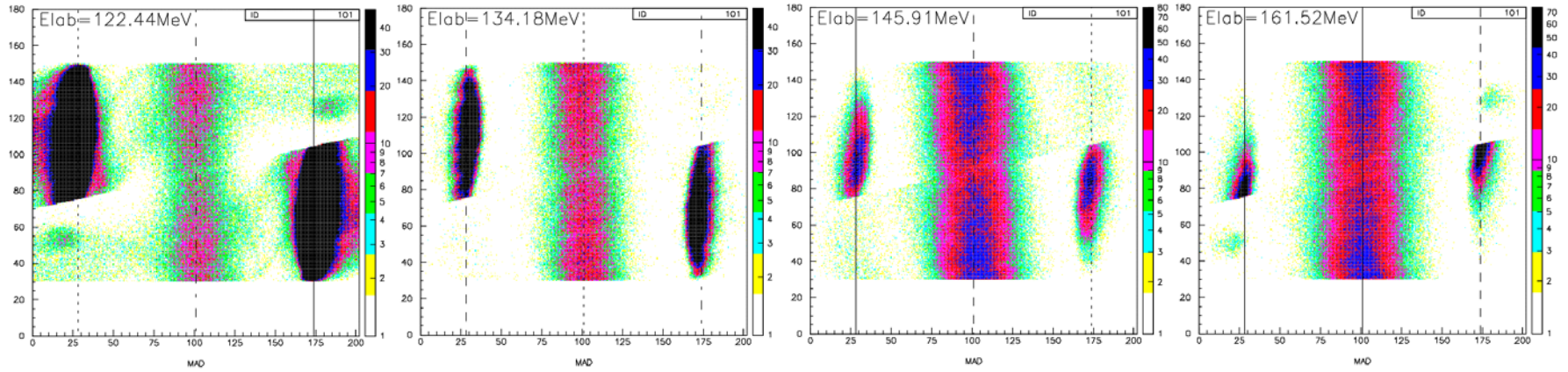
$\Delta T \rightarrow v_1$ & $v_2 \rightarrow m_1$&m_2 / TKE

$$\begin{cases} v_1 = \dfrac{d_1 \sin\theta_1 + d_2 \sin\theta_2}{d_2 \sin(\theta_1+\theta_2) + \Delta T v_c \sin\theta_1} \cdot v_c \\ v_2 = \dfrac{d_1 \sin\theta_1 + d_2 \sin\theta_2}{d_1 \sin(\theta_1+\theta_2) - \Delta T v_c \sin\theta_2} \cdot v_c \end{cases}$$

Fusion and fission study for $^{32}S+^{170}Er$ and $^{28}Si+^{174}Yb$

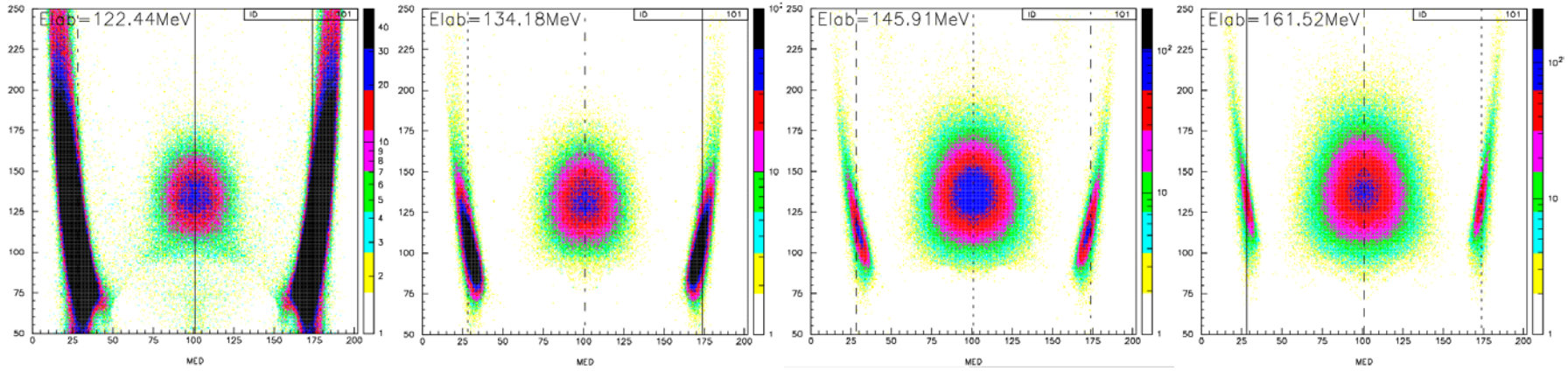
MAD & MED – $^{28}Si+^{174}Yb$

MAD



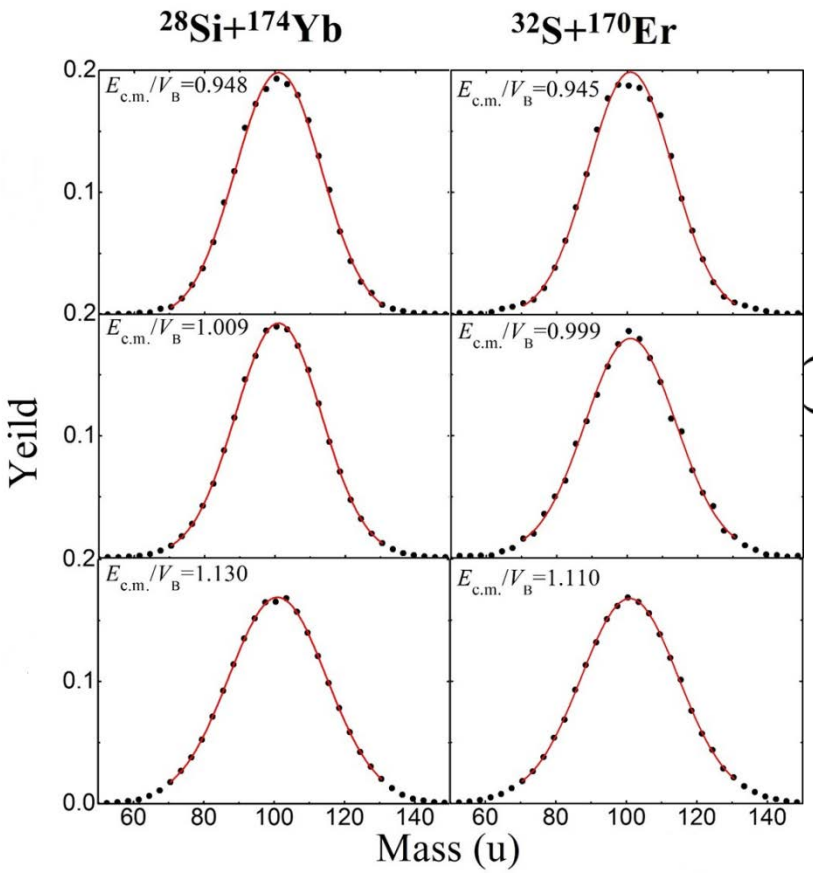
E_{lab}: 122.44 MeV 134.18 MeV 145.91 MeV 161.52 MeV

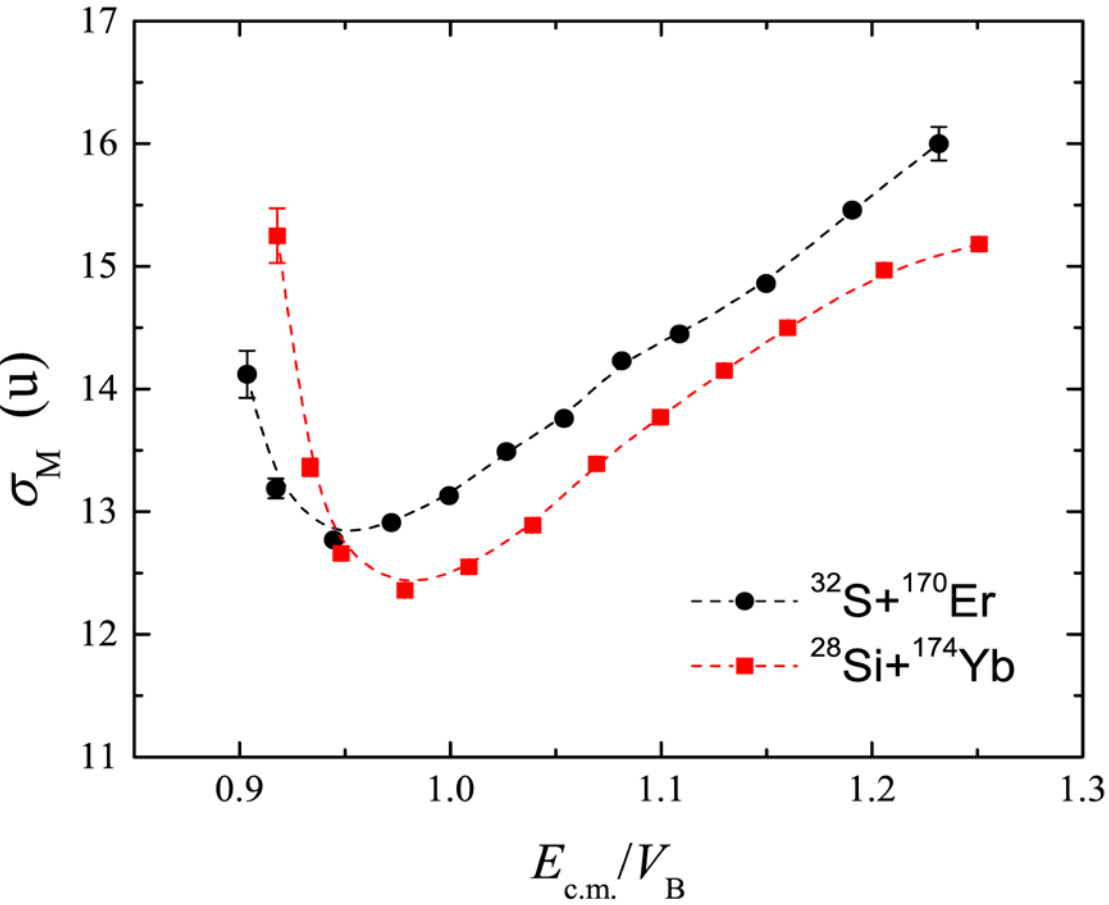
MED



Fusion and fission study for $^{32}S+^{170}Er$ and $^{28}Si+^{174}Yb$

Mass distributions – energy dependence



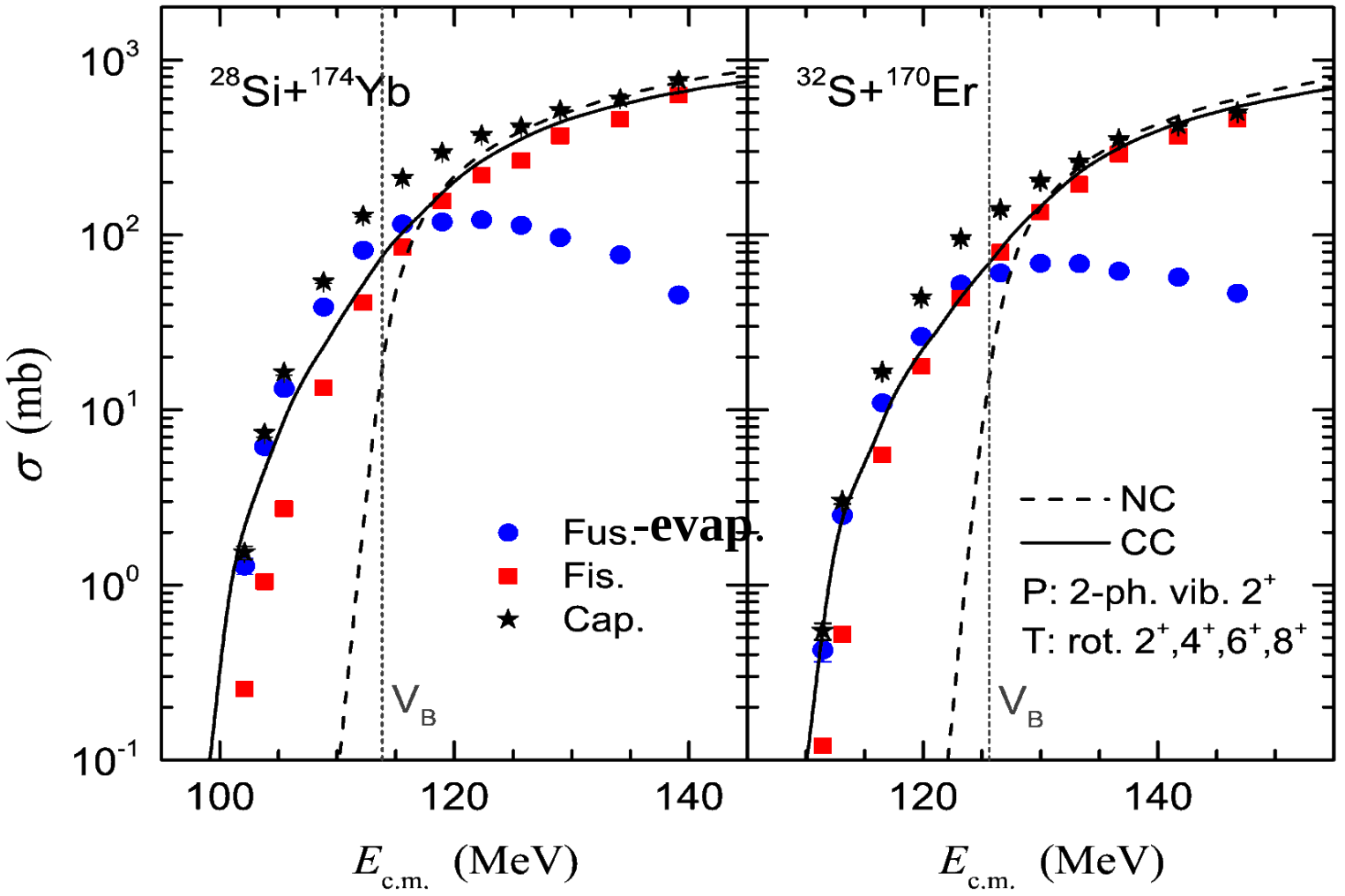


The width of fission fragment mass distribution, the increase at sub-barrier is a signature of QF.

Still need the angular anisotropy of the fission fragments.

Fusion and fission study for $^{32}S+^{170}Er$ and $^{28}Si+^{174}Yb$

Excitation Functions – fusion-evaporation, fission, and capture



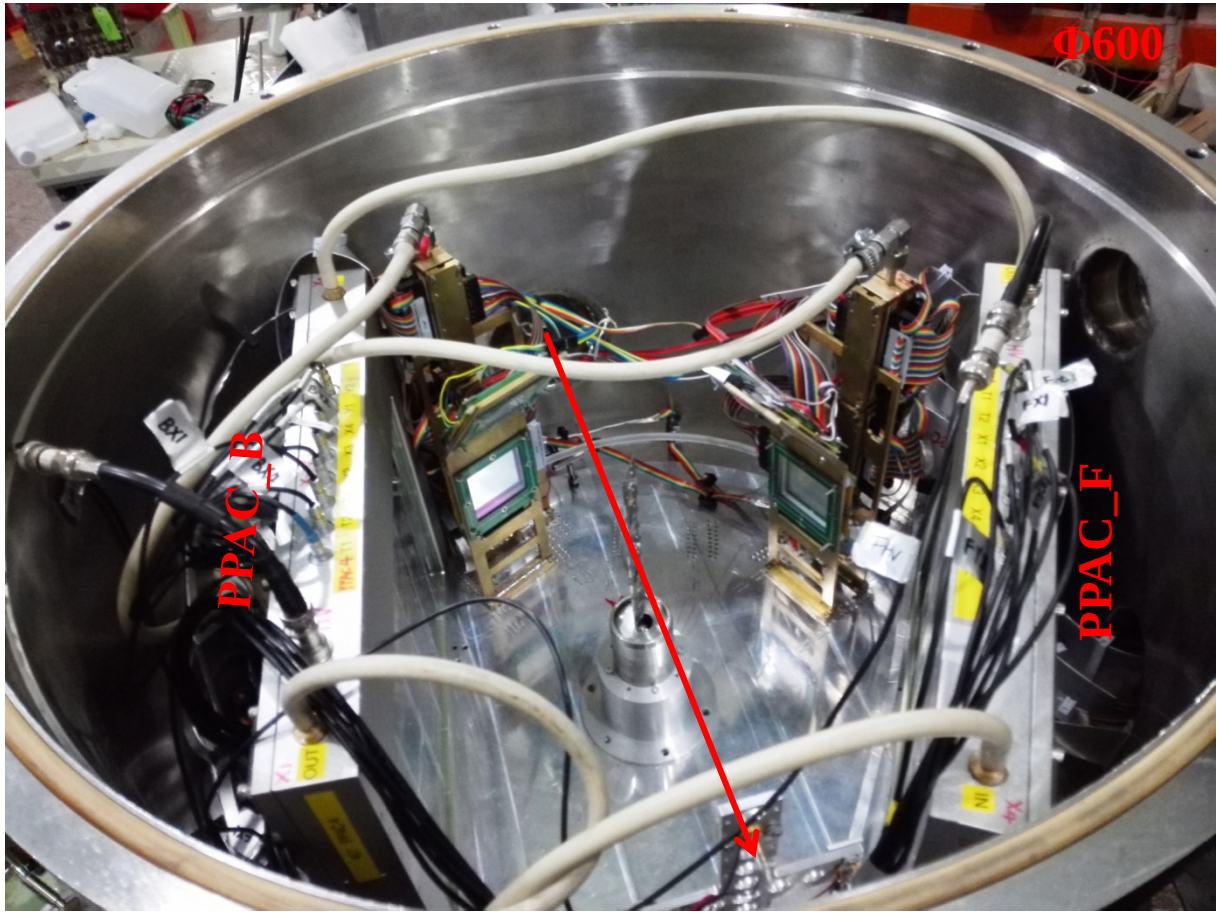
Generally reproduce the expt. results, except a deviation at near-barrier energy region.

CCFULL: K. Hagino *et al.*, CPC 123, 143 (1999).

The recent experiment for $^{7}Li+^{238}U$ reaction mechanism

ICF/transfer mechanism (for weakly-bound projectile)?

- A. Pal *et al.*, PRC **99**, 024620 (2019);
- K.J. Cook *et al.*, PRL **122**, 102501 (2019);



→Two beam energies (~2.5 pnA) :

- 37.0 MeV (1.10 V_B);
- 34.6 MeV (1.03 V_B);

→ **^{238}U**(3#):

C 50 μg/cm^2 + ^{238}U 148.5 μg/cm^2 + Al 13.5 μg/cm^2

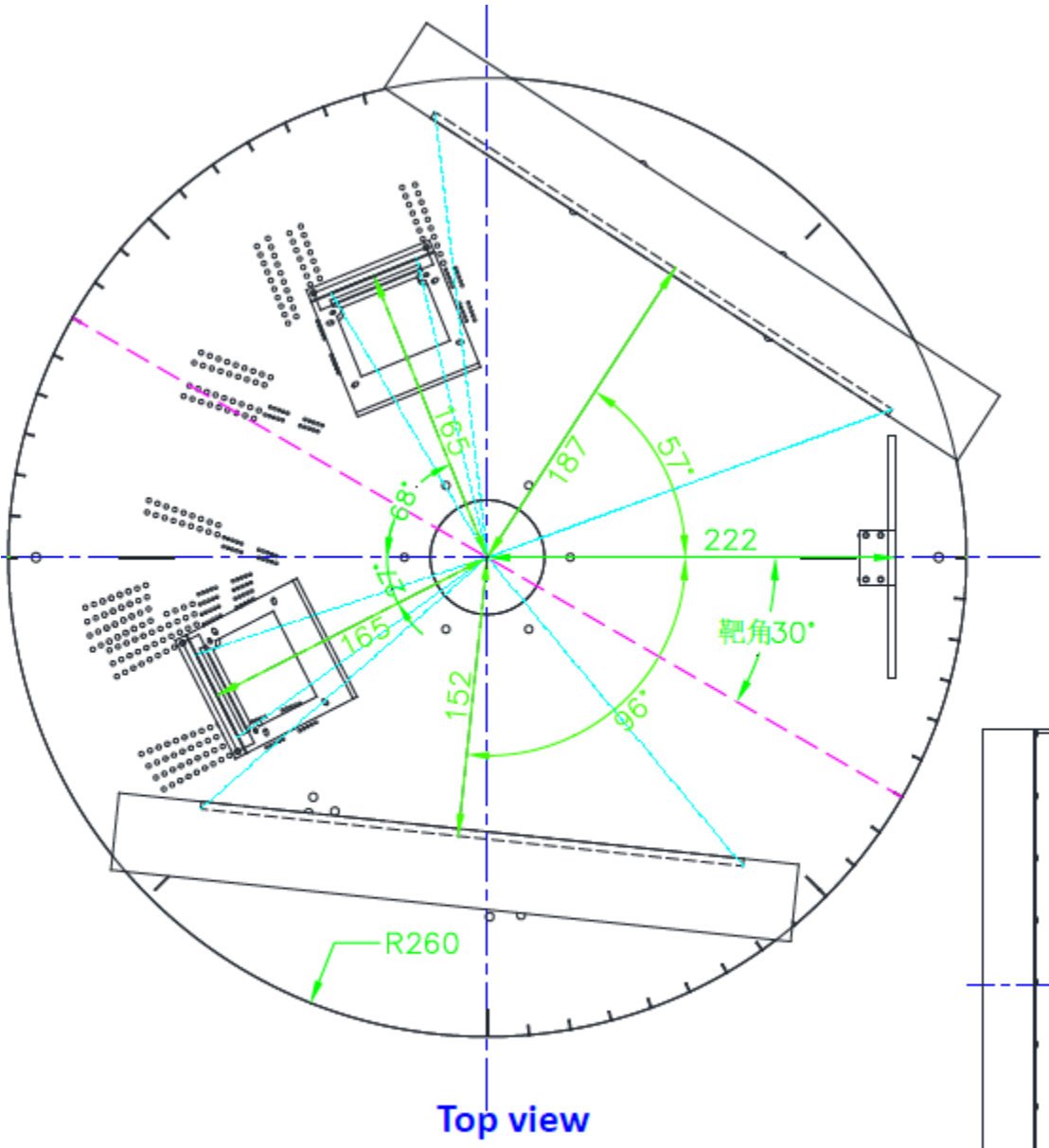
…by using the correlation measurement of the fission fragment of target-like nucleus with ^{4}He.

→ **PPAC**:

isobutane, 4.07 Torr, -530 V

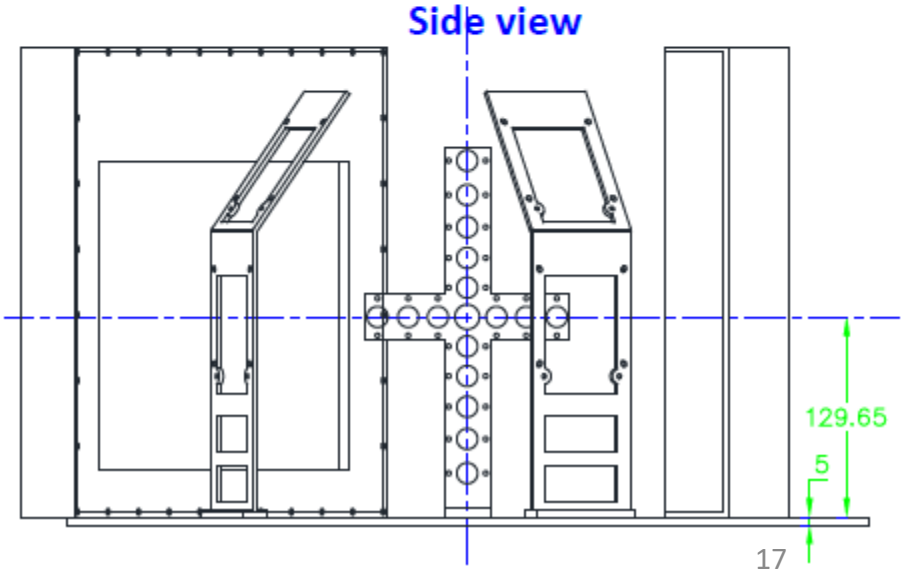
(…insensitive to ^{7}Li)

The recent experiment for $^{7}Li+^{238}U$ reaction mechanism



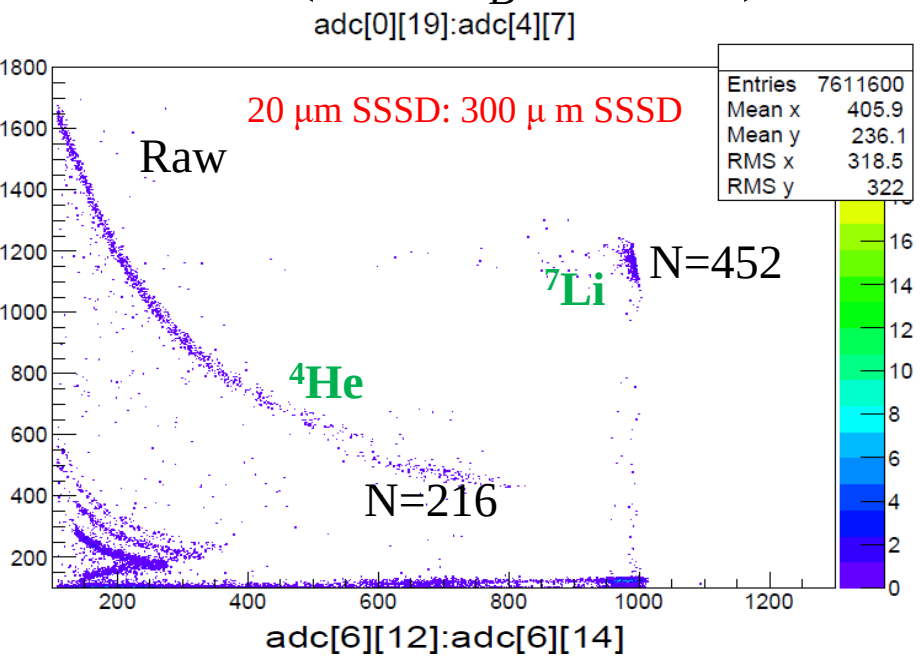
- **2 PPACs:** Fission fragment
- **4 Telescopes:** (112° & 153°)
  20 μm SSSD +
  300 μm SSSD/QSD +
  1000 – 1500 μm QSD

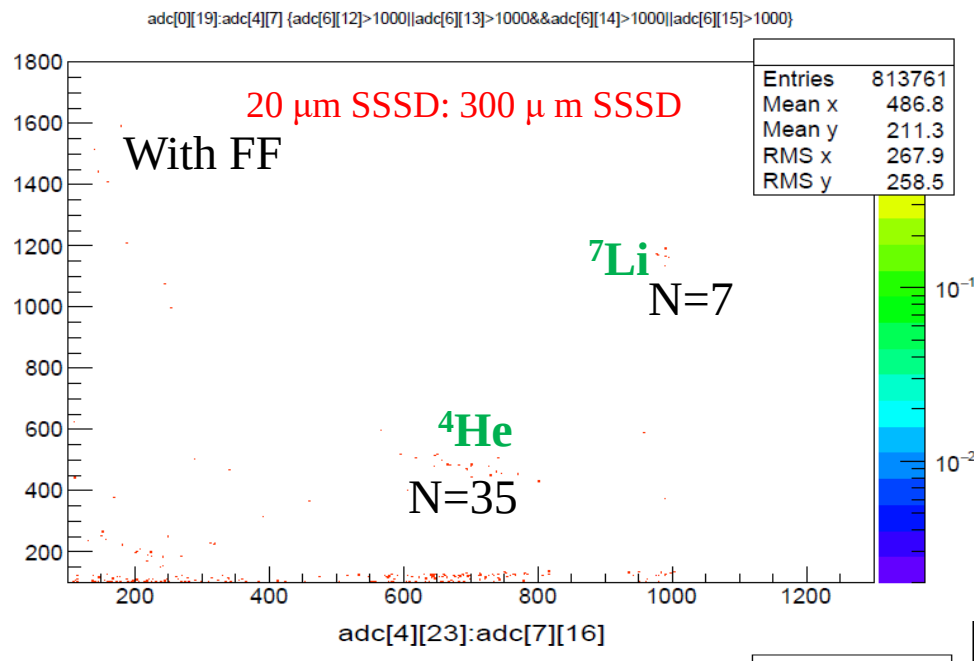
  Fiss. + Trans. + Eva.
- **4 Monitors:** PIN-diodes
  ± 15° (L&R), ϕ.5 mm, 3.8 pps;
  ±20° (U&D), ϕ1 mm, 4.9 pps.

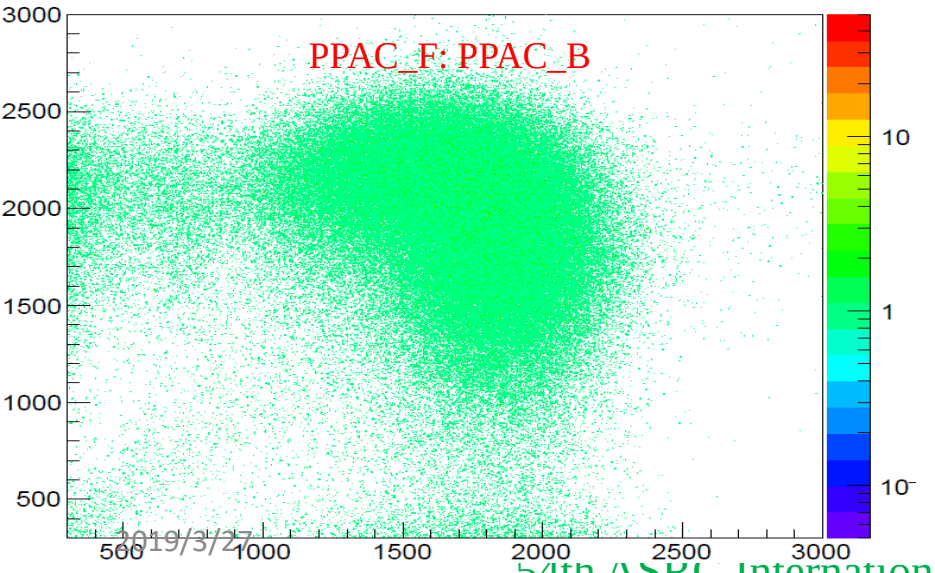


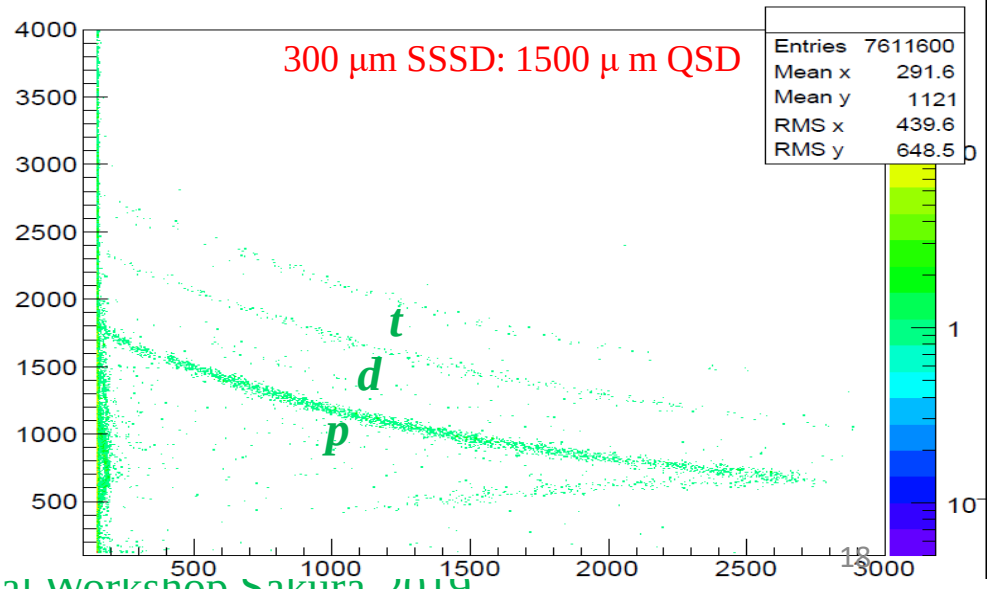
The recent experiment for $^{7}Li+^{238}U$ reaction mechanism

37.0 MeV (1.10 V_B, 390 mb) $^{7}Li+^{238}U$ @Rn0381 some spectra



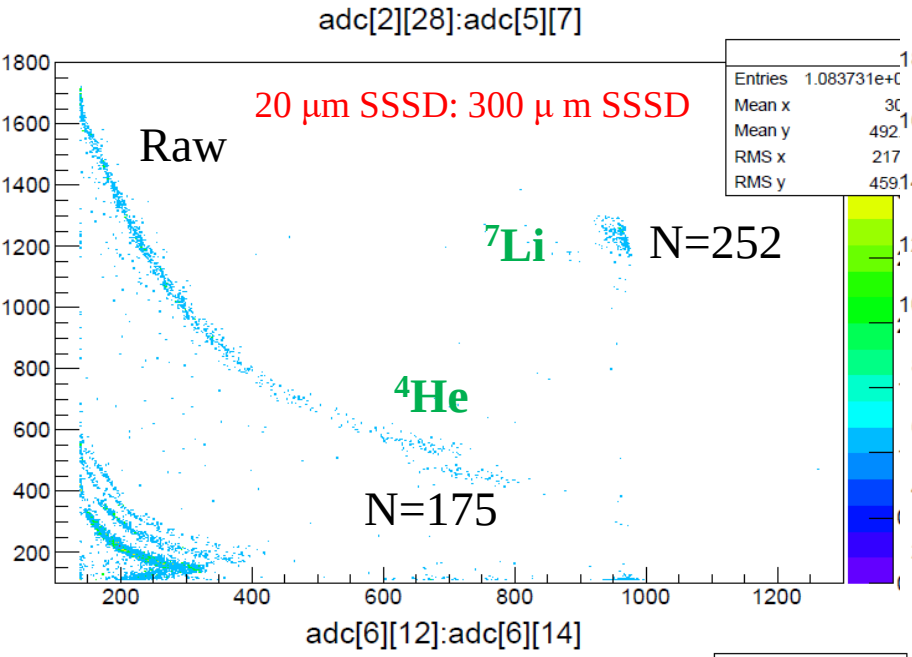


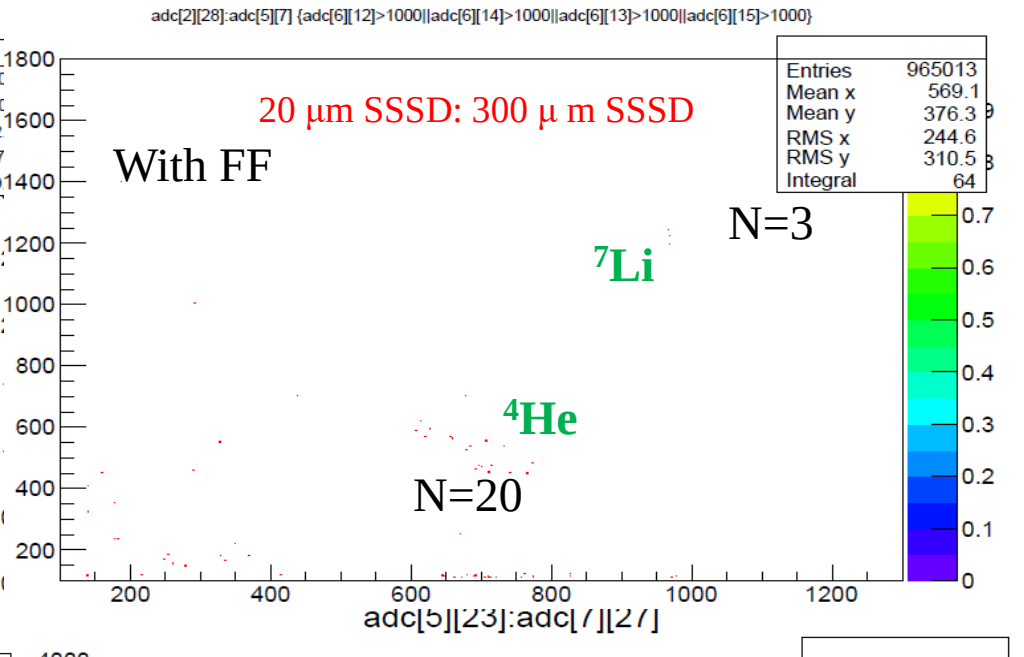


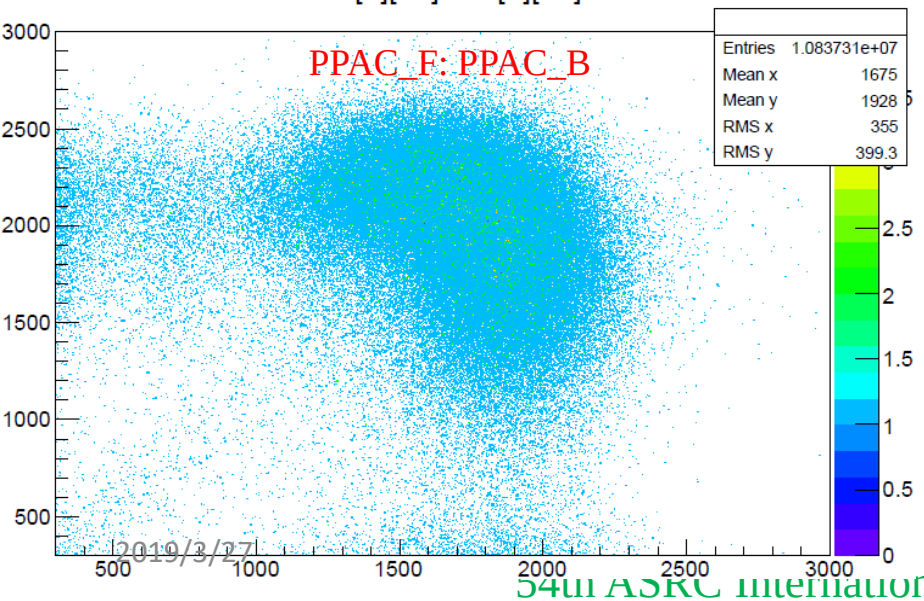


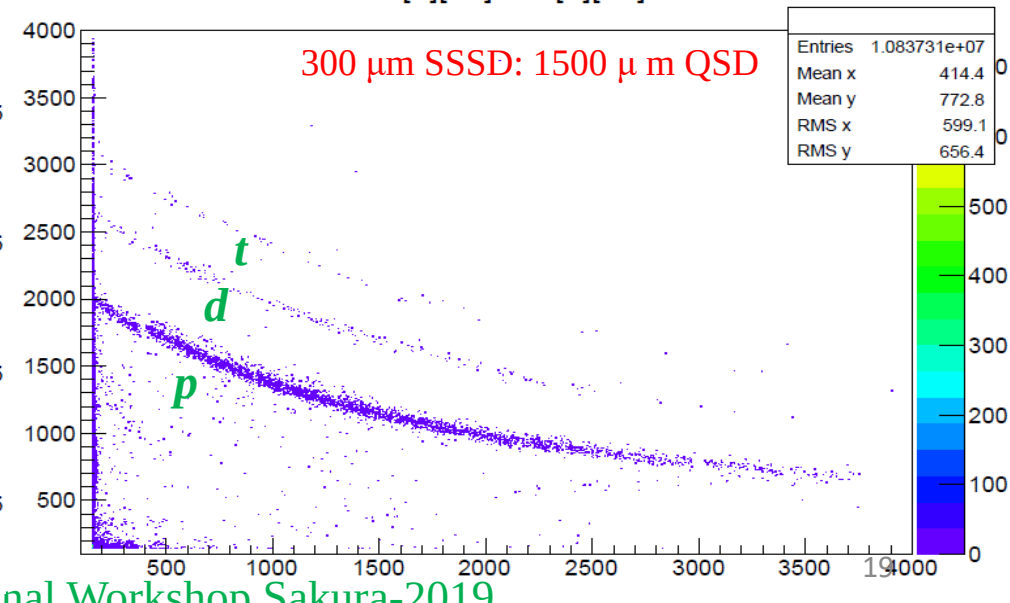
The recent experiment for $^{7}Li+^{238}U$ reaction mechanism

34.6 MeV (1.03 V_B, 140 mb) $^{7}Li+^{238}U$ @Rn0444 some spectra









The recent experiment for $^{7}Li+^{238}U$ reaction mechanism

Online spectra：

For $^{7}Li+^{238}U$, FF-correlated direct ^{4}He-products were observed at both energies.

Upcoming data analysis:

- …the angular distributions of FF which correlated with ^{4}He;
- …the angular distributions of ^{4}He which correlated with FF;

…the double-differential cross section of direct alpha on energy and angle (may prefer the transfer mechanism based on the limited angular coverage) .

Next step:

60 μm DSSD + 1500 μm QSD (more suitable for ^{7}Li)

…with large solid angle (higher statistics)

…with large angle (larger range angular distribution)

To study the deformation of ^{254}Es by using backward QEL

- Try to get the deformation parameter:

See talks:

Theory:

3.25 10:00 Paul Stevenson;

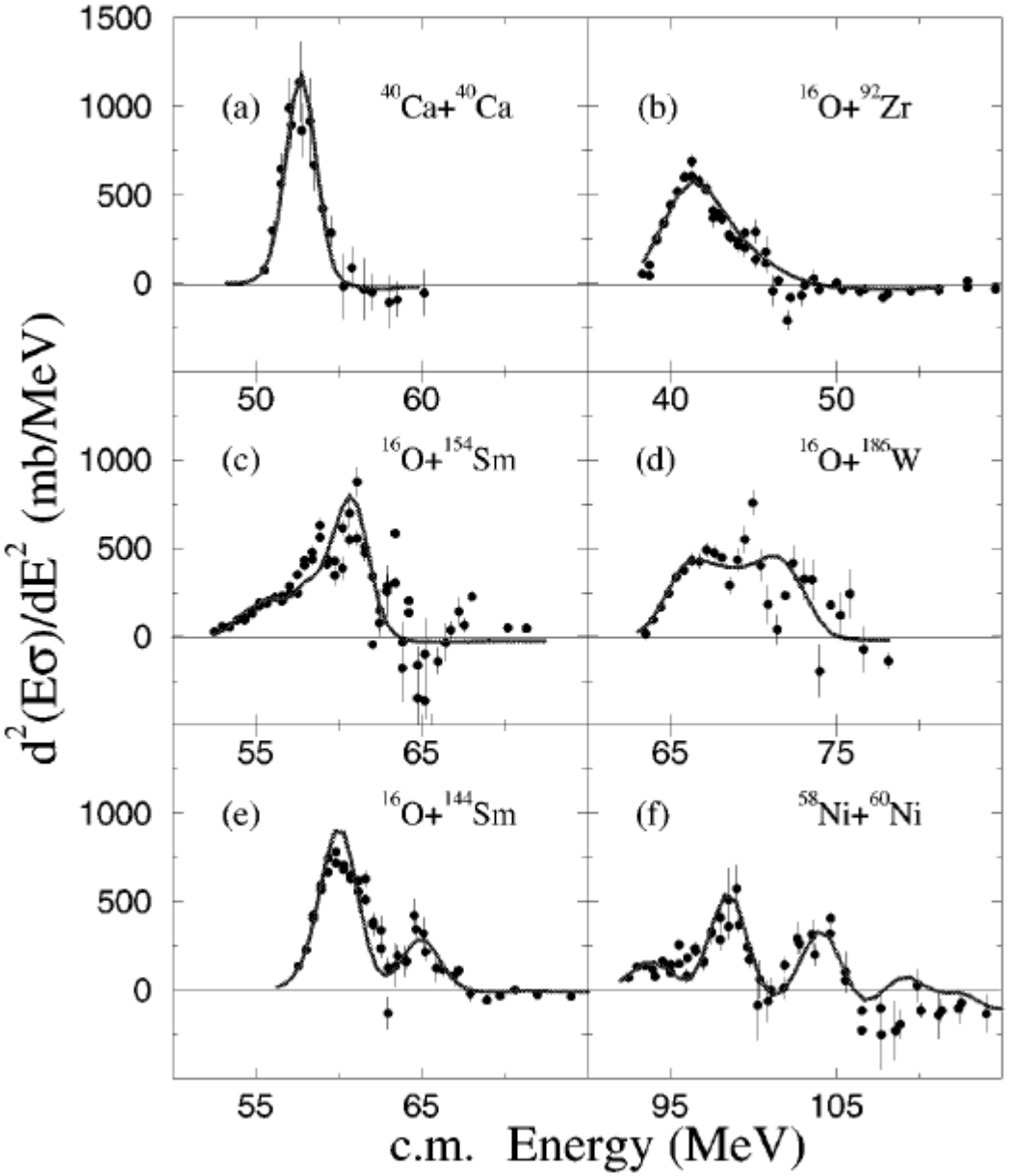
Experiment:

3.25 11:00 Eiji Ideguchui (Coulomb excitation);

- Deformation parameter is an important input parameter in theoretical calculations.

…role of deformation in nuclear reaction.

See 3.26 11:20 Hagino's talk.



M. Dasgupta *et al.*, Annu. Rev. Nucl. Part. Sci. **48**, 401 (1998).

To study the deformation of ^{254}Es by using backward QEL

Fusion (T), QEL (R)
…two complementary processes.

$$D_{qel}(E) = -\frac{d}{dE}\left(\frac{d\sigma_{qel}}{d\sigma_R}\right)$$

H. Timmers *et al.*, NPA **633**, 421 (1998).

^{16}O+^{254}Es

^{16}O: double-magic, higher excitation energy larger than the barrier curvature, so does not change the shape of the fusion barrier distribution.

QEL: a simple Expt. setup

- …forward Si for beam monitors and data normalization;
- …backward Si for QEL counts;
- Coulomb barrier, V_{B_cm}=89.89 MeV, V_{B_Lab}=95.55 MeV;
- ~25 energy points (with equal energy step);
- 3-day beam-time;

Summary

- The positive *Q*-value 2*n*-stripping channel shows only a modest sub-barrier fusion enhancement compared with the corresponding x*n*-pickup channels.
- The preliminary experimental data show a signature of QF for both $^{32}S+^{170}Er$ and $^{28}Si+^{174}Yb$ from the mass width (yet to be finally finished).
- Substantial direct ^{4}He, which is correlated with FFs, emerge for near-barrier $^{7}Li+^{238}U$ by using a coincident measurement. Further data analysis will be performed.
- A simple experiment was proposed to extract the deformation parameter of ^{254}Es (by using the near-barrier backward quasi-elastic scattering).

Thanks for your attention!