中国原子能科学研究院
China Institute of Atomic Energy

The effect of positive *Q*-value neutron transfers on near-barrier fusion of heavy-ions

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Contents

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● Nuclear reactions of heavy-ions at near-Coulomb-barrier energies are processes which involve complex dynamic process between the two reactants.

● The reaction mechanism for fusion of heavy-ions at near-barrier energies is important, but it is still not yet understand well up to now.

It involves the basic quantual tunneling mechanism and the coupled-channels effect.

See G. Montagnoli's talk on 14 May.

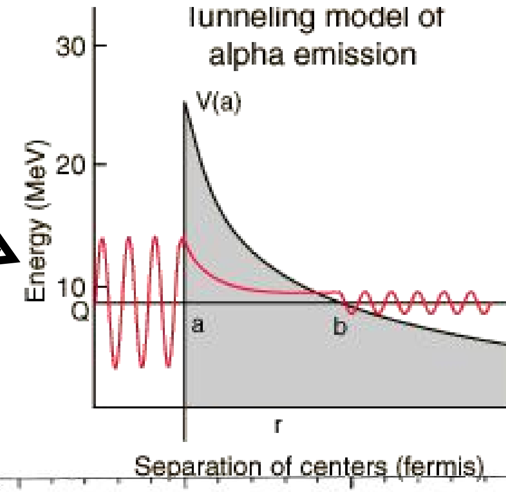
The reaction mechanisms, such as the sub-barrier fusion enhancement correlated with x*n*-transfer channels and transfer/breakup-induced InComplete Fusion (ICF) are still current hot-topics.

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

● The (multi-nucleon) transfer mechanism itsef is still not very clear:

c.f. S. Silner's talk about pari-transfer on 13 May.

Near- and sub-barrier fusion (for smaller $Z_P Z_T$)



● **The foremost theory base**:

Fusion can be seen as an inverse process of α-decay which explain by George Gamow @1928, also by Ronald Wilfrid Gurney & Edward Uhler Condon.

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

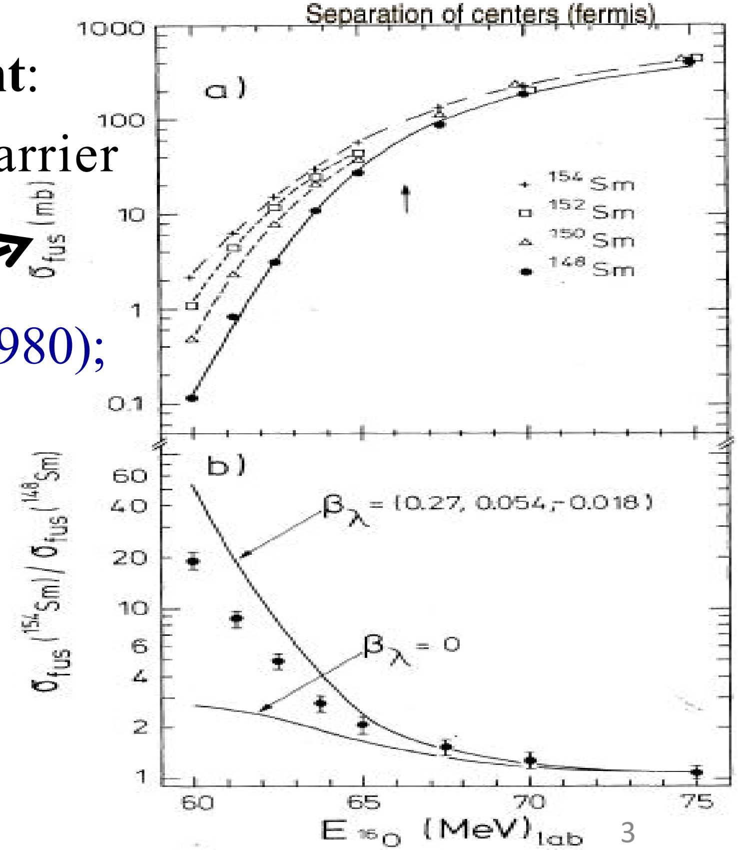
J.F. Miller et al., PR 81, 288 (1951)

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

The anomalous isotopic dependence of the sub-barrier fusion cross sections.

$^{16}O+^{A}Sm$, R.G. Stokstad et al., PRL 41, 465 (1978);

$^{58,64}Ni+^{58,64}Ni$, M. Beckerman et al., PRL 45, 1472 (1980);



● **Fusion barrier distribution (BD):** [fingerprint of fusion dynamics]

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

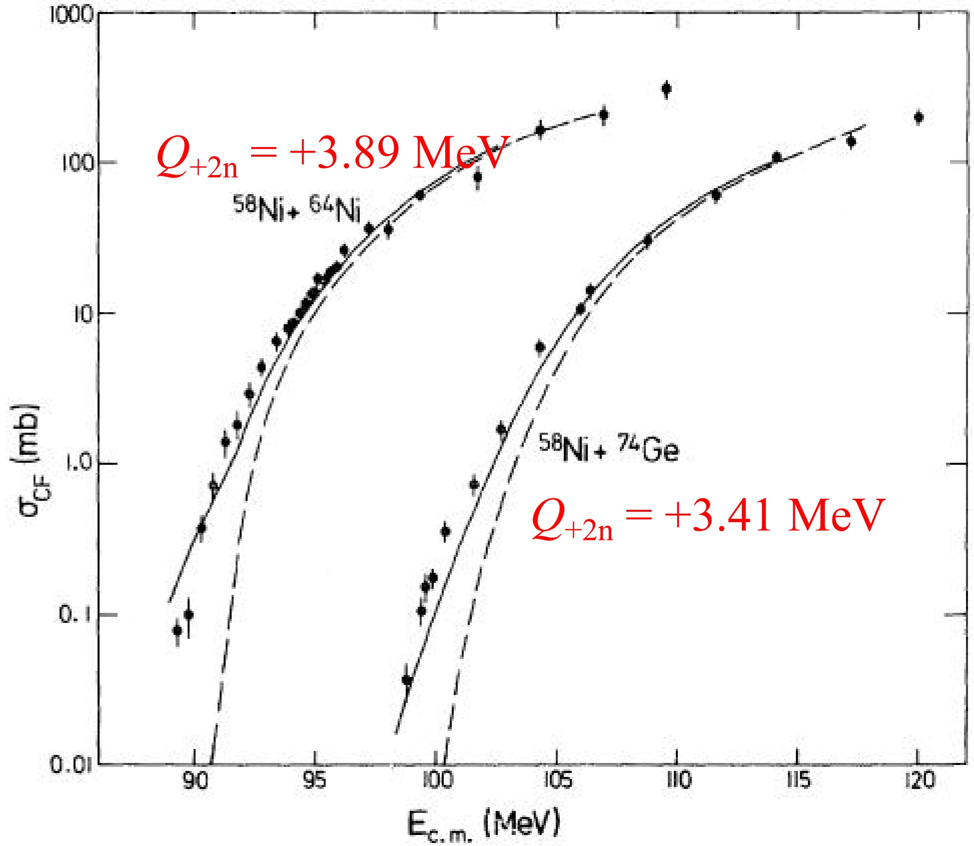
● **Many Explanations--Coupling effects:**

Nuclear structure (collective excitations)

Reaction dynamics (transfer/breakup reactions)

Near- and sub-barrier fusion enhancement

The *collective* excitation effect can be well described by the coupled-channels 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 (at large distance) enhances the transmission probability.

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

Based on a two-step process picture,

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

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

- DC-TDHF: Transfer (isovector) induces the barrier for ^{16}O+^{208}Pb [depends on Q_{tr} (isospin)]. see A.S. Umar's talk on 13 May.

How to study the transfer effect on fusion experimentally?

● to extract the fusion barrier distribution

→ a lower energy stretched barrier distribution (tail);

● to compare 2 nearby systems w/wo $+Q_{gs}$ neutron transfer channels;

c.f. A.M. Stefanini et al., PRC 76, 014610 (2007).

● to correlate the enhanced fusion with the measured transfer cross sections (transfer strength):

c.f. G. Montagnoli et al., EPJA 15, 351 (2002).

→ two-step process

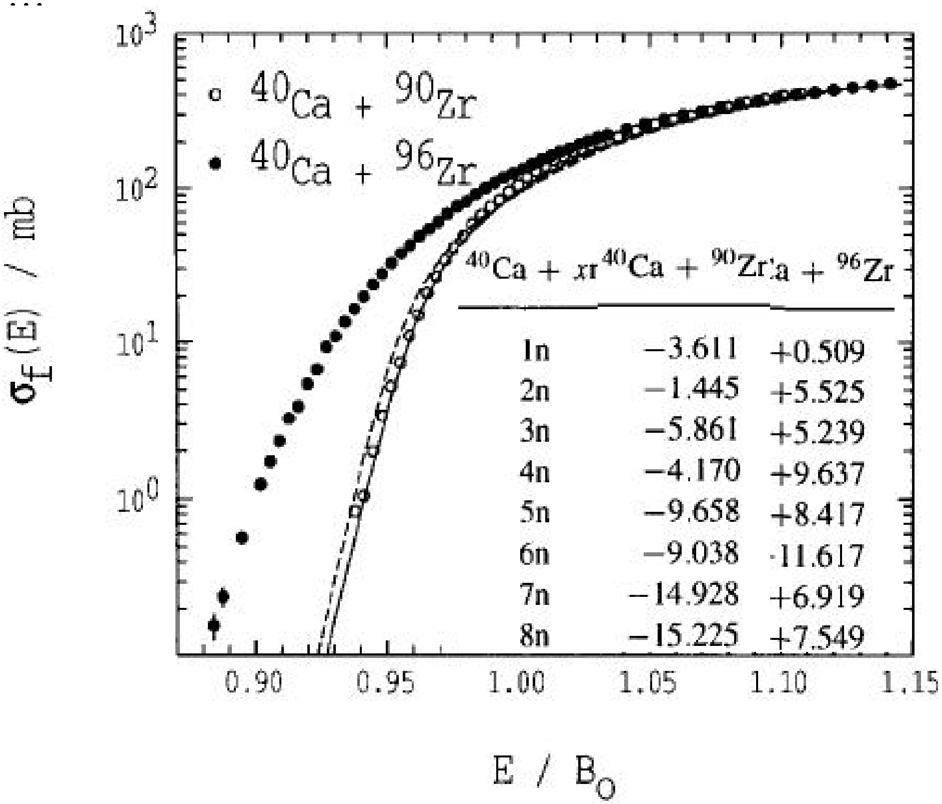
→ coupled-channels

About the neutron transfer effect on fusion

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).

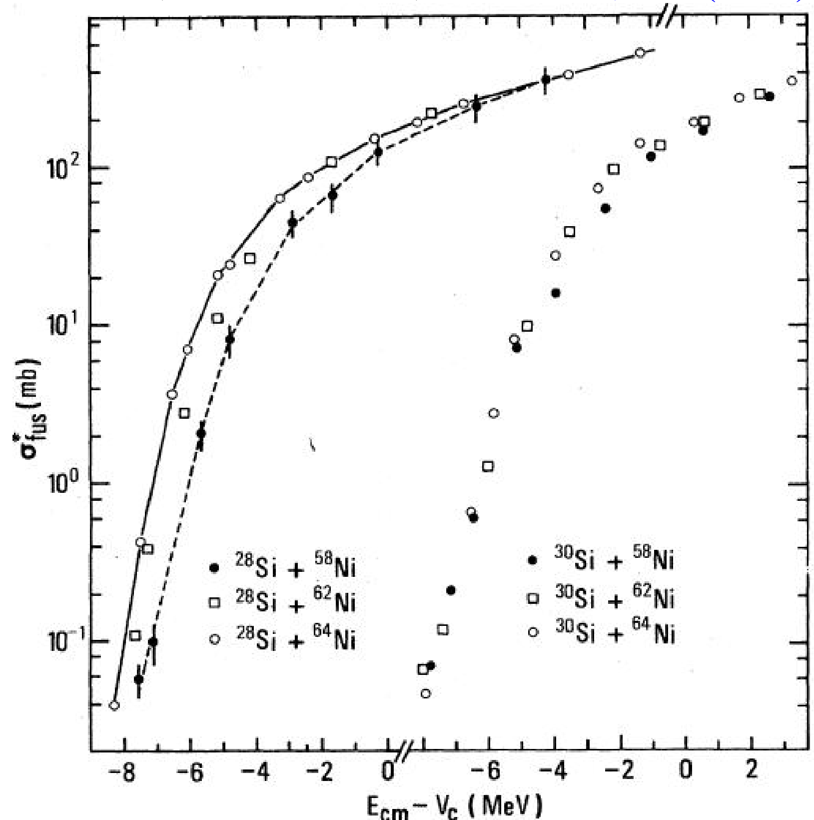
…



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).

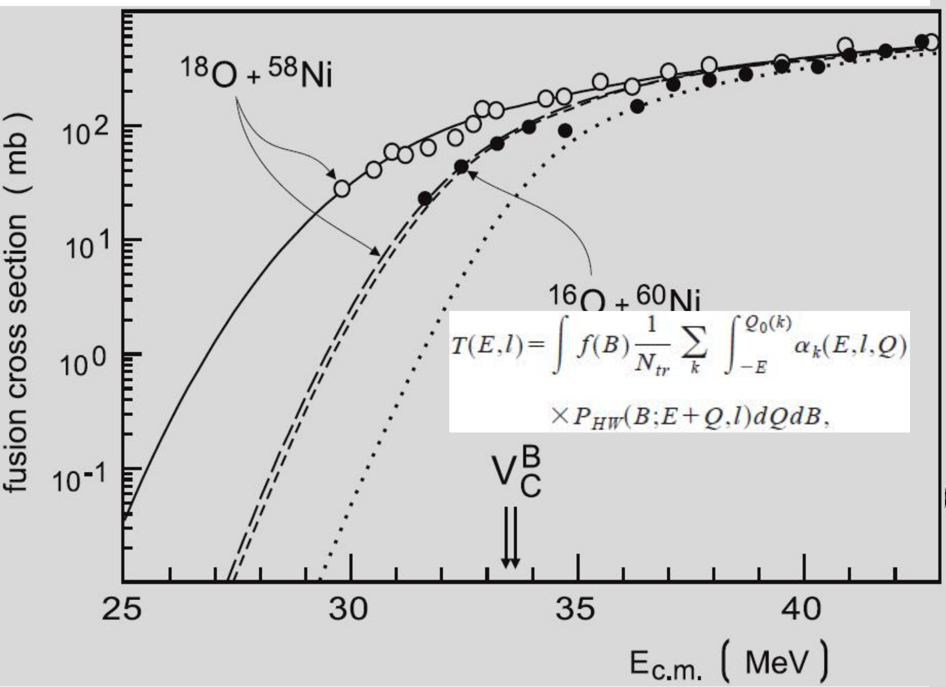
…



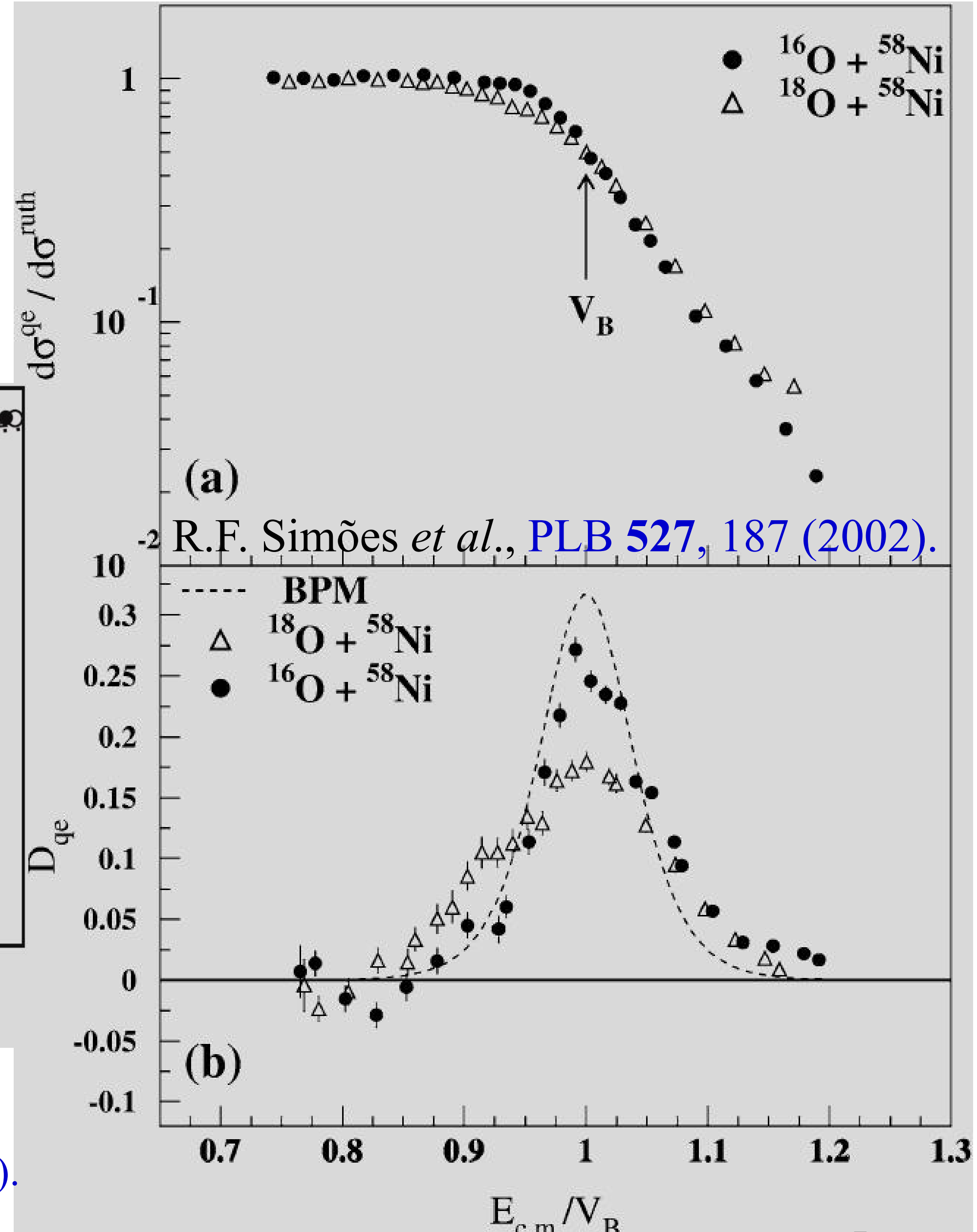
About the neutron transfer effect on fusion

A special case (for 2n stripping):

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).

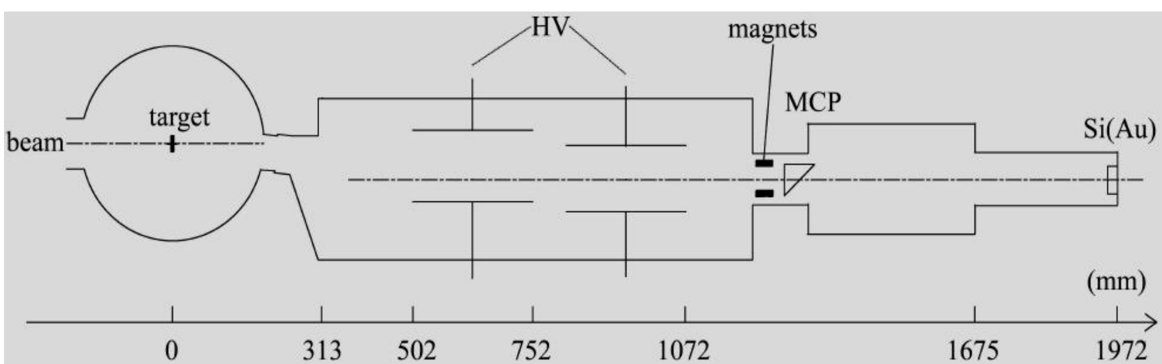


R.F. Simões *et al*., PLB **527**, 187 (2002).

Experimental study for *n* transfer (pickup/stripping) effect on fusion

- Electrostatic deflector
- HI-13 tandem accelerator at CIAE

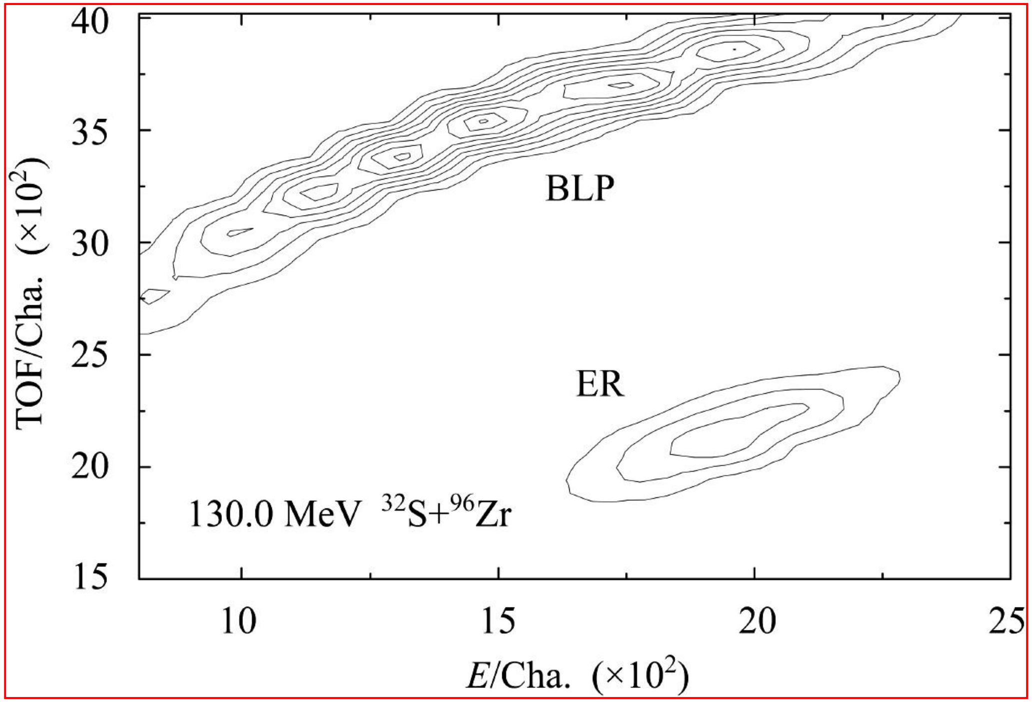
- Separation:
  electrical rigidity $\eta = E/q$;
  Optimal high voltage;
- Identification:
  TOF-E (MCP + QSD);
- Angular distribution;
- Transmission efficiency.

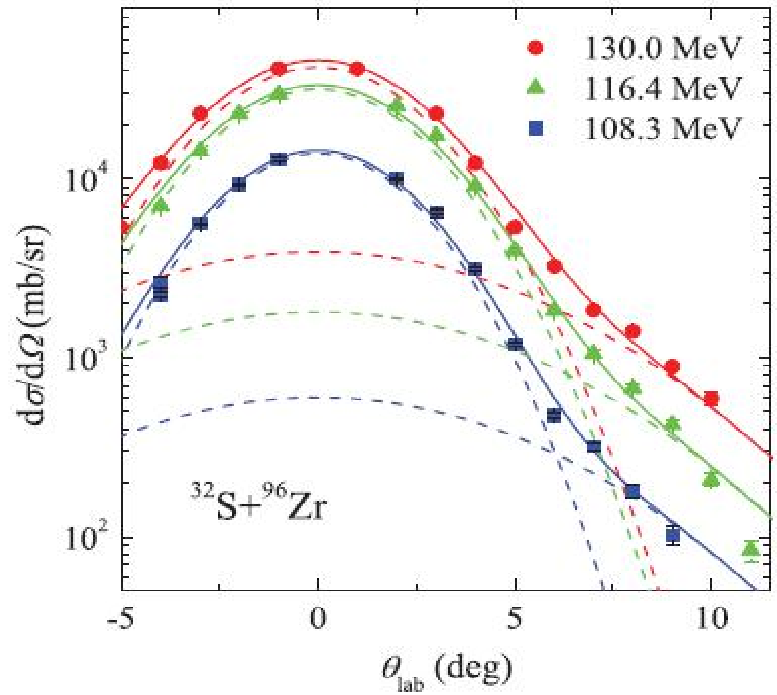


- Beam: ^{16,18}O, 2-20 pnA, 31.8 – 60.0 MeV, energy step 2.4/1.2/0.6 MeV.
- Target: ^{58}Ni, 99.80% isotope enrichment, thin, C backing.
- Beam monitors: 4 Si detectors at $\theta_{lab.} = 17°$.

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

Experimental study for *n* transfer (pickup/stripping) effect on fusion





pickup

System	+1n	+2n	+3n	+4n
$^{32}S + ^{90}Zr$	-3.33	-1.23	-6.59	-6.32
$^{32}S + ^{94}Zr$	+0.42	+5.10	+3.45	+6.15
$^{32}S + ^{96}Zr$	+0.79	+5.74	+4.50	+7.66

stripping

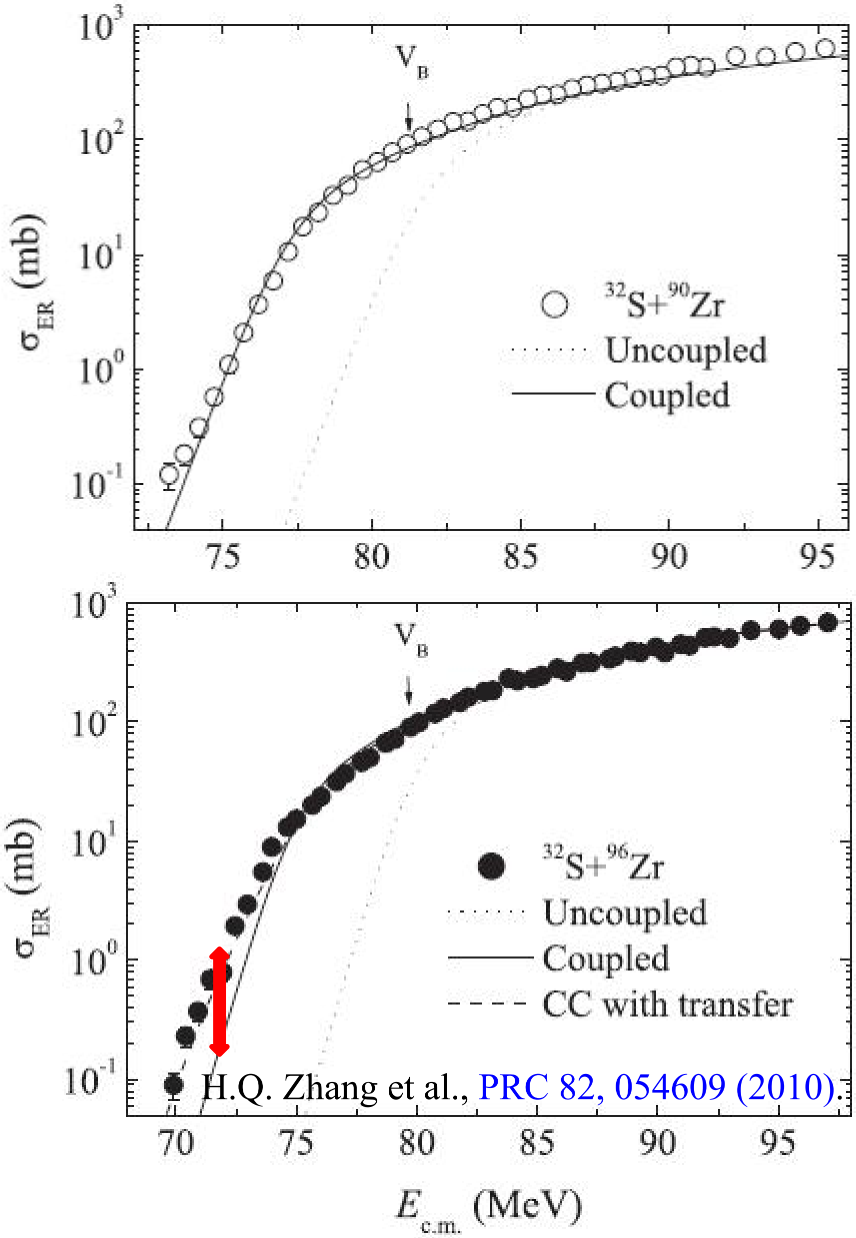
$^{16}O + ^{76}Ge$

$^{18}O + ^{74}Ge$ Q_{-2n} = +**3.75** MeV

System	-1n	-2n	-3n	-4n	V_B
$^{18}O + ^{50}Cr$	+1.22	**+9.11**	+1.39	-2.12	27.19
$^{18}O + ^{52}Cr$	-0.10	**+5.47**	-3.95	-8.92	26.98
$^{18}O + ^{58}Ni$	+0.96	**+8.20**	+0.36	-2.27	31.21

Experimental result

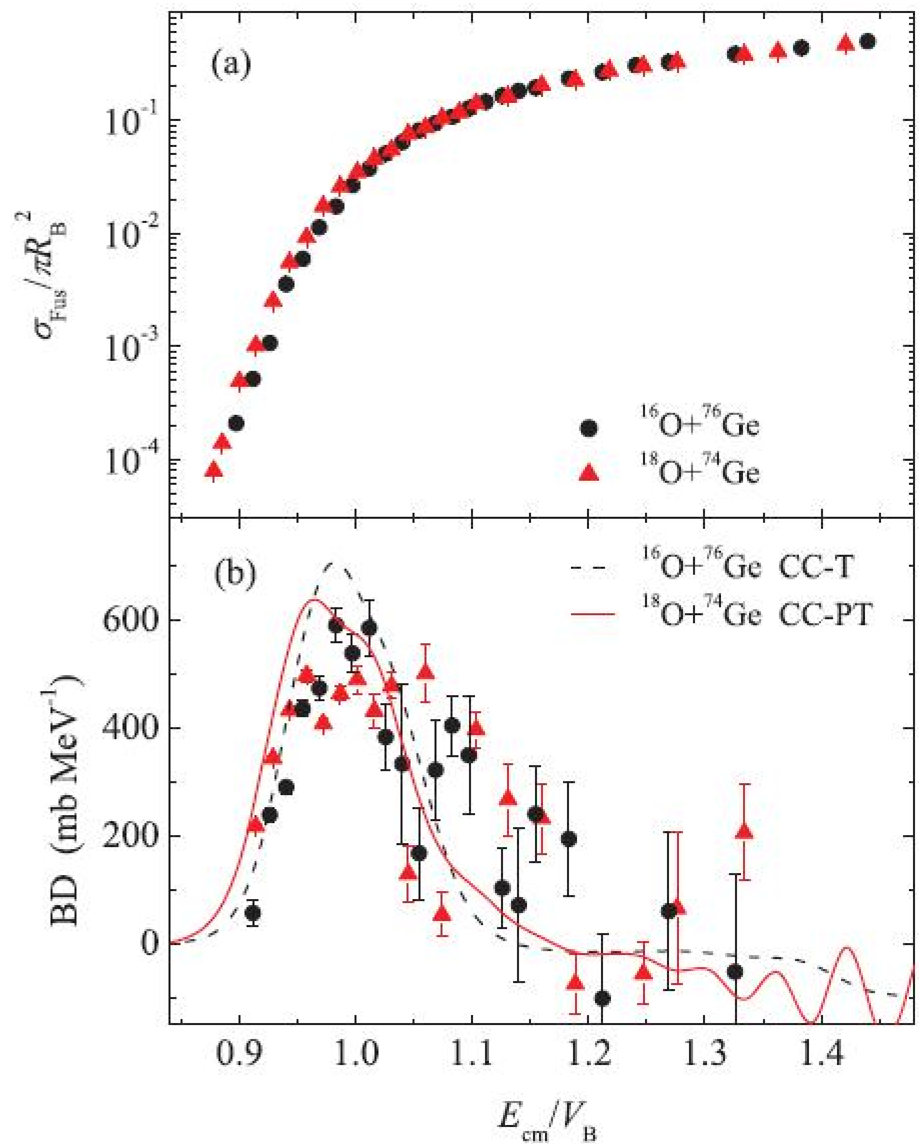
pickup



H.Q. Zhang et al., PRC 82, 054609 (2010).

Experimental result

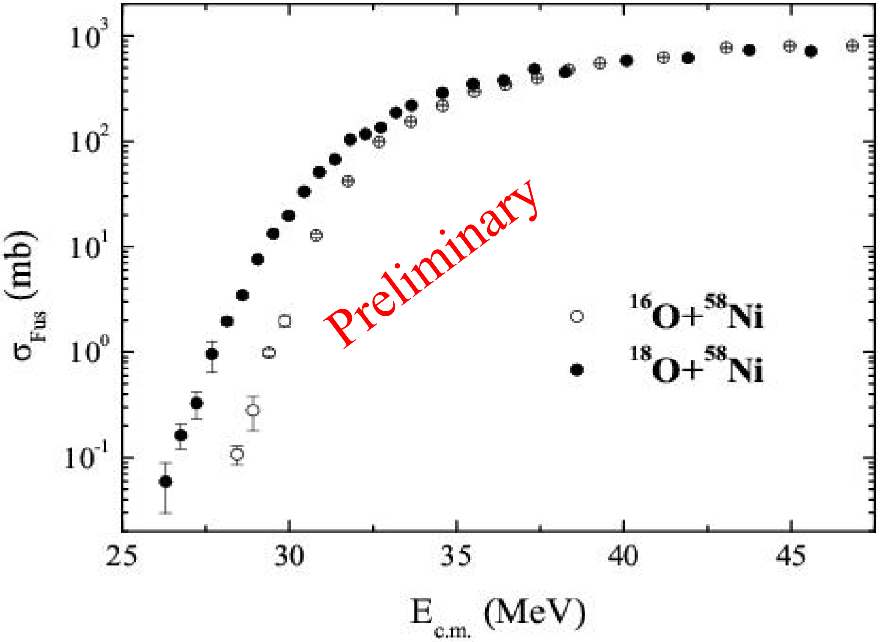
stripping

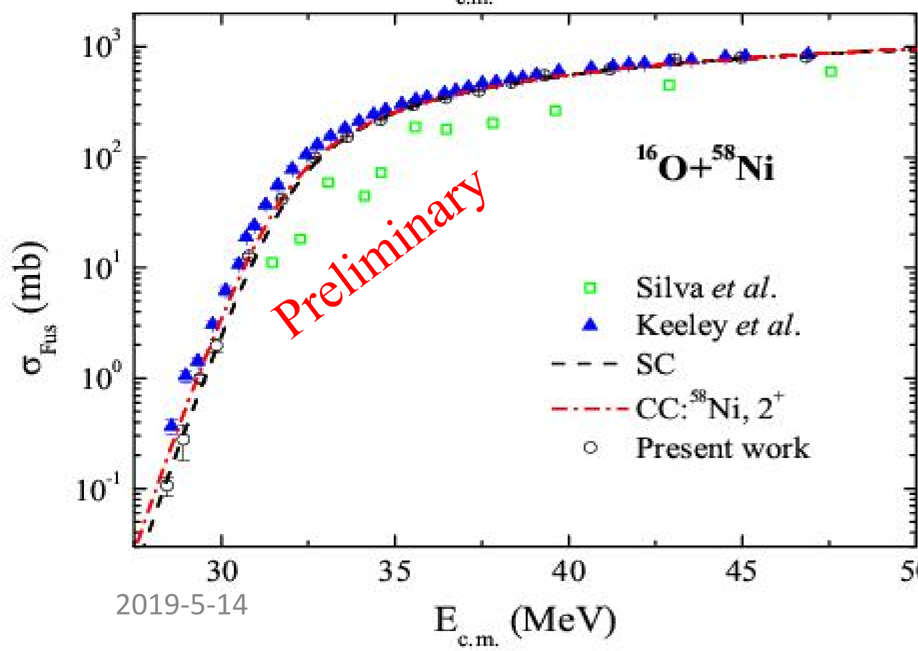


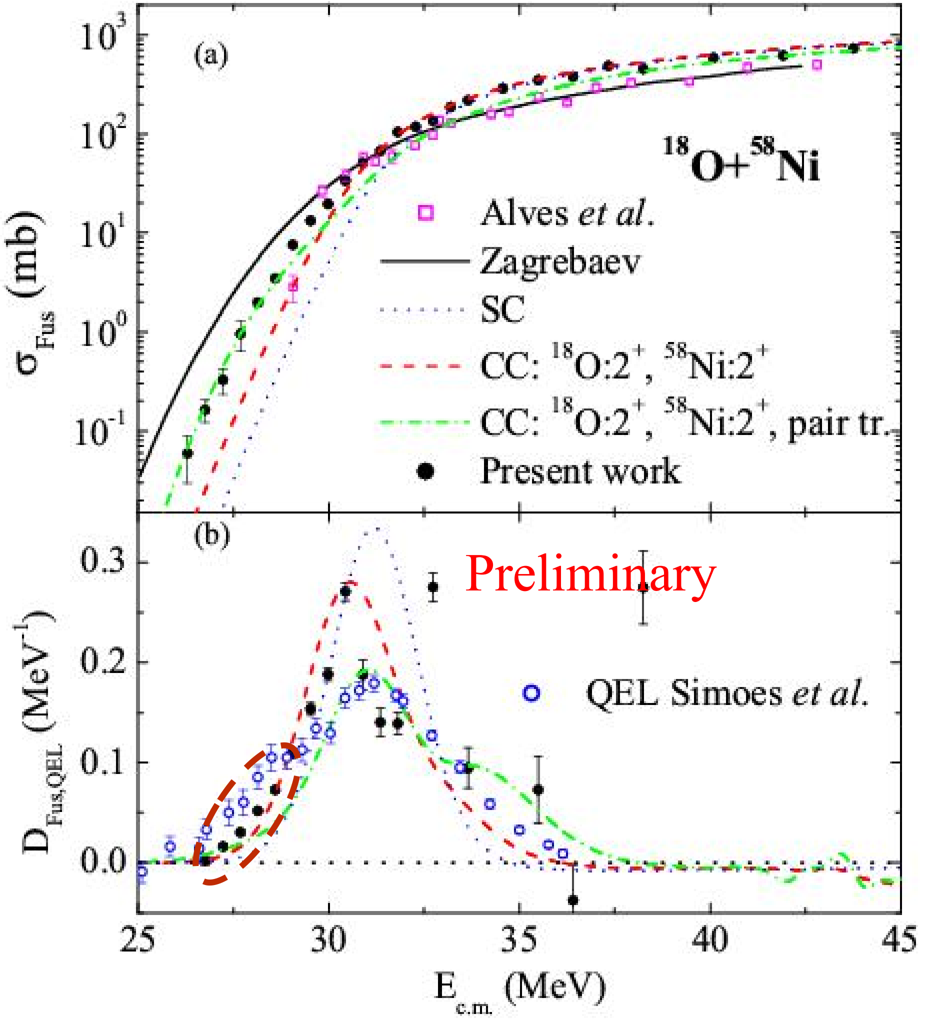
H.M. Jia et al., PRC 86, 044621 (2012).

Experimental result

stripping







- Only **modest enhancement** (if exists) for the system with positive Q_{tr}-value $2n$-stipping channel, compared to the pickup channel (considering its high Q_{tr} and high Q_{tr}/V_B).
- …the possible difference between D^{Fus} and D^{QEL} (information for coupling form factor)?

A self-consistent RE Analysis (to reduce the data)

Here 'self-consisitent' means 'the effect of excitation states is 'calibrated' by the experimental data'.

RE definition:

Residual enhancement (RE) (except the main inelastic coupling effect)

$$\mathrm{RE} = \sigma_{\mathrm{Exp}}/\sigma_{\mathrm{CC}}$$

Benchmark: RE ~ 1 for the reference systems without expected PQNT effect (to 'calibrate' the effect of collective excitations).

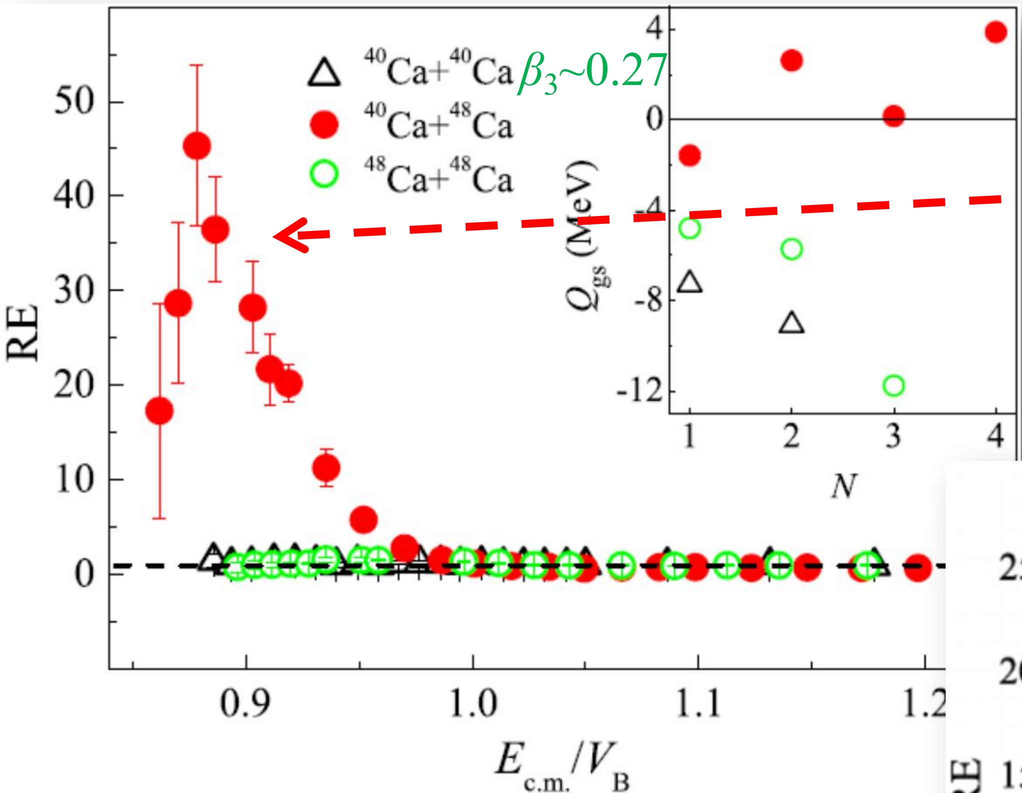
Experimental consderation: some fusion data are inconsistent → choose the data set from the same setup.

Theoretical consideration: different models (parameters) give different explanations → to use the CCFULL code – 'the coupling effect to the main inelastic can be well described').

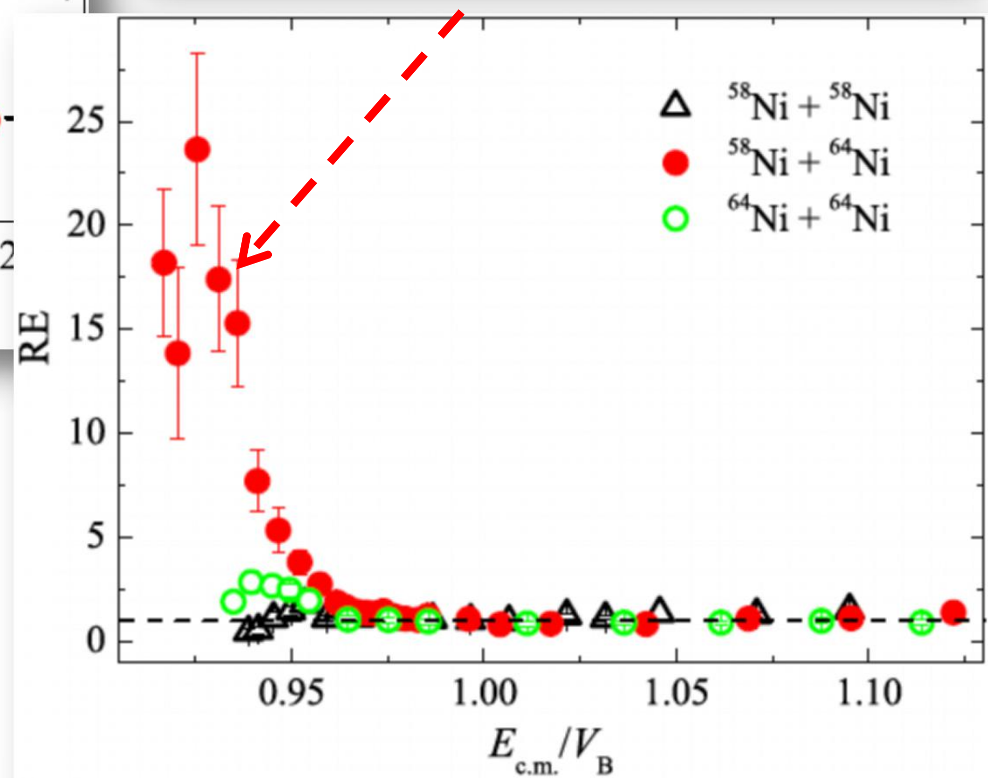
- …bare Akyüz-Winther energy-independent potential;
- ...coupled-channels effect due to collective excitations.

H.M.J.et al., PLB **755**, 43 (2016).

A self-consistent RE Analysis (to reduce the data)



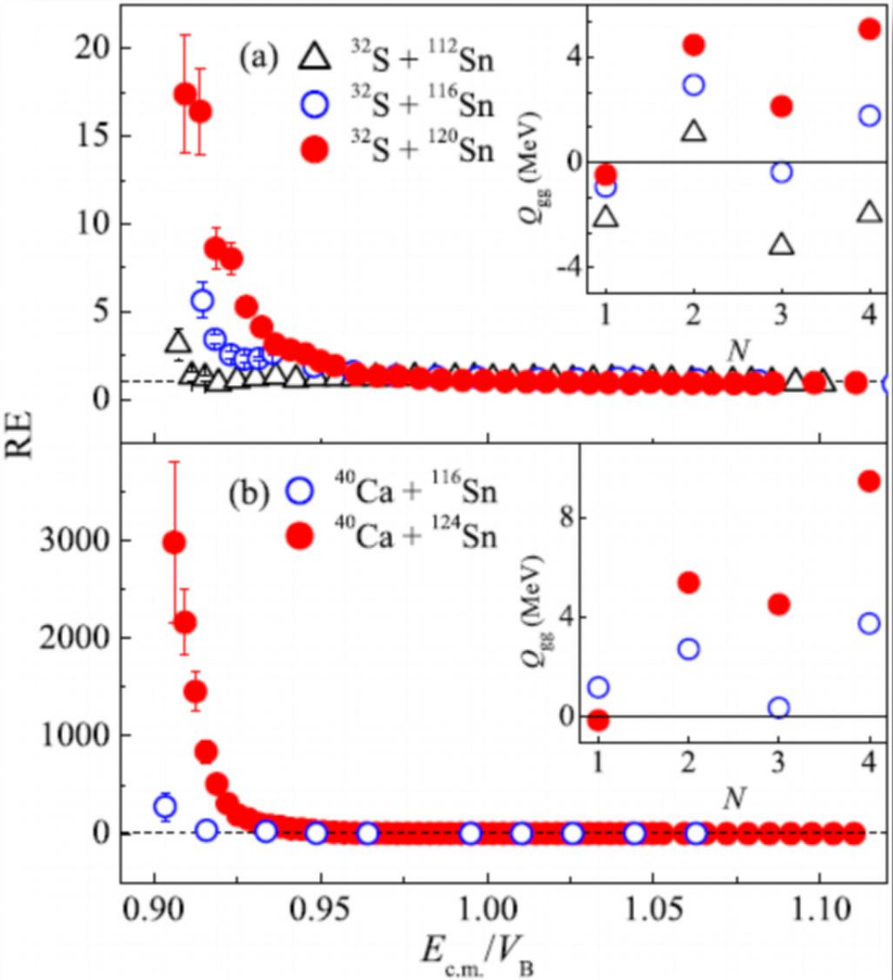
System	Q_{+1n}	Q_{+2n}	Q_{+3n}	Q_{+4n}
^{40}Ca + ^{40}Ca	-7.28	-9.09	-18.12	-21.78
^{40}Ca + ^{48}Ca	-1.58	2.62	0.16	3.88
^{48}Ca + ^{48}Ca	-4.80	-5.72	-11.76	-14.45
^{58}Ni + ^{58}Ni	-3.22	-2.08	-10.90	-14.50
^{58}Ni + ^{64}Ni	-0.66	3.89	1.11	3.89
^{64}Ni + ^{64}Ni	-3.56	-1.45	-6.23	-6.26

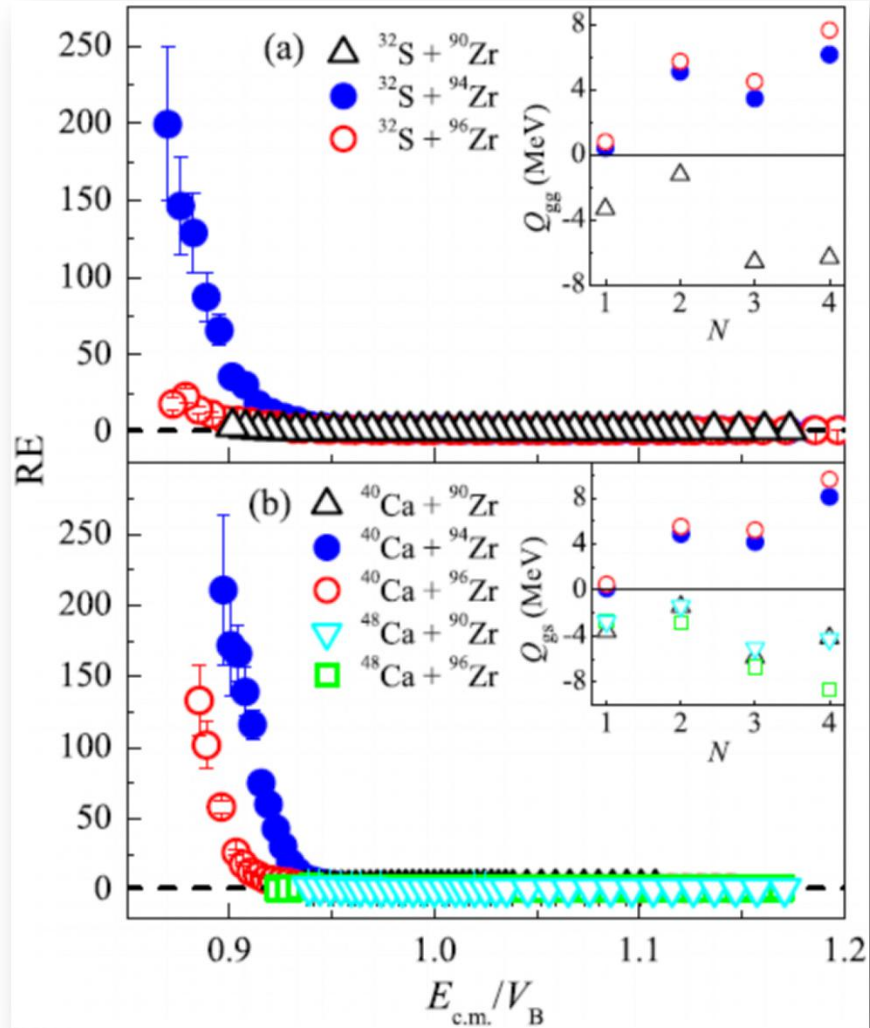


…really shows correlation with Q_{gs}-values.

H.M.J.et al., PLB **755**, 43 (2016).

A self-consistent RE Analysis (to reduce the data)





…agree with the argument of no direct correlation between RE and Q_{tr}-values.

H.M.J.et al., PLB **755**, 43 (2016).

Discussion:
something still need to calrify for collective excitation?

1. ...the effect of 3_1^- state of ^{40}Ca in fusion? (the response of the extraced structral inofrmation with its effect in fusion?)

... a reduced β_3~0.27 as for the system of ^{40}Ca+^{90}Zr [NPA 633, 421 (1998)] (~60% of 0.43)....

2. …still lack of a benchmark for the coupling effect of the collective excitation states of ^{94}Zr.

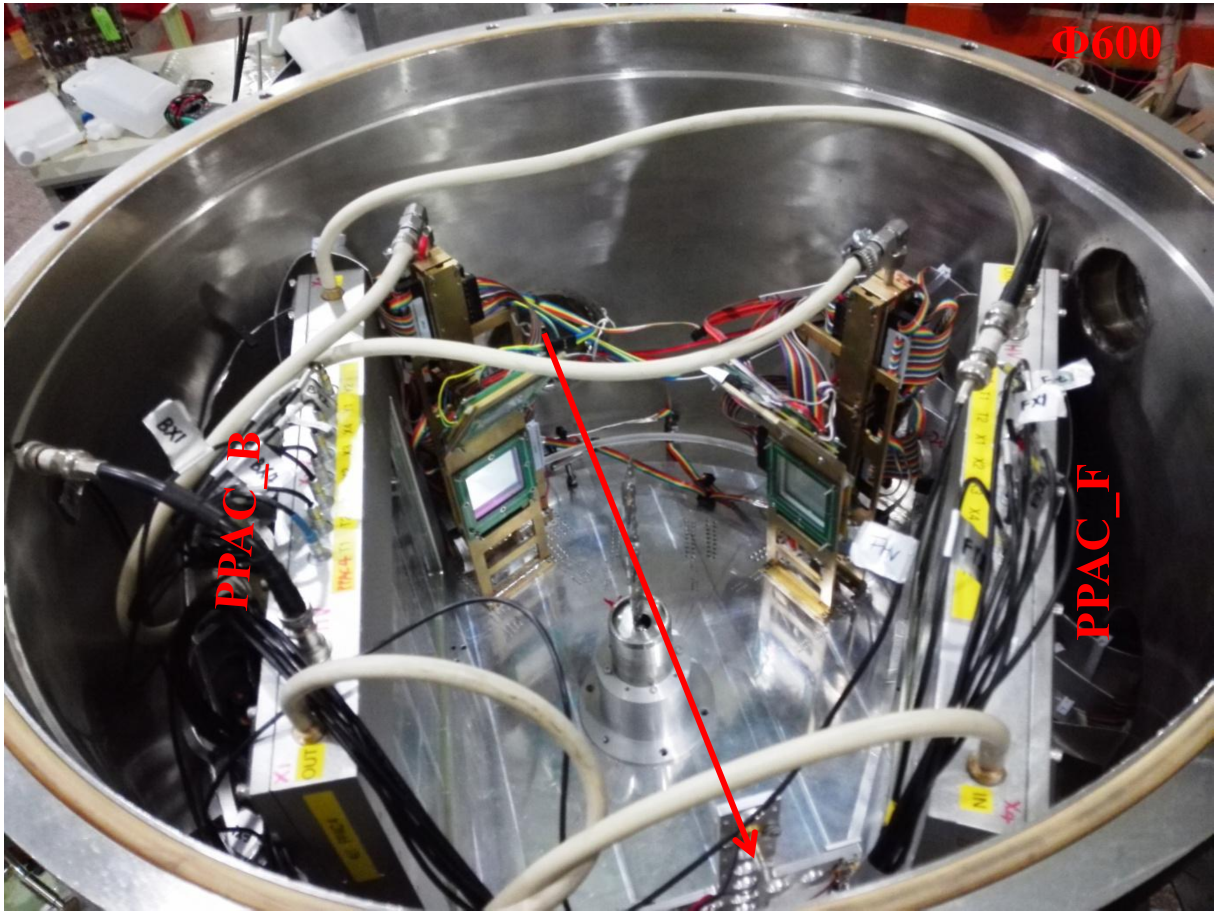
..need to 'calibrate' the effect of inelastic collective state of ^{94}Zr.

Do we really know the effect of (higher energy) collective excitation states in fusion as well as usually claimed?

The recent experiment for ^{18}O,^{7}Li+^{238}U reaction mechanism

- MNT transfer mechanism
- Tr/ICFfor weakly-bound projectile

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



→^{18}O: 93.5 MeV

→^{7}Li: 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

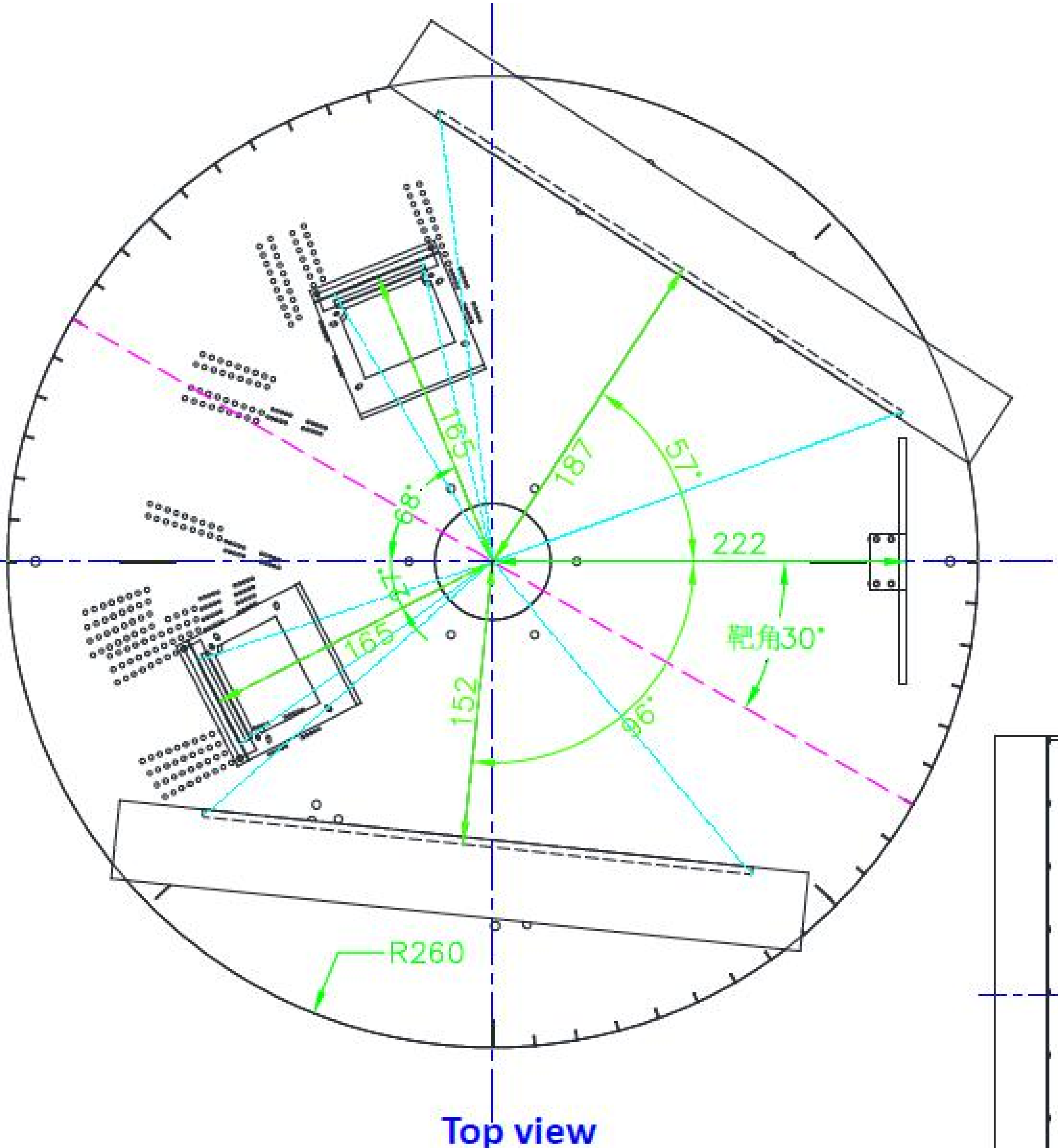
…by using the correlation measurement of the fission fragment of target-like nucleus with ^{4}He.

→ **PPAC**:

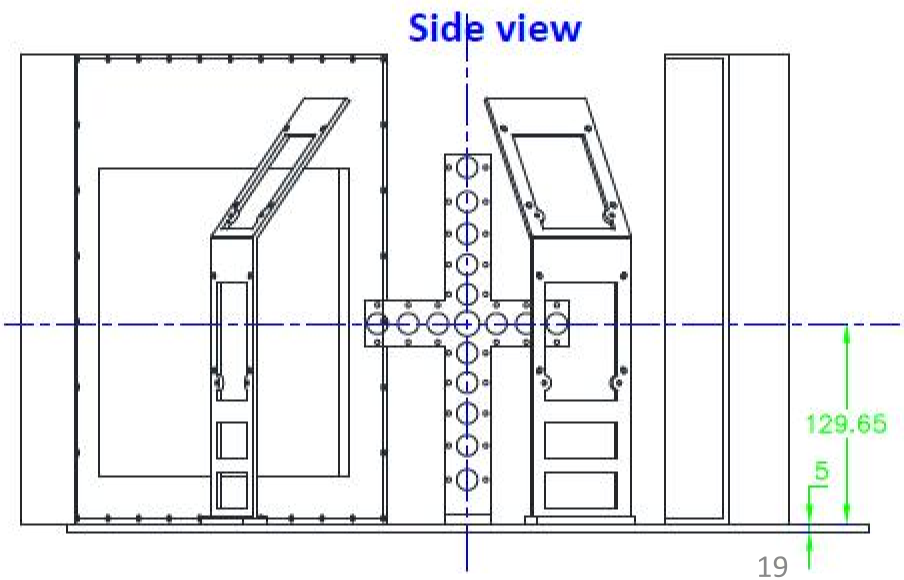
isobutane, 4.07 Torr, -530 V

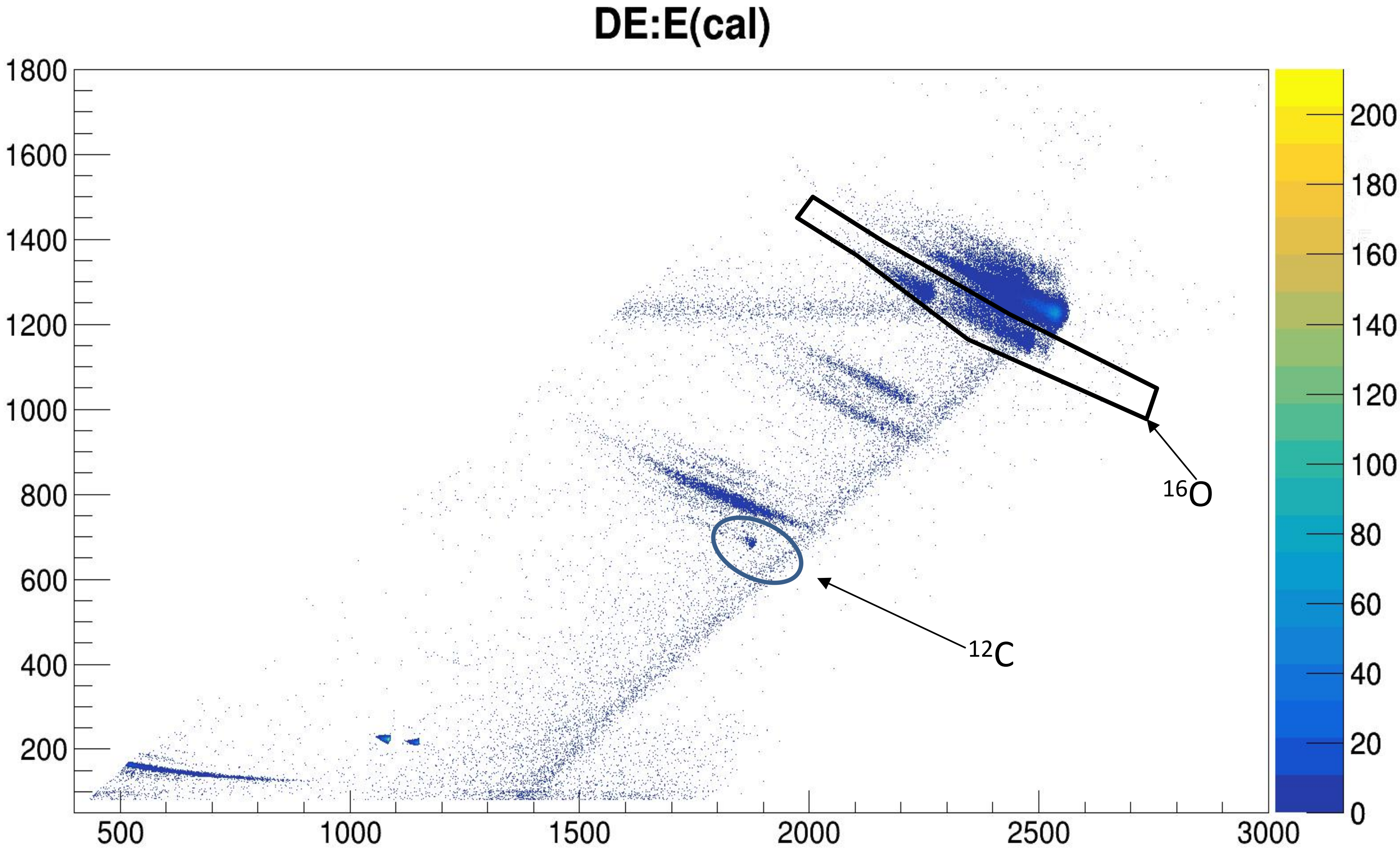
(…insensitive to ^{7}Li)

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

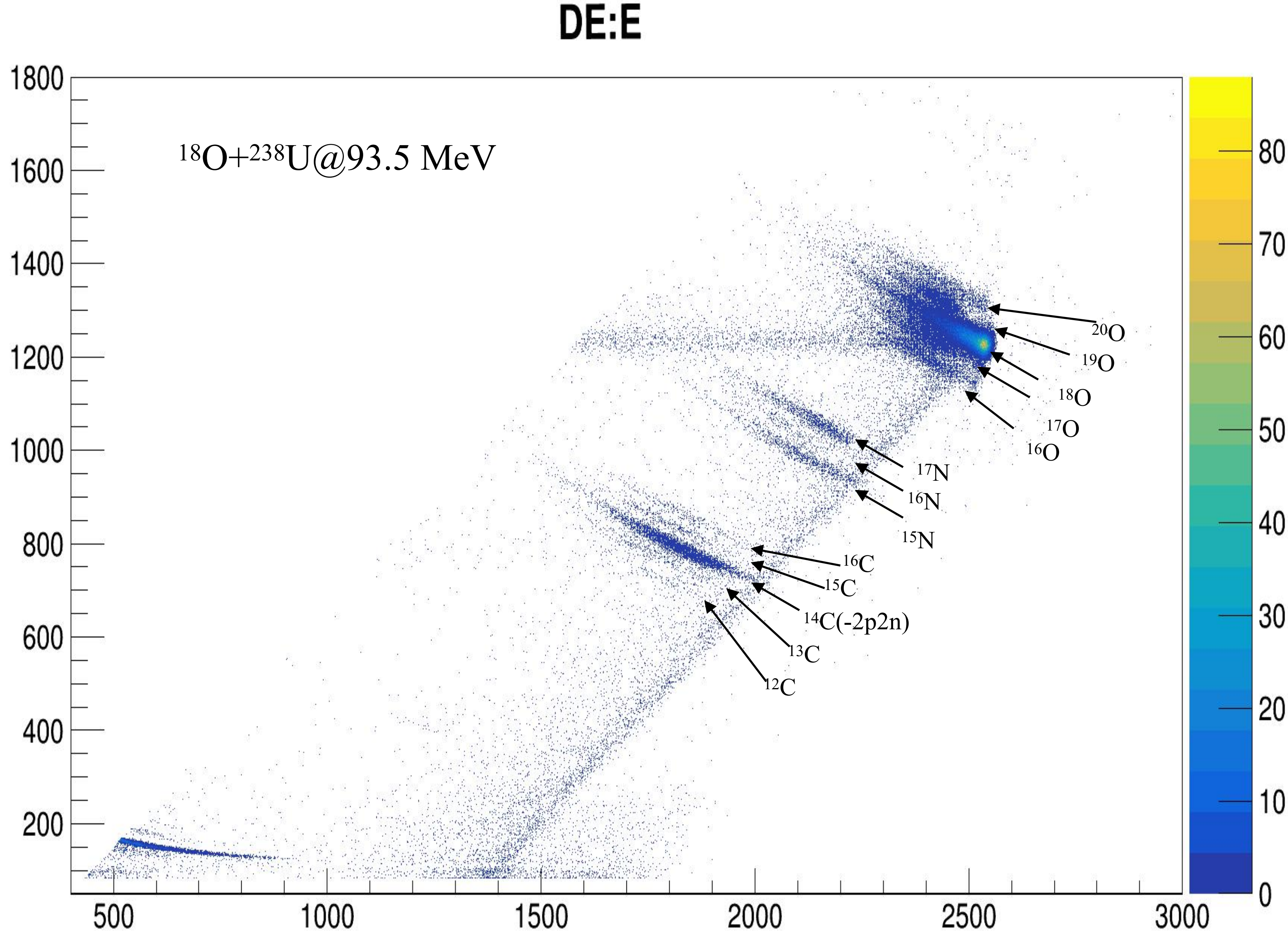


- **2 PPACs:** Fission fragment
- **4 Telescopes:** (112° & 153°)
  20 μm SSSD +
  300 μm SSSD/QSD +
  1000 – 1500 μm QSD
  Fiss. + Trans. + Eva.
- **4 Monitors:** PIN-diodes
  ± 15° (L&R), ϕ.5 mm, 3.8 pps;
  ±20° (U&D), ϕ1 mm, 4.9 pps.





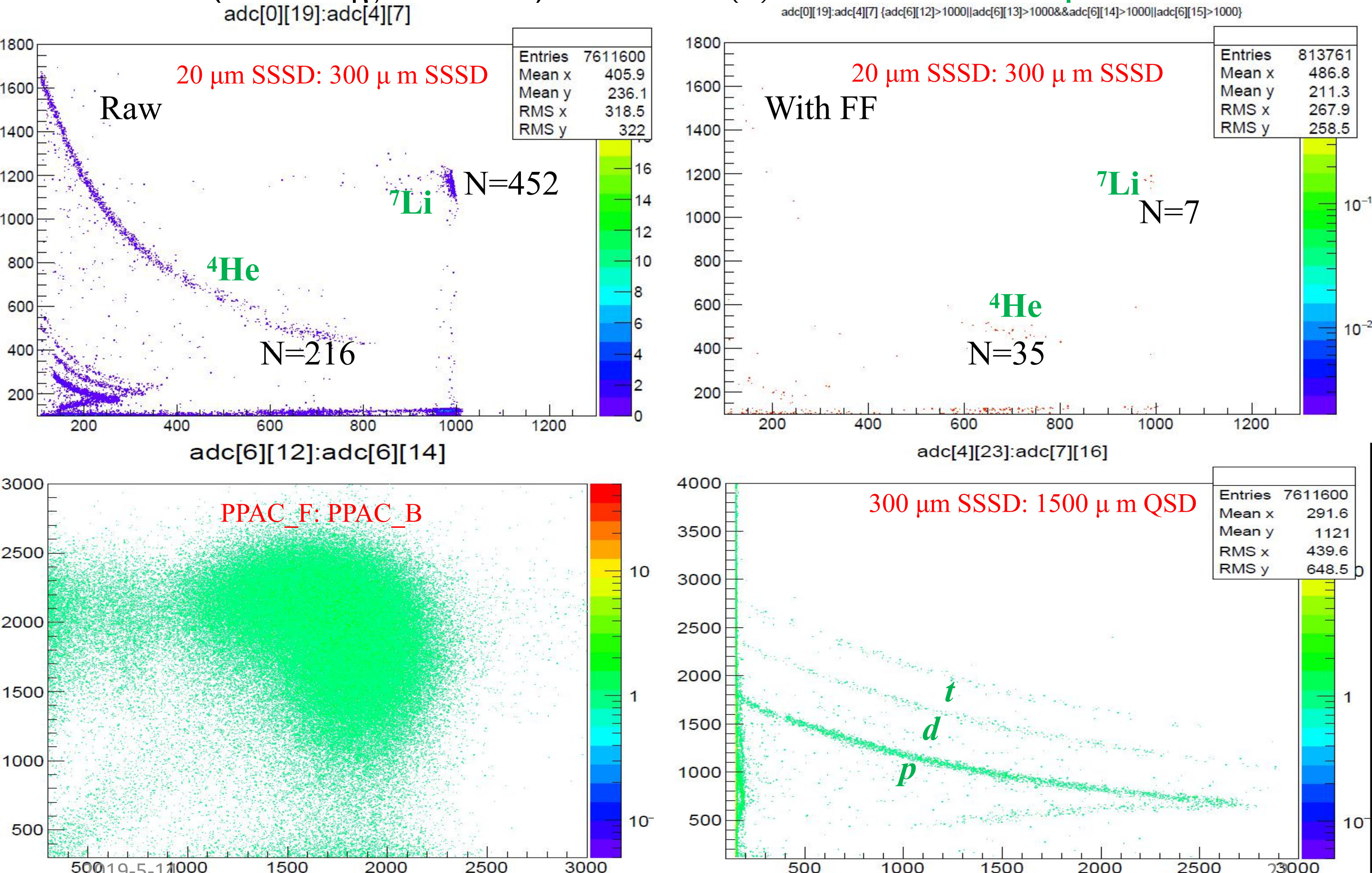
- ...calibrate the isotopes by using the low-energy elastic scattering



- Strong ^{14}C…similar with $^{18}O+^{208}Pb$ in D.C. Rafferty et al., PRC 94, 024608 (2016).
- For transfer mechanism: measured final products → primary transfer products?

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

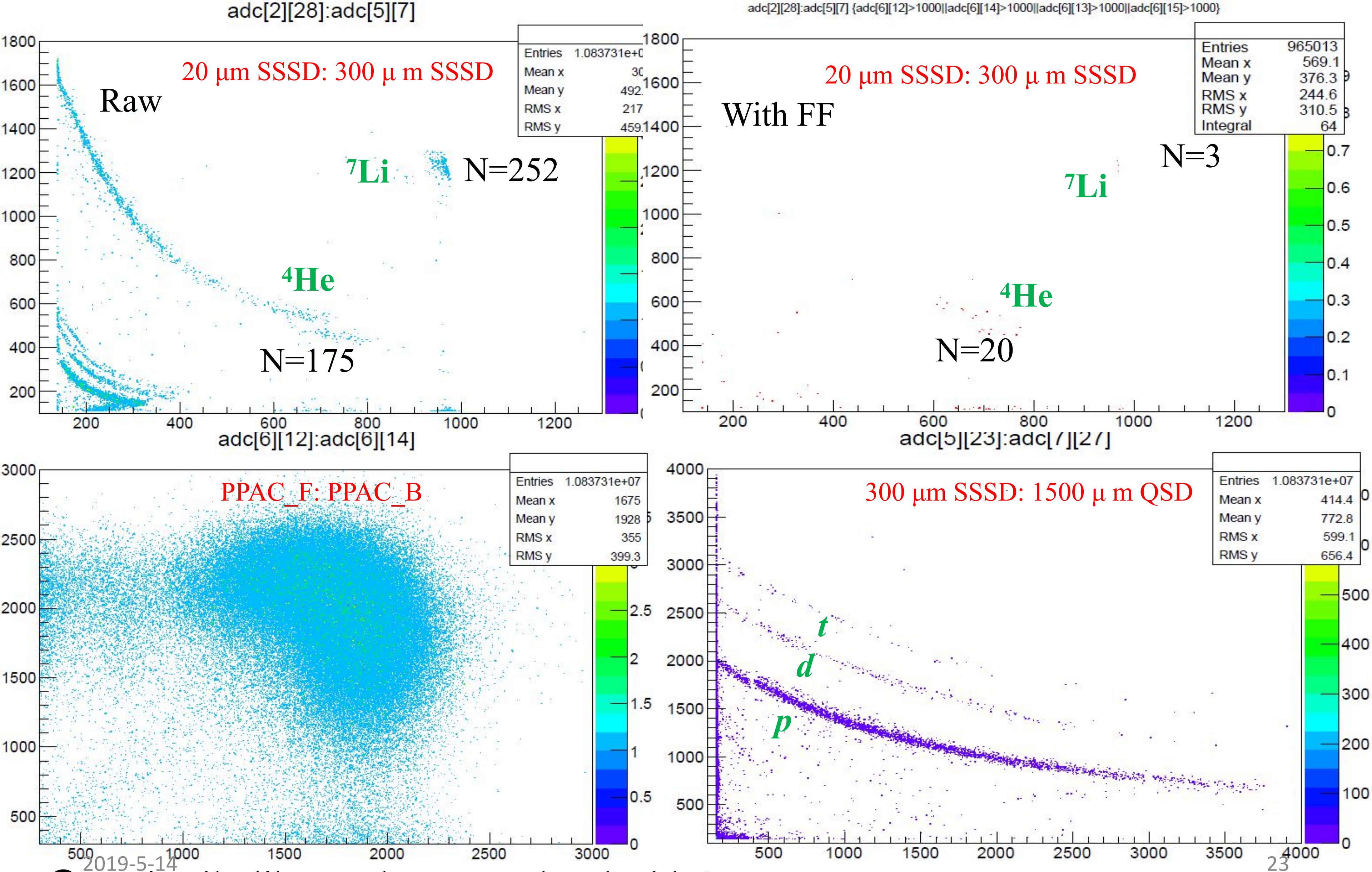
37.0 MeV (1.10 V_B, 390 mb) ^{7}Li+^{238}U @Rn0381 some spectra



- Projectile-like products correlated with 2FFs

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



- Projectile-like products correlated with 2FFs

Summary / Conclusion

- The experimental fusion excitation functions show different correlations with positive Q-value neutron transfer channels.

...2n-stripping channel shows only modest sub-barrier fusion enhancement compared with the corresponding xn-pickup channels.

- A self-consistent systematic analysis was proposed to reduce the calculation uncertainties, based on CCFULL code and really provides a further reliable proof for the occurrence of the PQNT effect.

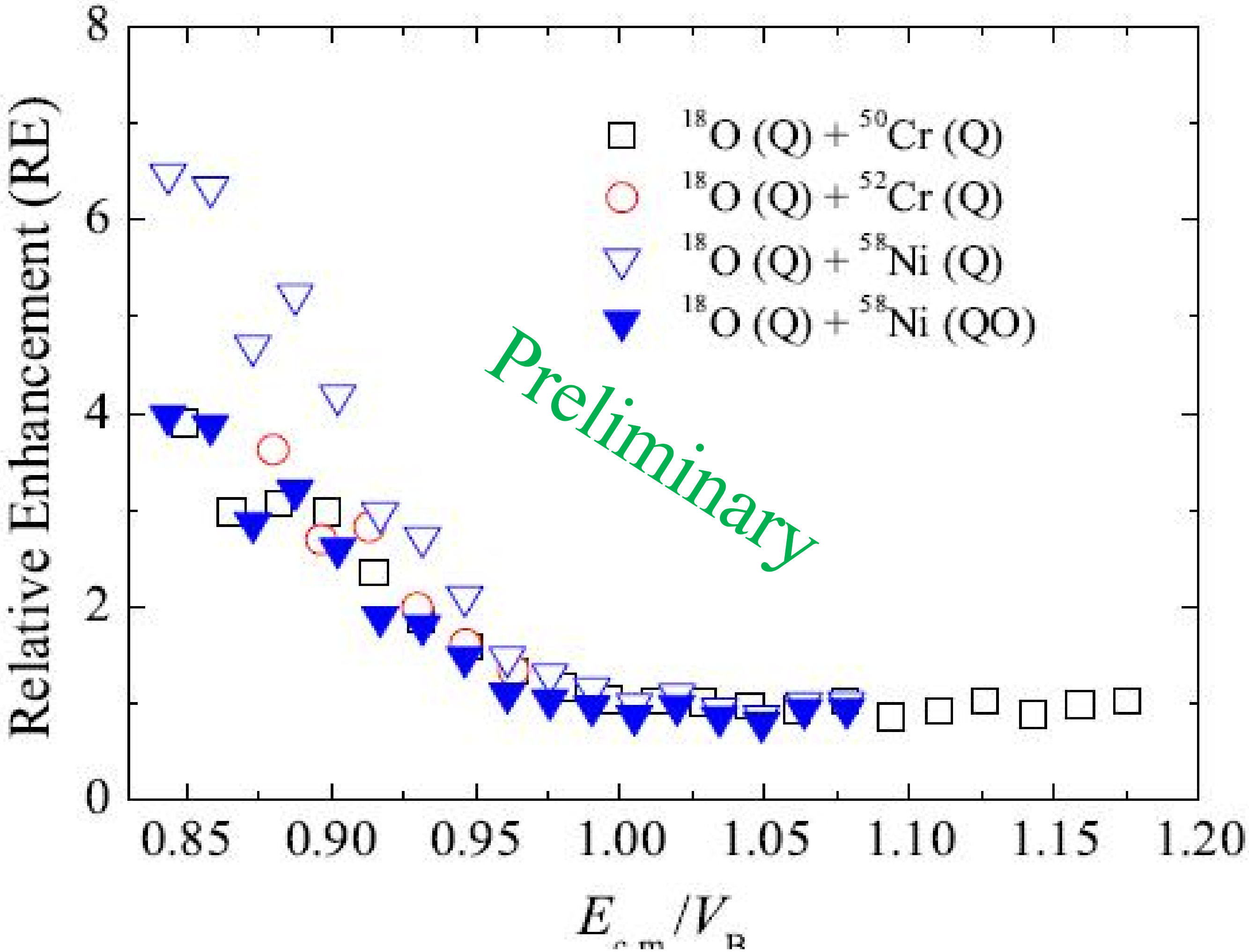
...gives a visualized sub-barrier fusion enhancement excluding the inelastic coupling effect.

...also shows a complex correlation of the enhancement effect with the positive Q-value neutron-transfer channels.

- Strong ^{14}C emerges for near-barrier $^{18}O+^{238}U$.

Substantial direct ^{4}He, which is correlated with FFs, emerges for near-barrier $^{7}Li+^{238}U$ by using a coincident measurement.

Thanks for your attention!


Relative Enhancement (RE)
$E_{c.m.}/V_B$
^{18}O (Q) + ^{50}Cr (Q)
^{18}O (Q) + ^{52}Cr (Q)
^{18}O (Q) + ^{58}Ni (Q)
^{18}O (Q) + ^{58}Ni (QO)
Preliminary
0
2
4
6
8
0.85
0.90
0.95
1.00
1.05
1.10
1.15
1.20