中国原子能科学研究院
中核集团 CHINA INSTITUTE OF ATOMIC ENERGY

Experimental Research on the Reactions and Decays of Exotic Nuclei

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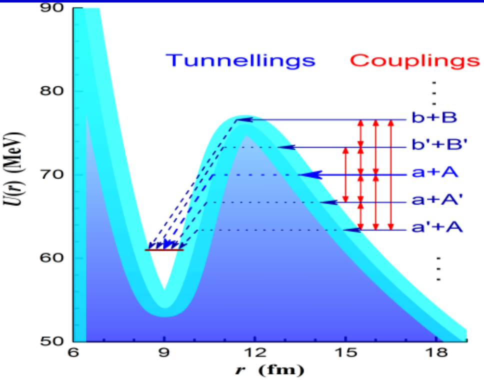
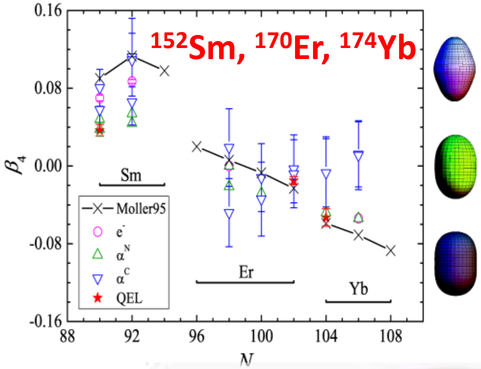
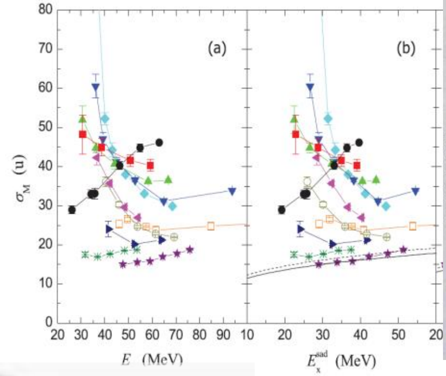
"Nuclear Fission and Structure of Exotic Nuclei"
Japan Atomic Energy Agency, Tokai, Japan, 25-27 March 2019

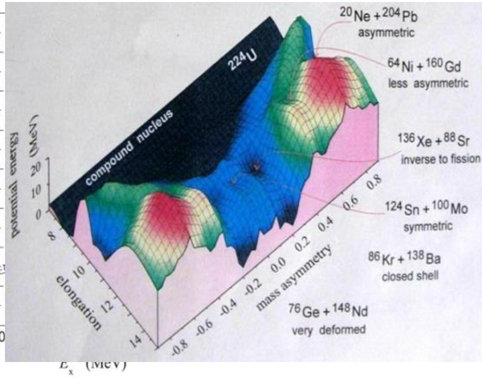


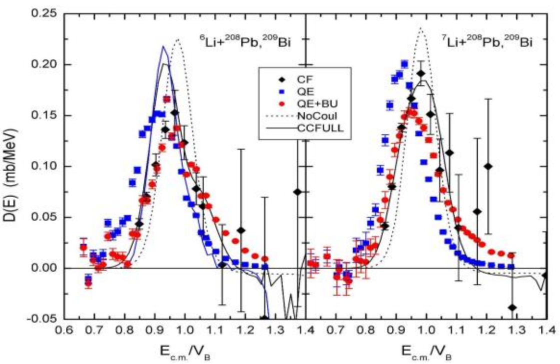
Research Activities in NRG

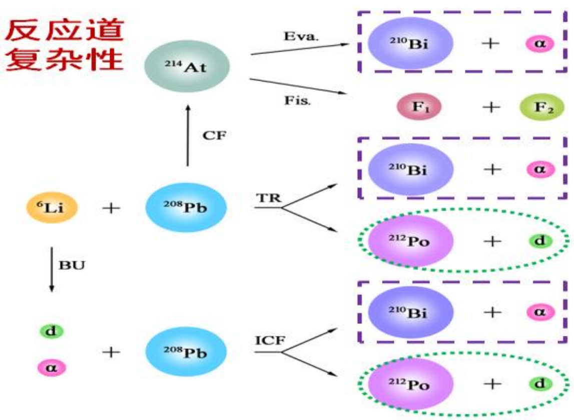


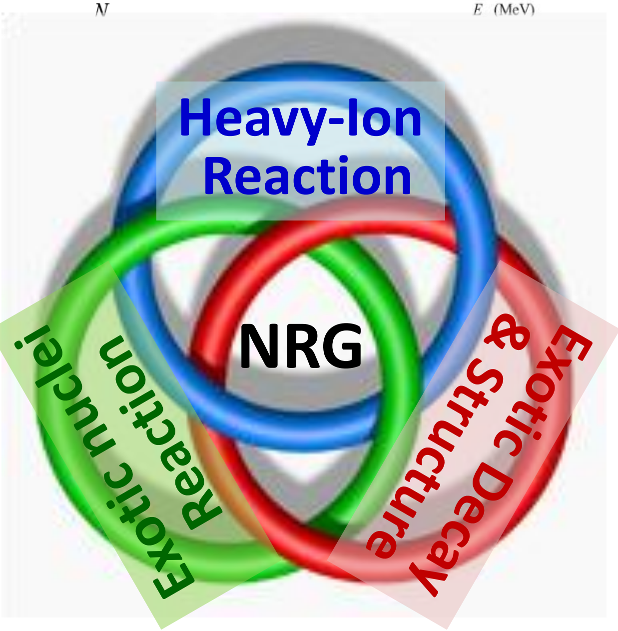


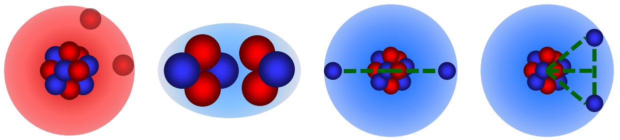


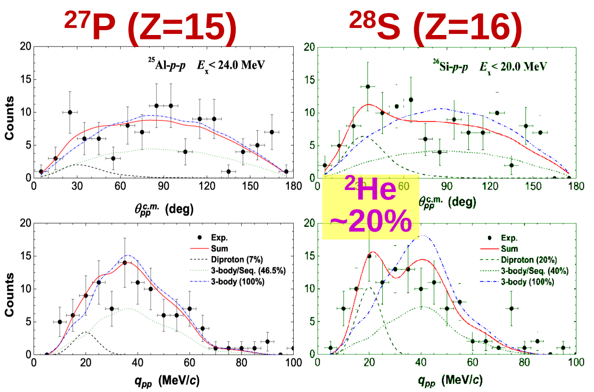


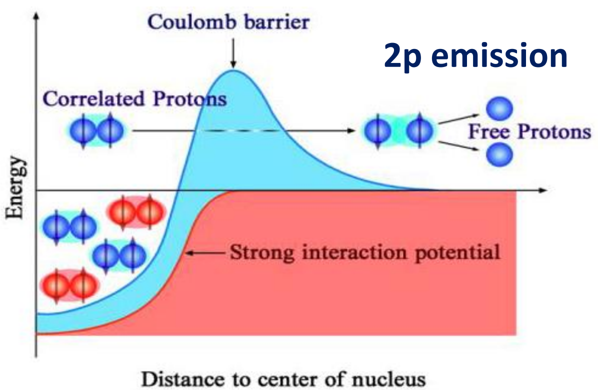












Topics

1. Potentials of exotic nuclear systems
2. Reactions with weakly-bound nuclei
3. 2*p* emissions from excited states
4. Decays of extremely *p*-rich nuclei

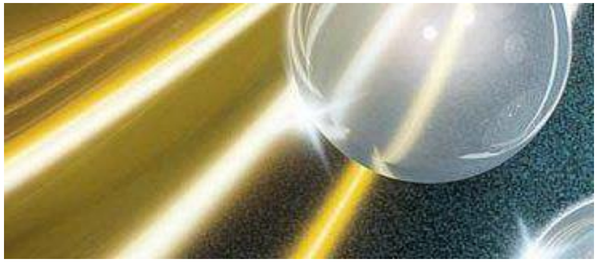
Optical Model Potential

- ♠ Optical Model is a successful model to explain the nuclear scattering and reaction, which resembles the case of light scattered by an opaque glass sphere.

Optical Model Potential (OMP):

$$U = V(r) + iW(r)$$

$V(r)$ → **attractive** $iW(r)$ → **absorptive**



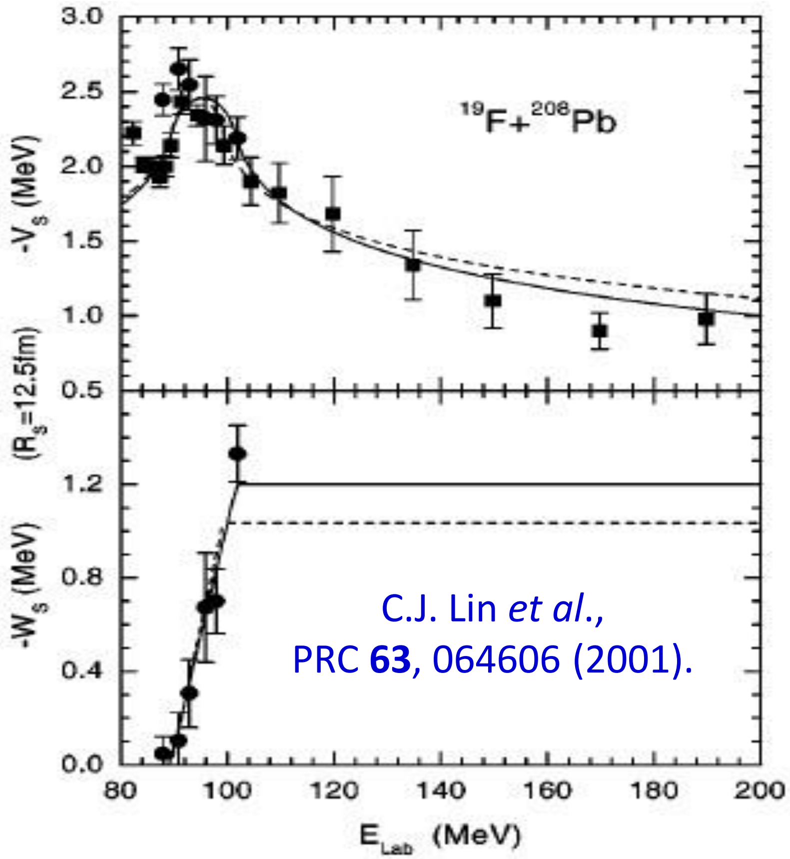
★phenomenological potential, independent on energy.

- ♠ A basic task in nuclear reaction study is to understand the nuclear interaction potential.

Cf: 1) S. Fernbach, R. Serber, and T. B. Taylor, Phys. Rev. **73**, 1352 (1949).
2) H. Feshbach, “The optical model and its justification”, Ann. Rev. Nucl. Sci. **8**, 49 (1958).

Threshold Anomaly (TA)

A universal phenomenon within the Coulomb barrier energy region



tightly-bound nuclear systems

$$U(r;E) = V(r;E) + iW(r;E)$$

$$V(r;E) = \underline{V_0(r;E)} + \underline{\Delta V(r;E)}$$

Space — Time

Nonlocality

Dynamic polarization potential:

$$\Delta V(r;E) = \frac{\mathrm{P}}{\pi}\int_0^{\infty}\frac{W(r;E')}{E'-E}dE'$$

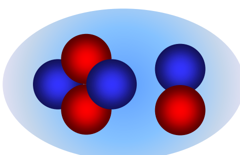
Dispersion relation
(results from the causality)

Cf: 1) M. A. Nagarajan, C. C. Mahaux, and G. R. Satchler, Phys. Rev. Lett. **54**, 1136 (1985).
2) C. Mahaux, H. Ngo, and G. R. Satchler, Nucl. Phys. **A449**, 354 (1986).
3) G. R. Satchler, Phys. Rep. **199**, 147 (1991).

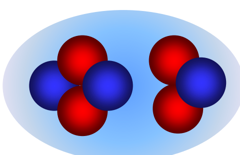
Abnormal TA: weakly-bound nuclei

- Exotic nuclei: weakly-bound & having specified structures (cluster, halo/skin)
- Reactions: easily breakup, strongly coupling to continuum, complex mechanisms

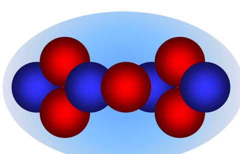
cluster



^{6}Li (α+d)
S_α = 1.47 MeV

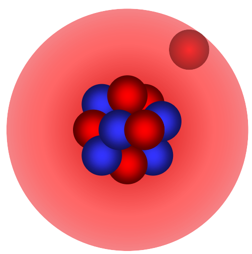


^{7}Li (α+t)
S_α = 2.47 MeV

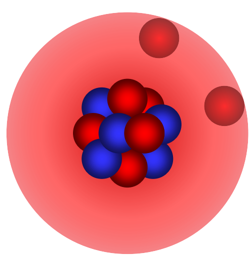


^{9}Be (α+n+α)
S_n = 1.66 MeV

halo

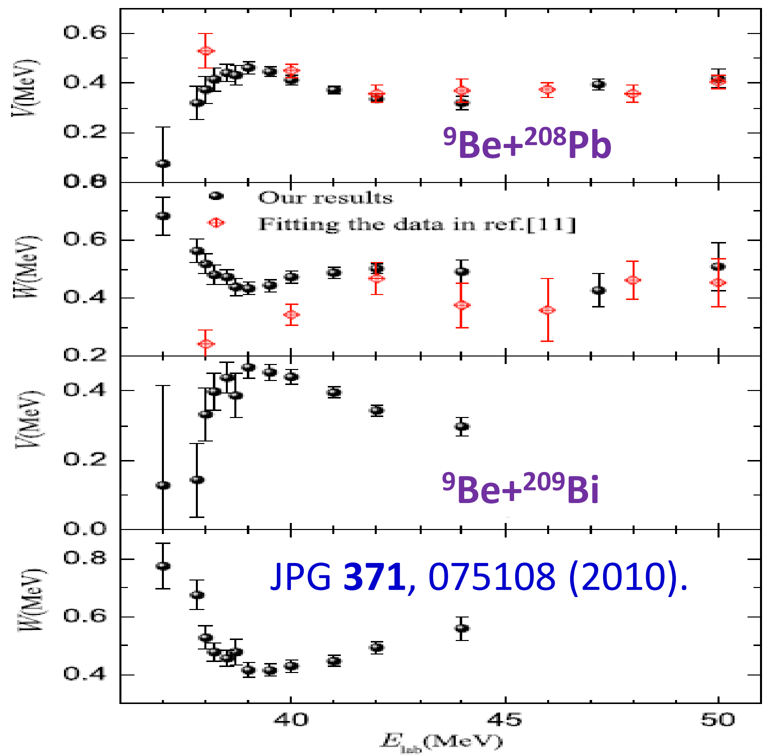


^{11}Be (^{10}Be+n)
S_n = 0.50 MeV



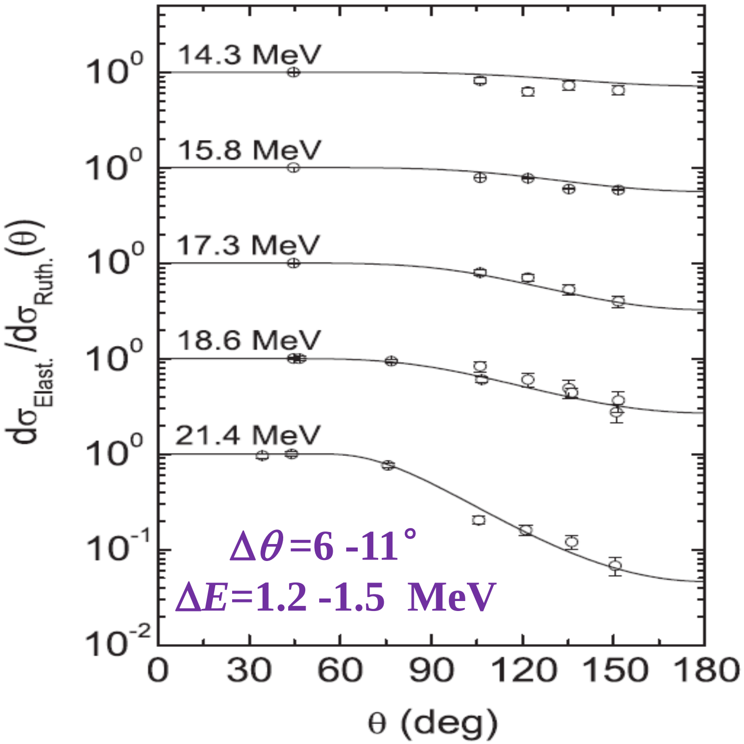
^{6}He (α+2n)
S_{2n} = 0.98 MeV

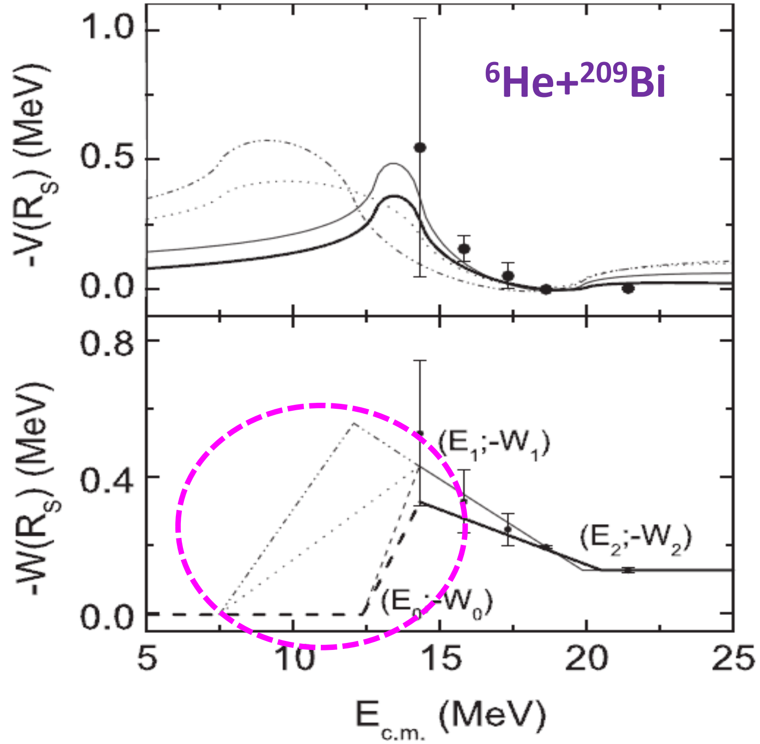
Abnormal Threshold Anomaly



Abnormal TA: unstable nuclei

OMPs are usually extracted from the elastic scattering.

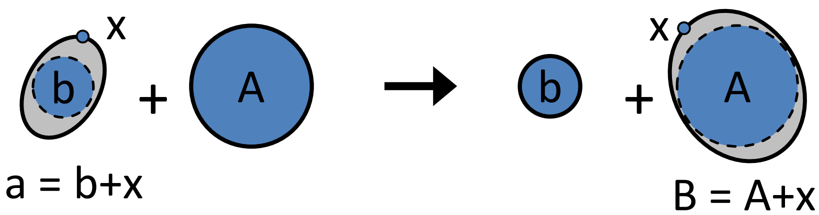




★ Rather difficult to extract an effective OMP at low energies.

Cf: 1) E.F. Aguilera *et al*., PRL **84**, 5058 (2000); PRC **63**, 061603R (2001).
2) A. R. Garcia *et al*., Phys. Rev. C **76**, 067603 (2007).

Transfer Method



$$\left(\frac{d\sigma}{d\Omega}\right)_{if} = P_{if}\left(\left(\frac{d\sigma}{d\Omega}\right)_{ii}\cdot\left(\frac{d\sigma}{d\Omega}\right)_{ff}\right)^{1/2}$$

Transfer reaction A(a,b)B

elastic scatting cross sections

Transition amplitude: $T = J\int d^3r_b \int d^3r_a \chi^{(-)}(\vec{\mathbf{k}}_\mathbf{f}, \vec{\mathbf{r}}_\mathbf{b})^* \left\langle bB|V|aA\right\rangle \chi^{(+)}(\vec{\mathbf{k}}_\mathbf{i}, \vec{\mathbf{r}}_\mathbf{a}),$

4 wave functions are needed,

♣ two bound states: b+x & A+x (single-particle potential model)

♣ two scattering states: incoming & outgoing (optical potentials)

Proposed: C. J. Lin et al., AIP Conf. Proc. **853**, 81 (2006), presented at the FUSION06.

^{16}O(^{14}N,^{13}C)^{17}F: Chin. Phys. Lett. **25**, 4237 (2008).

^{11}B(^{7}Li,^{6}He)^{12}C: Chin. Phys. Lett. **26**, 022503 (2009). Phys. Rev. C **87**, 047601 (2013).

^{208}Pb(^{7}Li,^{6}He)^{209}Bi: Phys. Rev. C **89**, 044615 (2014), Il Nuovo Cimento C **39**, 367 (2016), Chin. Phys. Lett. **31**, 092401 (2014), Phys. Rev. C **96**, 044615 (2017), Phys. Rev. Lett. **119**, 042503 (2017).

^{63}Cu(^{7}Li,^{6}He)^{64}Zn: Phys. Rev. C **95**, 034616 (2017).

Experiments: $^{208}Pb(^{7}Li,^{6}He)^{209}Bi$

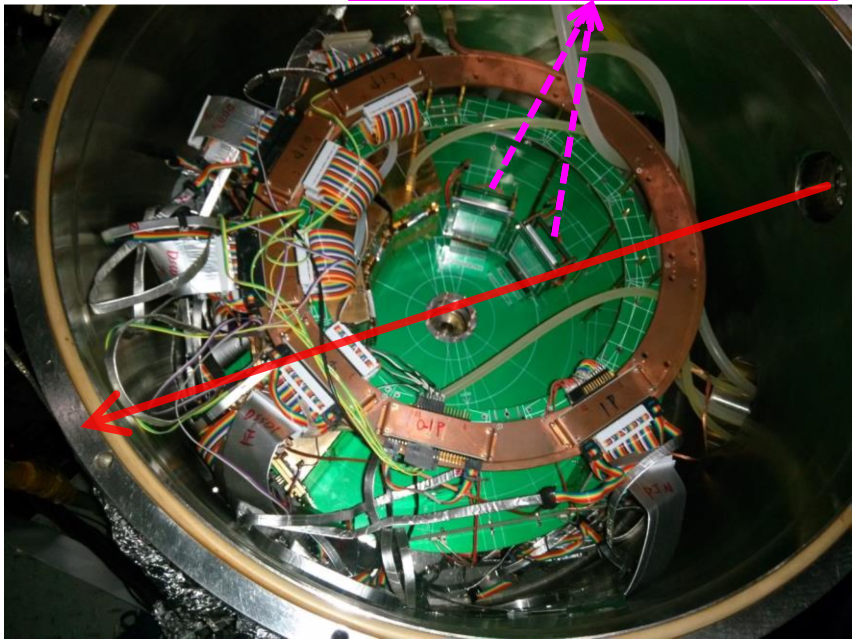
Two experiments have been done at HI-13 tandem accelerator @ CIAE

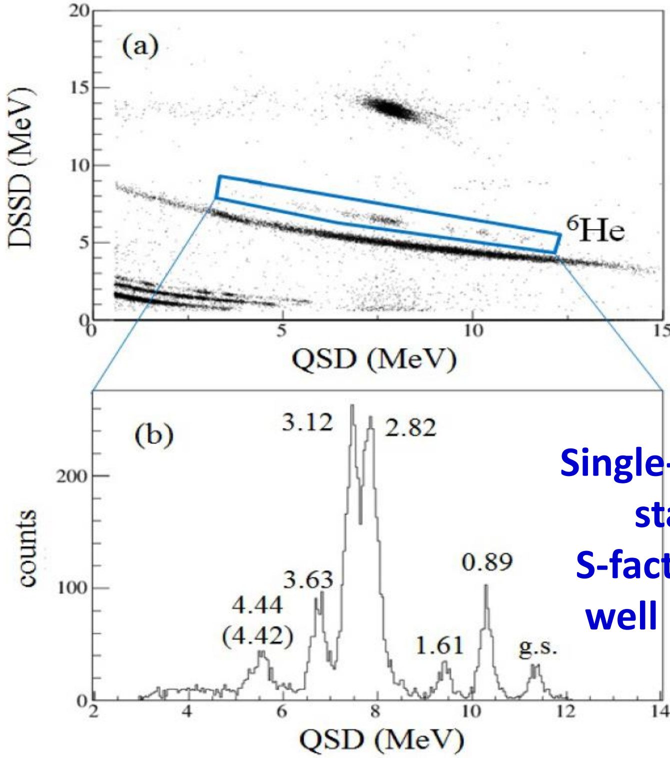
Exp1: E_{beam} = 42.55, 37.55, 32.55, **28.55**, 25.67 MeV – high energies 【2004.8】

Exp2: E_{beam} = **28.55**, 25.67, 24.3, 21.2 MeV -- low energies 【2016.4】

★Angular distributions of both **elastic** scattering and **transfer** were measured.

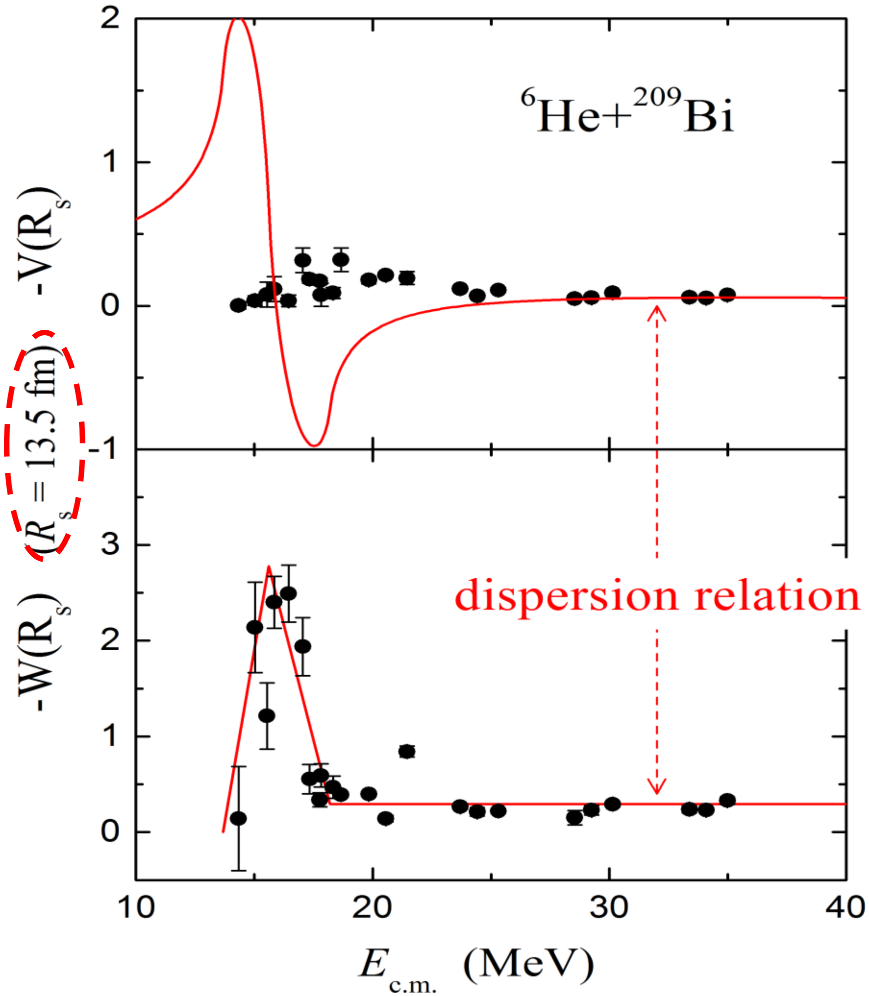
2 Telescopes: SSSD(20μm) + DSSD(60μm) + QSD(100μm)





Single-particle states
S-factors are well known

Results: OMPs of $^{6}He+^{209}Bi$



★ OMPs of the $^{6}He+^{209}Bi$ system are determined precisely for the first time;

★ The **decreasing trend** in the imaginary part is observed, and the **threshold energy** is about 13.73 MeV (~0.68V_B);

★ The behavior of real part looks normal, i.e. like a bell shape around the barrier;

★ The dispersion relation **does NOT hold** in this system.

L. Yang, C.J. Lin*, H.M. Jia et al., Phys. Rev. Lett. **119**, 042503 (2017);
Phys. Rev. C **96**, 044615 (2017).

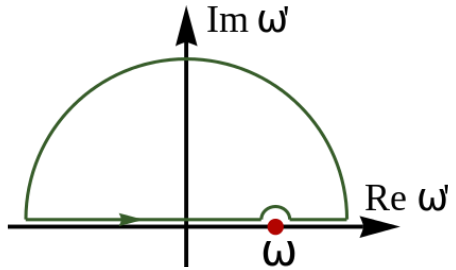
Discussions

★ Dispersion relation results from causality, connecting real and imaginary part;

★ Any wave/particle should follow this relation when it passes through a media;

★ The dispersion relation is **not** applicable for exotic nuclear systems.

Possible reasons:

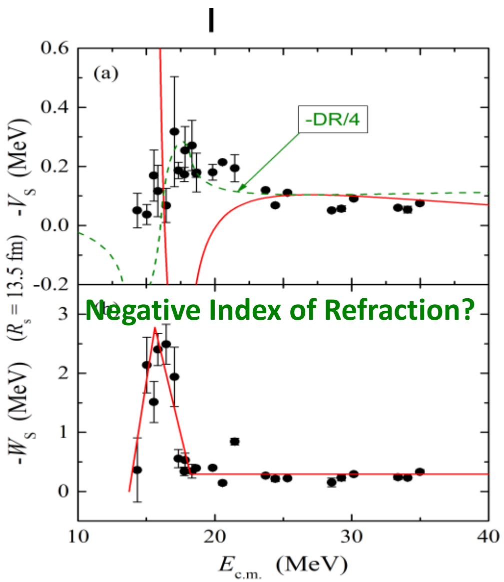


Cauchy's residue theorem

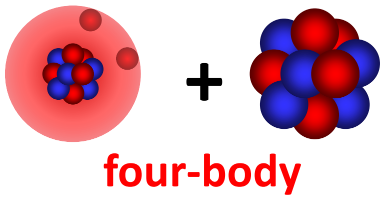
- **Causality → dispersion relation**
  stable systems: causality ↔ analyticity

- **Cauchy integration**
  infinity poles (breakup) & off-axis (multi-process)

- **Negative Index of Refraction**
  causality based criteria must be used with care
  [Phys. Rev. Lett. **101**, 167401 (2008).]



- **Locality vs. non-locality**
  equivalent local potential in Schrödinger equation



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Reactions with Exotic Nuclei

RIBs experiments

♠ **Elastic scattering**

3-body, 4-body

CDCC …

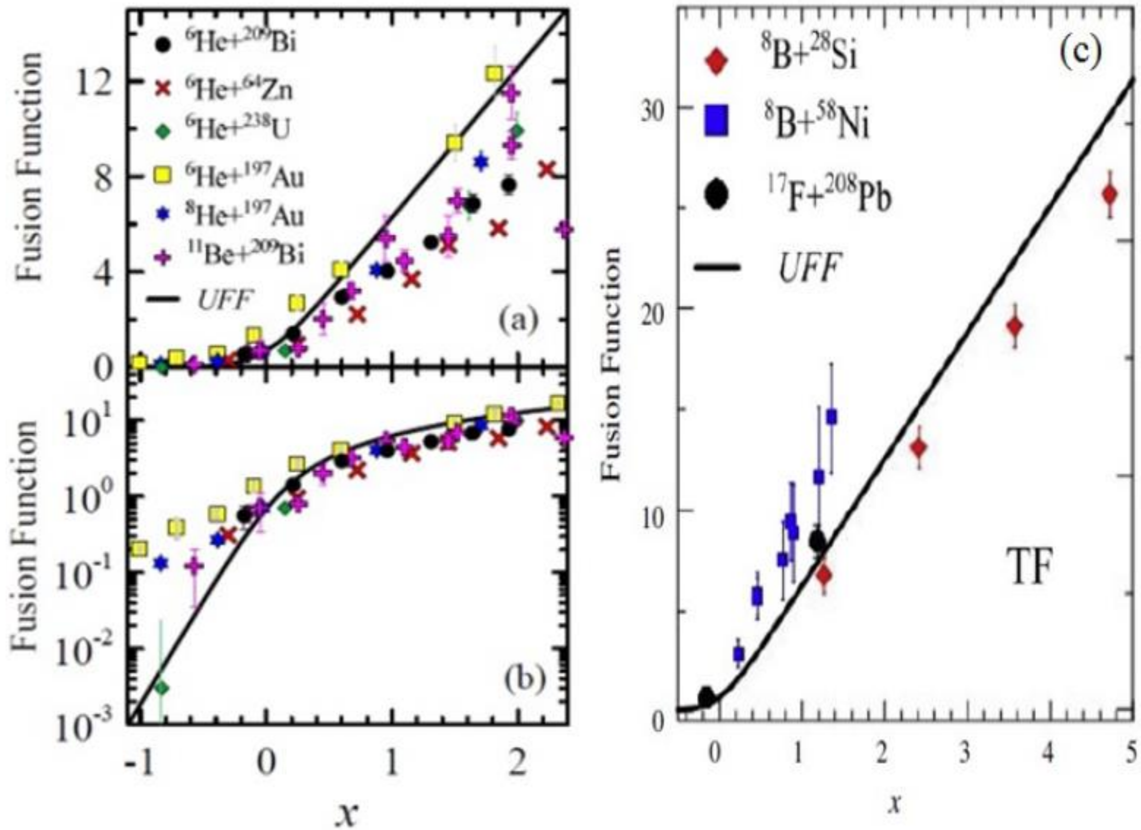
♠ **Fusion/Reaction**

TF = ICF + CF …

♠ **Breakup/transfer**

Effects & mechanisms

neutron-rich **proton-rich**



[1] L. F. Canto, P. R. S. Gomes, R. Donangelo et al., Phys. Rep. 424, 1 (2006).
[2] L. F. Canto, P. R. S. Gomes, R. Donangelo et al., Phys. Rep. 596, 1 (2015).
[3] B. B. Back, H. Esbensen, C. L. Jiang and K. E. Rehm, Rev. Mod. Phys. 86, 317 (2014).

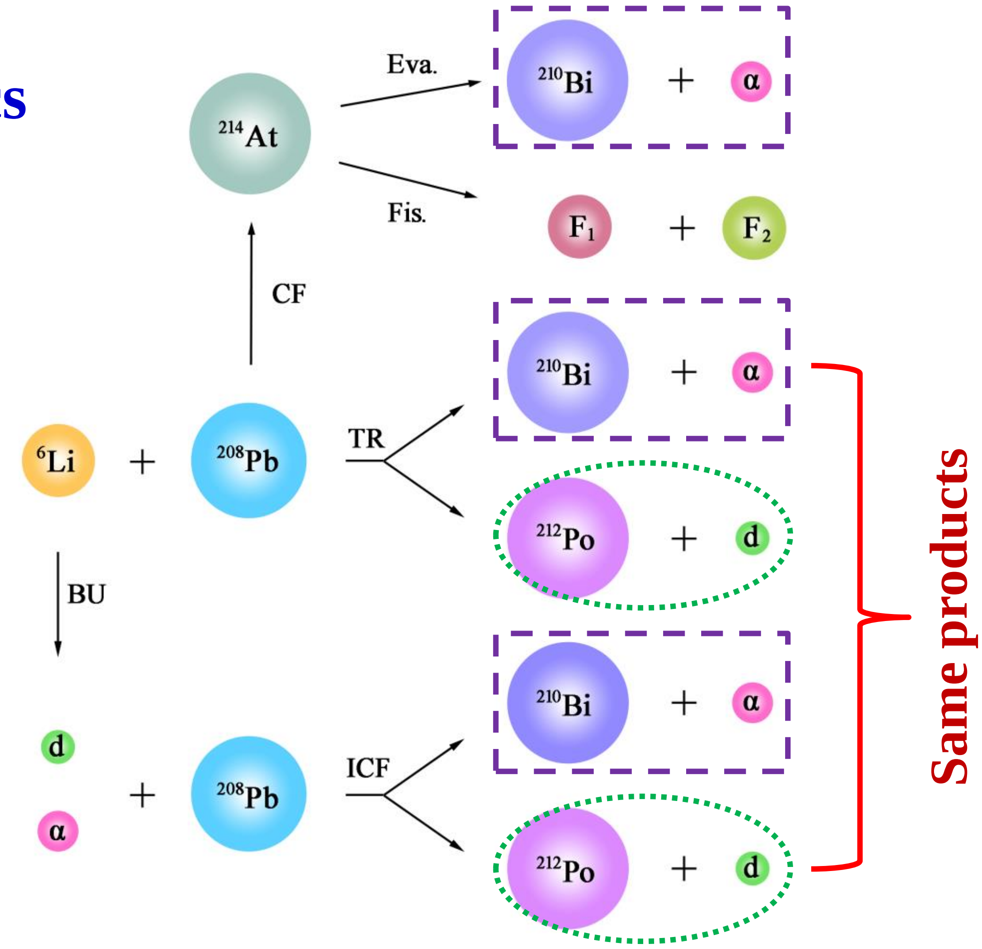
Reaction mechanism

★ **How to identify the different reaction process?**

complete-kinematics measurement

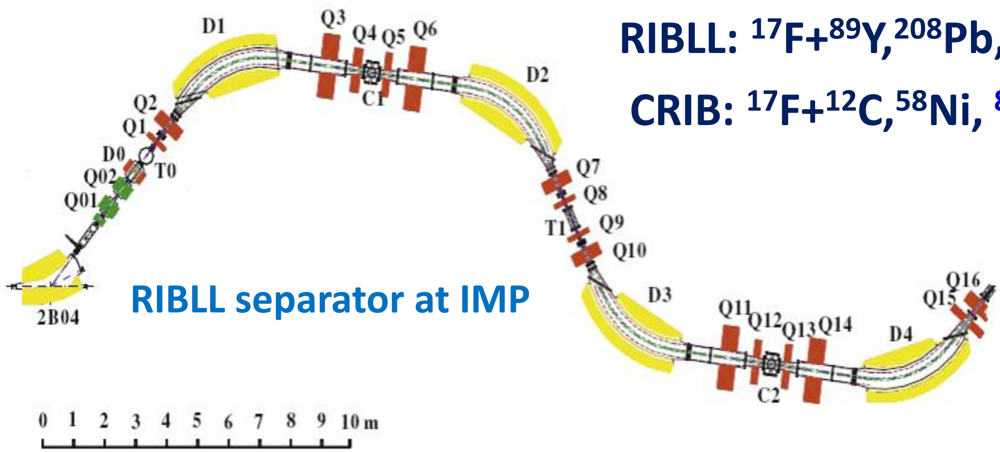
2-body kinematics ☞

3-body kinematics ☞



Experiments

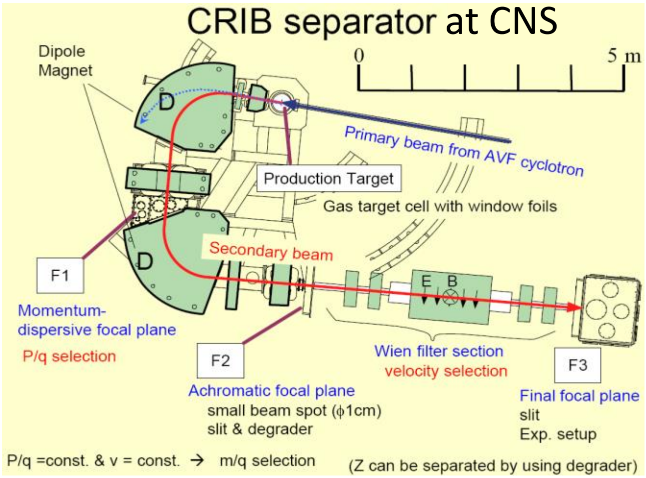
★ **Complete-kinematics measurement ;** ★ **Reactions induced by ^{7}Be, ^{8}B, ^{17}F …**

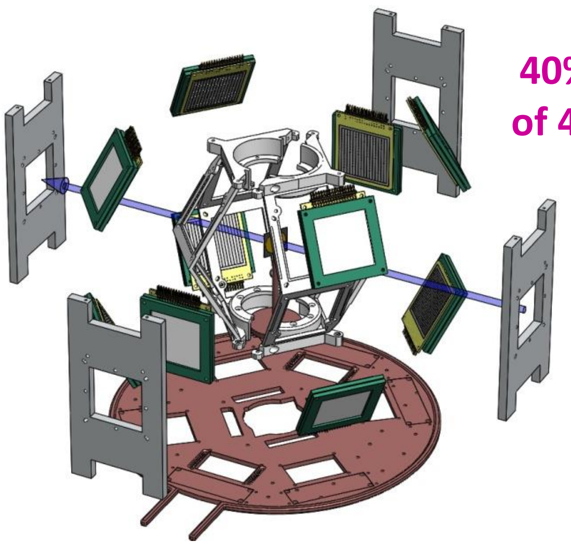


RIBLL separator at IMP

RIBLL: ^{17}F+^{89}Y,^{208}Pb,^{7}Be+^{209}Bi

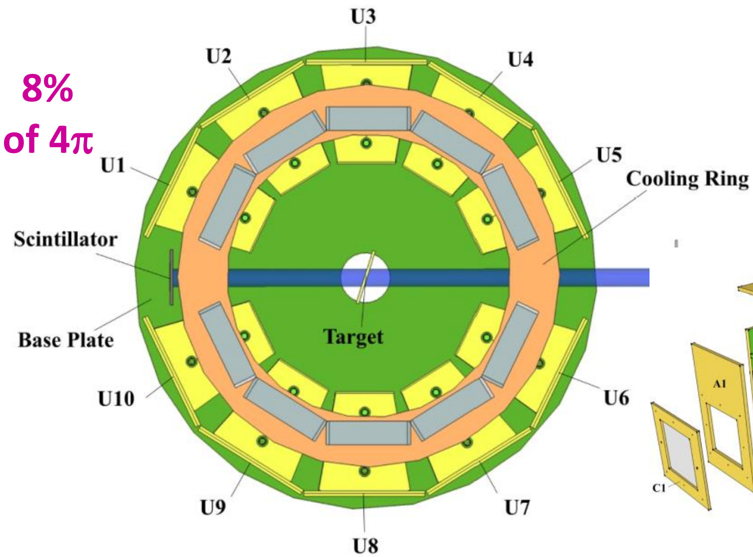
CRIB: ^{17}F+^{12}C,^{58}Ni, ^{8}B+^{120}Sn



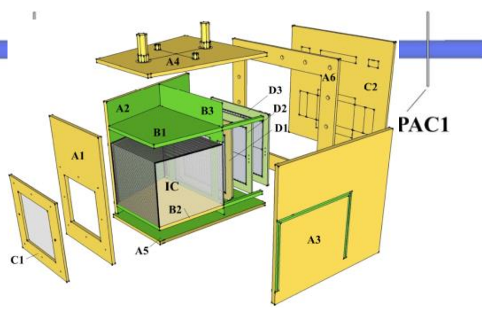


40% of 4π

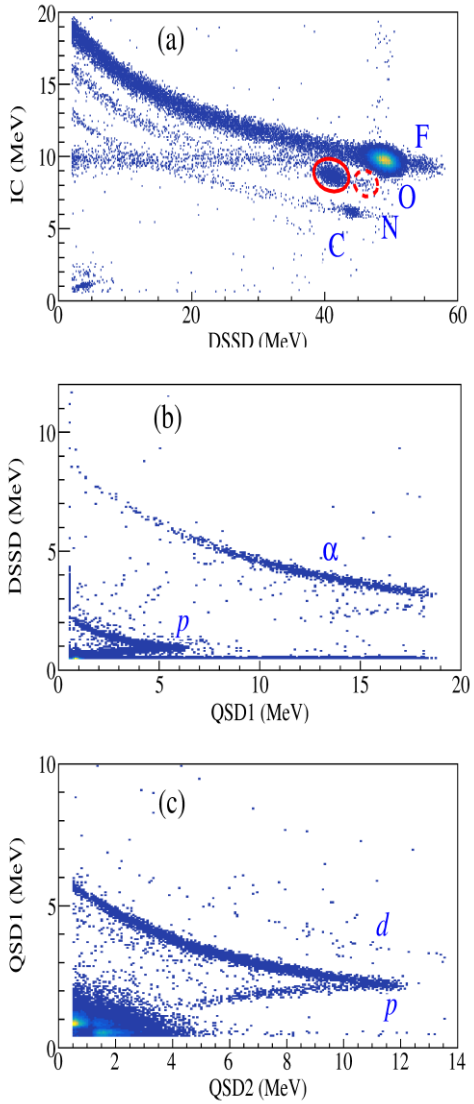
8% of 4π

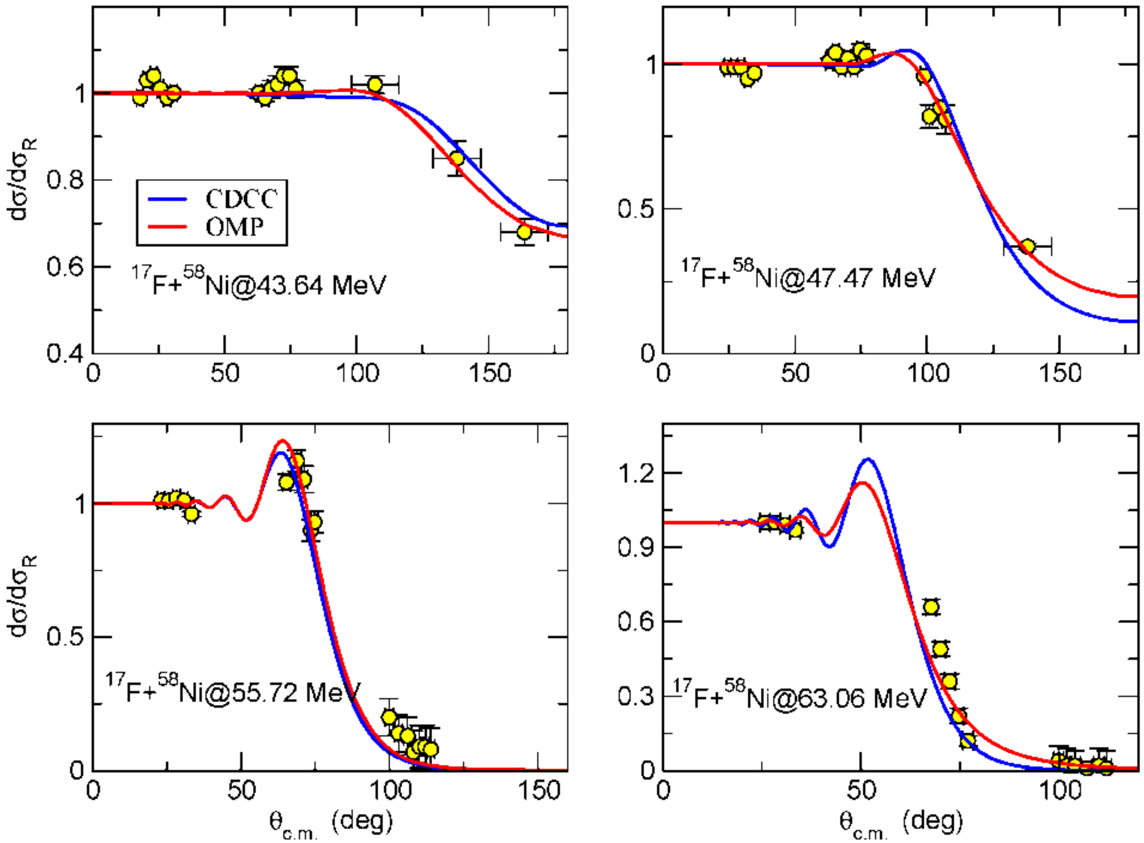


40/60 μm DSSD
300 μm QSD
1-1.5 mm QSD



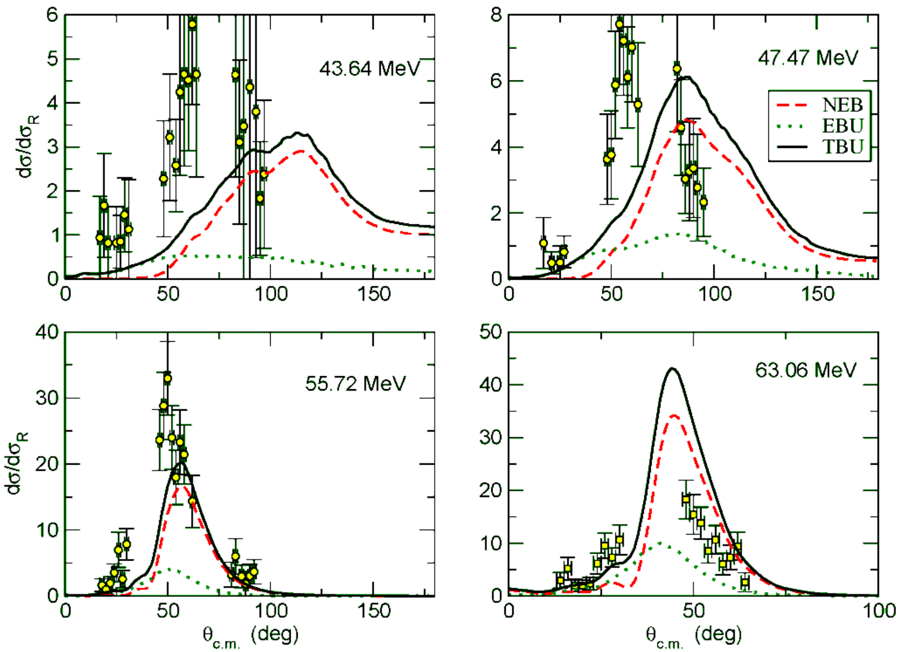
Preliminary Results: $^{17}F+^{58}Ni$





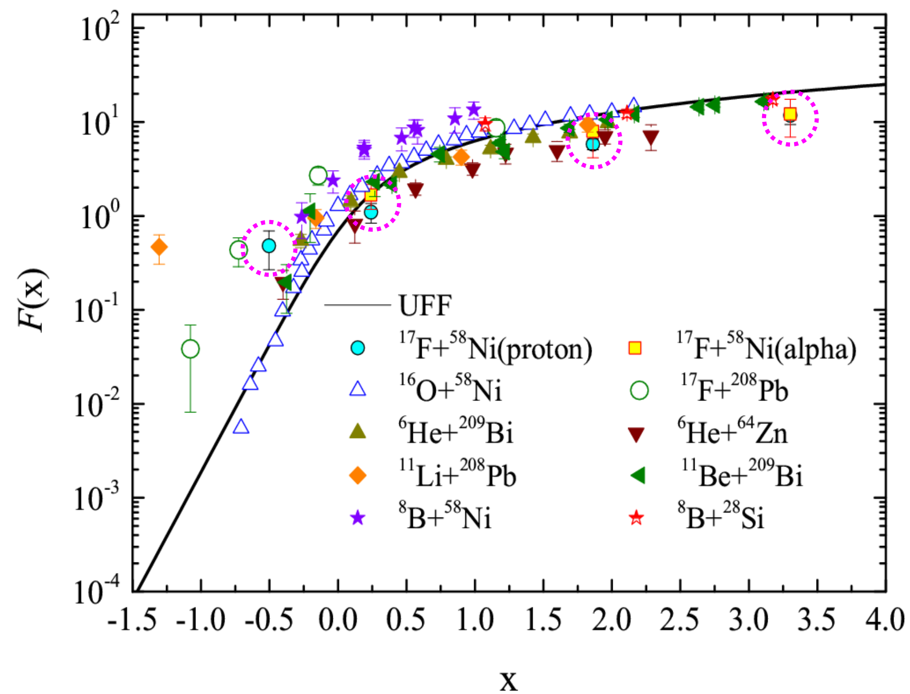
Angular distribution of **quasi-elastic scattering**.

(OMP & CDCC by Lei Jin)



Angular distribution of **breakups/transfer**

[Cf. Lei Jin & A. M. Moro, PRL 122, 042503 (2019)]



Fusion excitation function of $^{17}F+^{58}Ni$ and other systems

Preliminary conclusions:

- The non-elastic breakups are dominant;
- Fusions are suppressed at energies above the barrier but enhanced below the barrier.

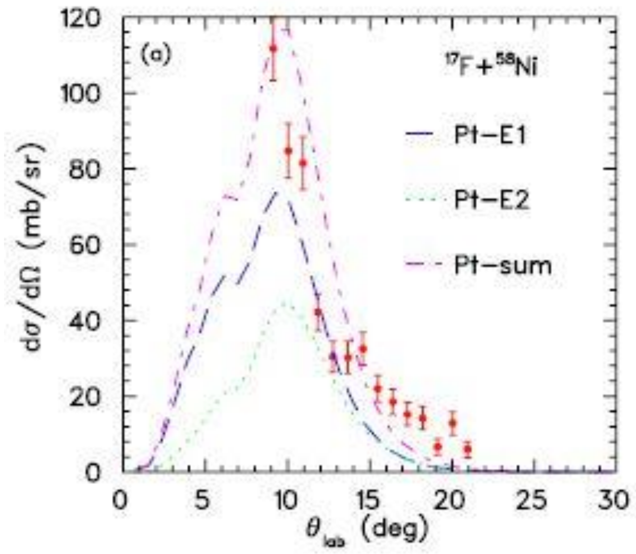
Discussions

★ **Exclusive breakup (^{16}O-*p*)**

Our result: **σ ~ 1.2 mb @ 63 MeV**;

Liang's result: **σ ~ 15.6 mb @ 170 MeV**. ☞

[J.F. Liang et al., PLB 681, 22 (2009).]



Why are the breakup cross sections so low?

- **Screen effects due to the dynamic polarization?**
- **Transfers are dominant?**
- **…**

$^{8}B+^{120}Sn$ experiment will be performed at CNS/RIKEN (2 -16 Apr., 2019)

^{17}F (S_p = 0.601 MeV), ^{8}B (S_p = 0.136 MeV)

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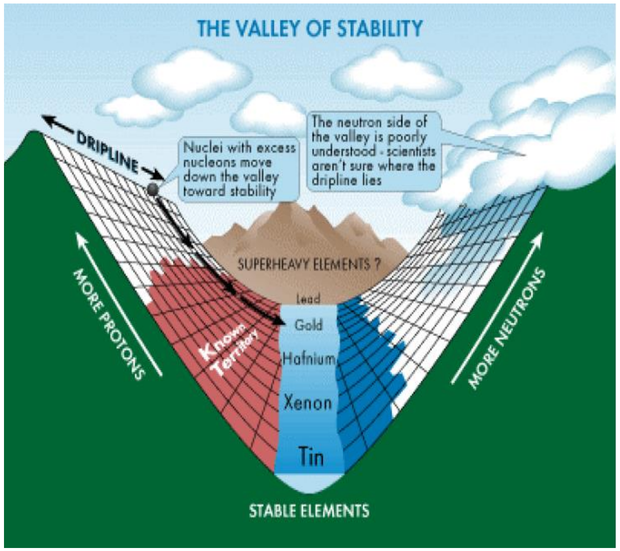
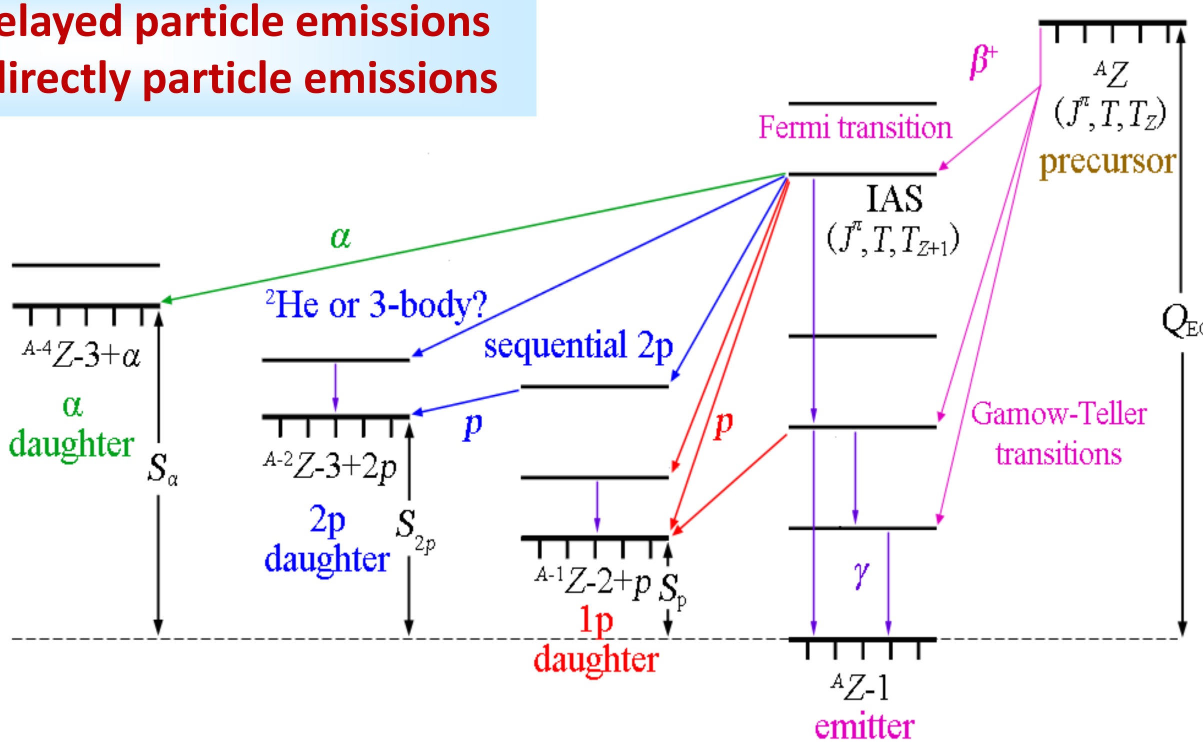
Exotic decays of *p*-rich nuclei

Bound states: β-delayed particle emissions
Unbound states: directly particle emissions

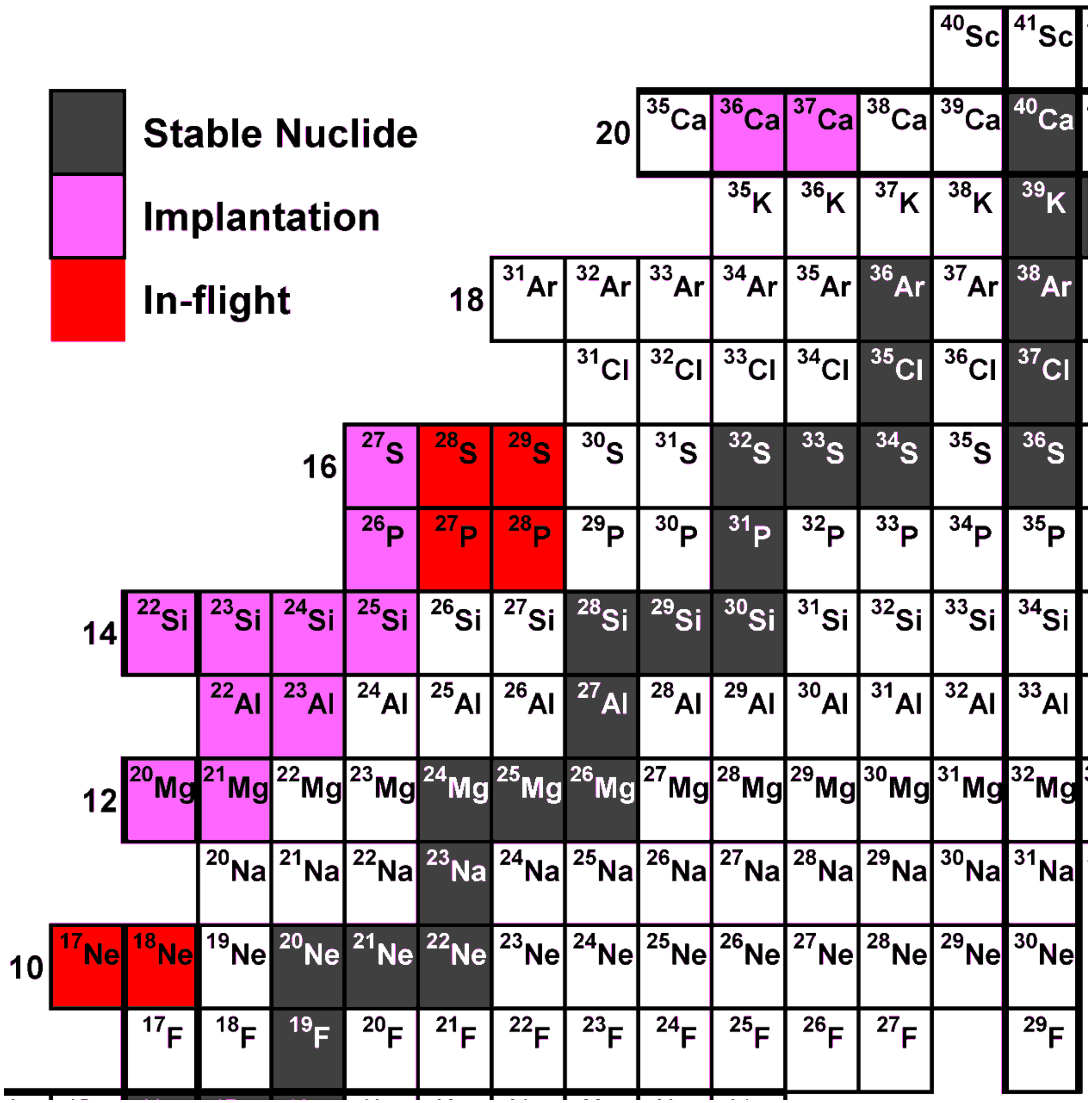




βp, $\beta 2p$, $\beta 3p$, $\beta p\gamma$, $\beta\gamma p$, $\beta\alpha$, $\beta 2\alpha$, $\beta\alpha p$, $\beta p\alpha$, $\beta p 2\alpha$, βn, $\beta 2n$, $\beta 3n$, βd, βt, βF…

- **Structures of *p*-rich nuclei close to/beyond the drip-line**
- **Effective interaction – pairing, isospin non-conserving (INC), three-body force**
- **Initial state interaction (ISI), final state interaction (FSI), quantum entanglement**
- **Nuclear astrophysics – (p,γ), (2p,γ), (α,γ) … processes**

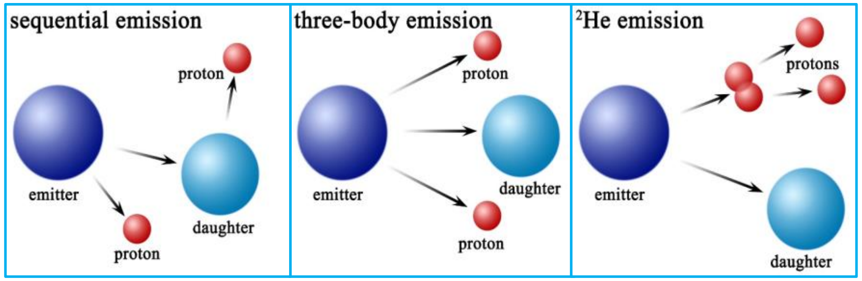
Overview of our research



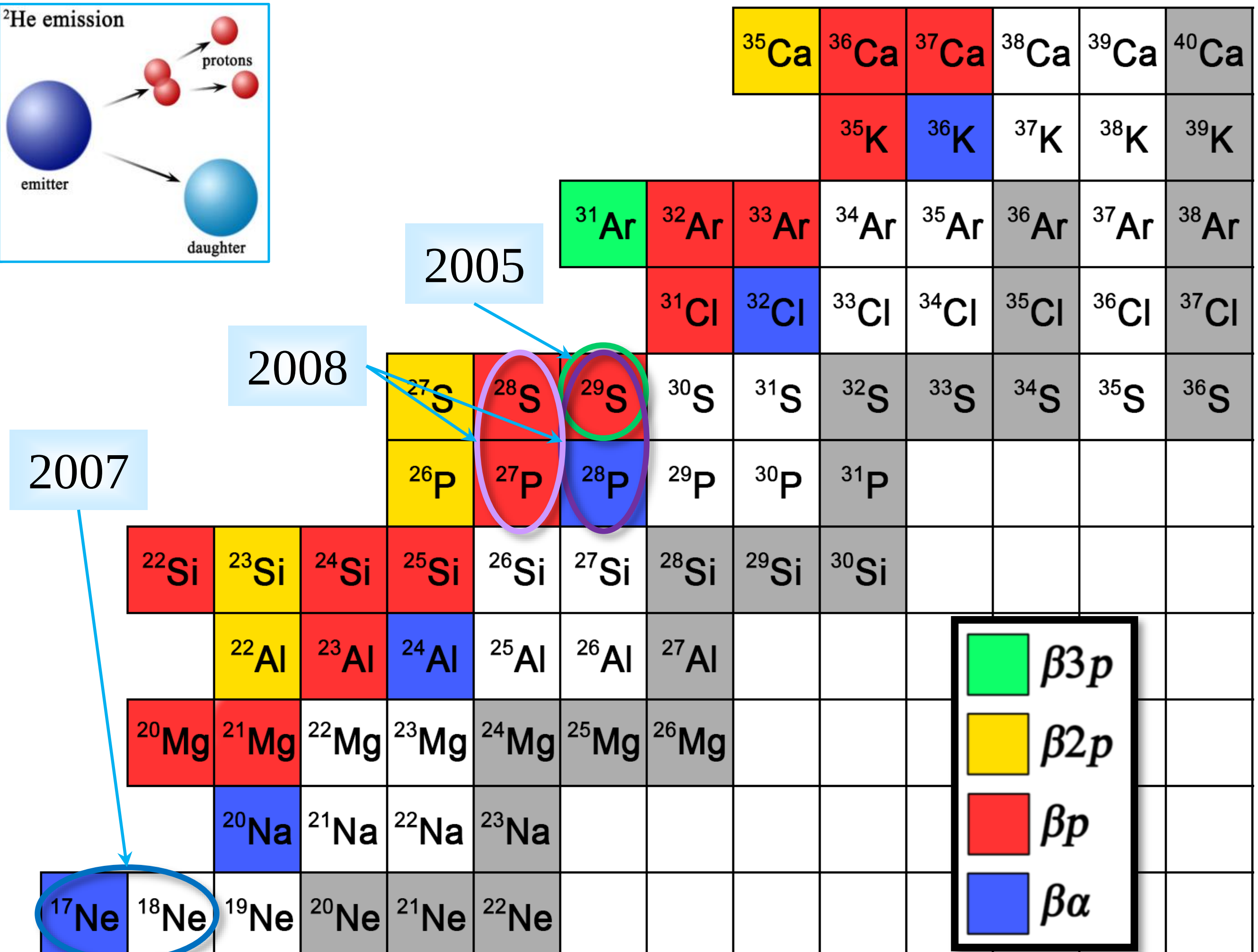
- Started from 2004
- **RIBLL@HIRFL (Lanzhou)**
- **In-flight** decay
  (Ex. states 2p emissions)
  ^{28,29}S/^{27,28}P;
  ^{17,18}Ne.
- **Implantation** decay
  (G.S. βp, β2p…)
  ^{36,37}Ca;
  ^{27}S/^{26}P/^{25}Si;
  ^{22}Si/^{20}Mg;
  ^{23}Si/^{22}Al/^{21}Mg;
  ^{24}Si/^{23}Al.

In-flight decays

☞ **2*p* emissions from high-lying excited states and related topics**

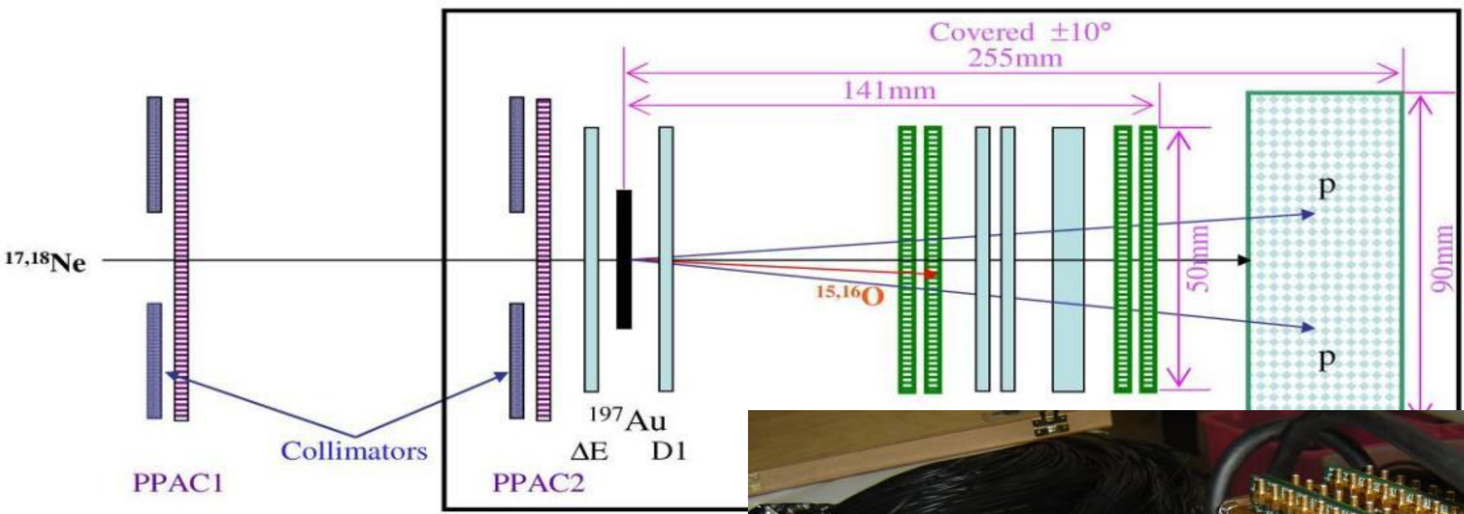


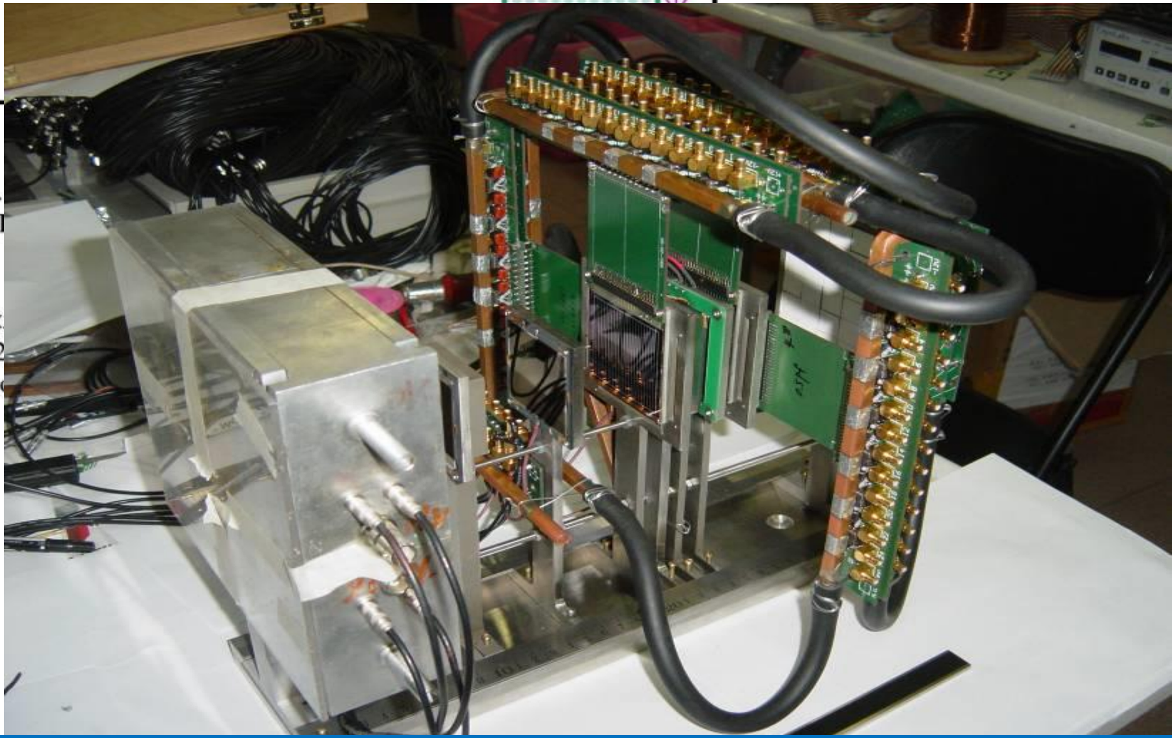
AIP CP 961, 117 (2007);
NPA 805, 403 (2008);
AIP CP 1165, 106 (2009);
CPL 26, 032301 (2009);
PRC 80, 014310 (2009).
PRC 82, 064316 (2010);
NPA 834, 450c (2010);
AIP CP 1409, 98 (2011);
SCPMA 54(S1), S73 (2011);
PST 14, 317 (2012);
PLB 727, 126 (2013);
JPS CP 1, 013026 (2014);
NPR 33, 160 (2016).



Exp. setup 1

RIBLL Experimental Setup 2007





Note:

Collimators: PPAC1: ϕ30 mm; PPAC2: ϕ20 mm.

ΔE: 300μm Si ΔE detector, combined with TOF (I

^{197}Au: target, 200-250 μm, ϕ28 mm.

D1,D2,D3: 300μm Si, 48mm×48mm.

D4: 1000μm Si detector with 4 segments, 50mm×

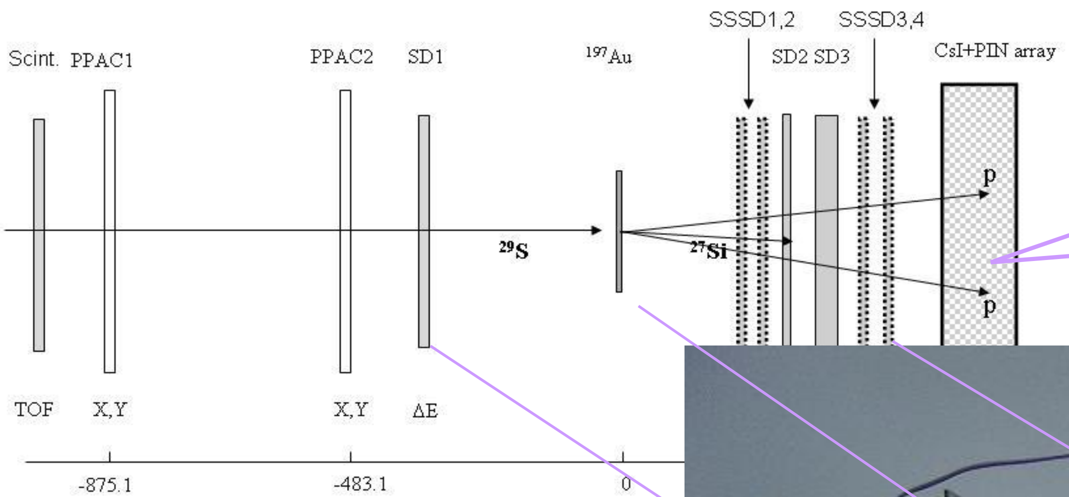
X1,Y1,X2,Y2: 300μm Si strip detectors, each of 2

CSI: CSI(Tl)+PIN detectors, 20 mm length, total

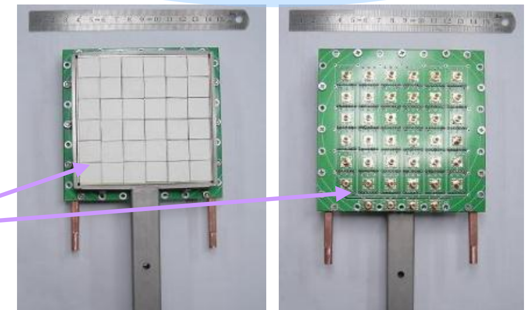
Complete-kinematics measurements

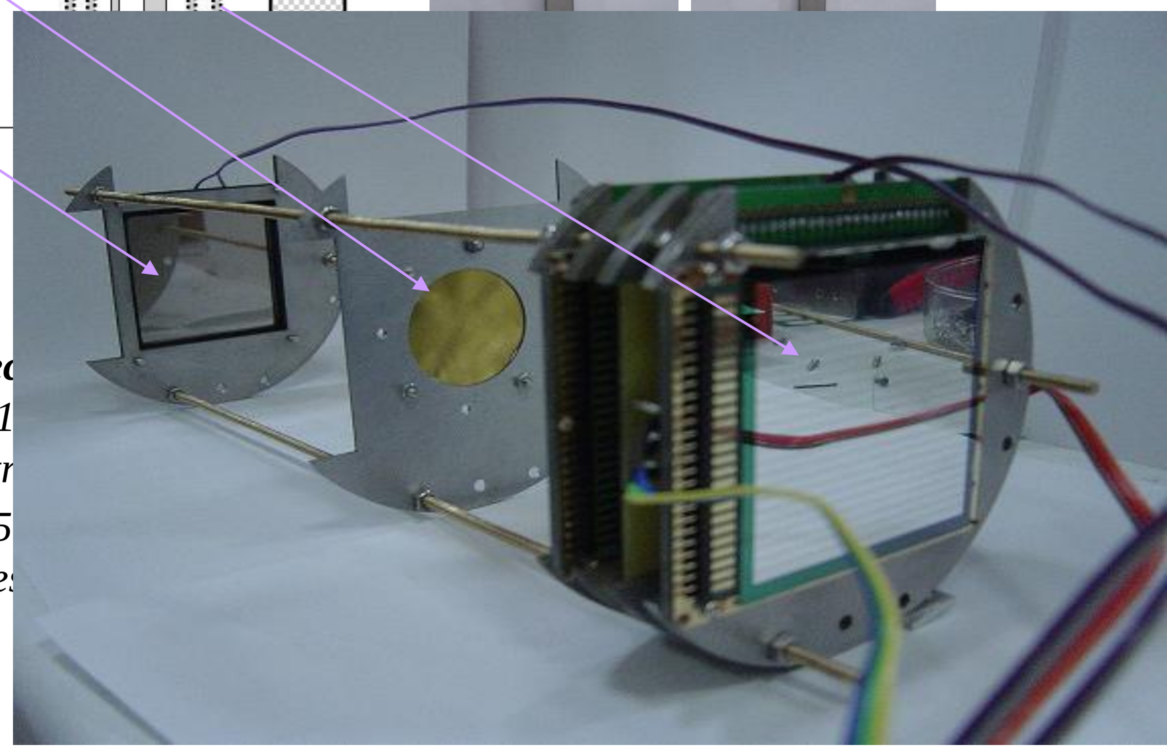
Exp. setup 2

Detector array for $^{28,29}S$ experiment



Complete-kinematics measurements





Secondary target: ^{197}***Au****, 100 μm*

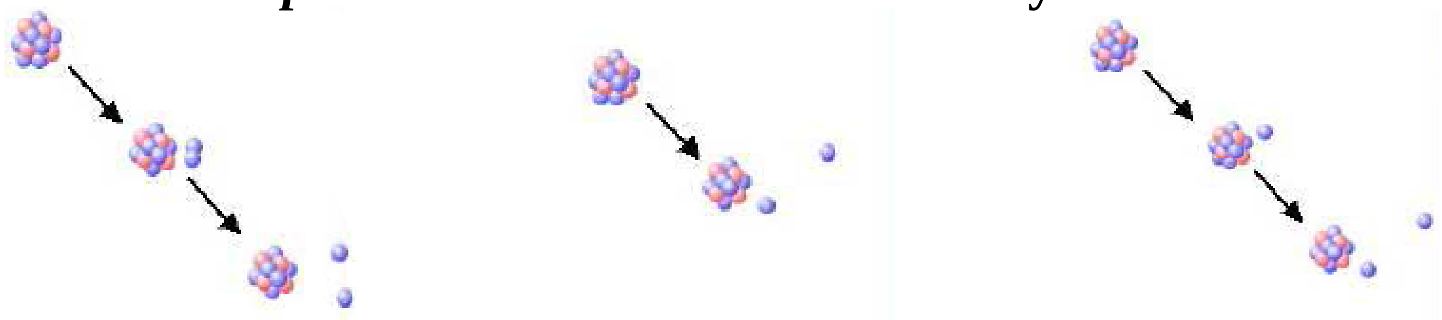
SD: ***Silicon detectors****, 325, 1000 μm*

SSSD: ***Single sided Silicon Strip Detec***
with 2 mm in the width and 0.1
the construction of the particle tr

CsI(Tl) array*: 6×6 lattices, each 15*
through ***PIN*** *photodiode*

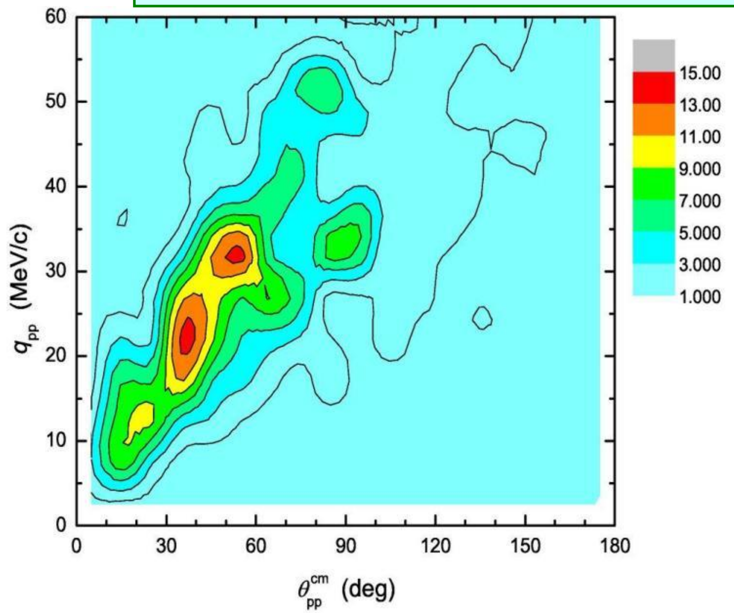
2*p*-decay modes

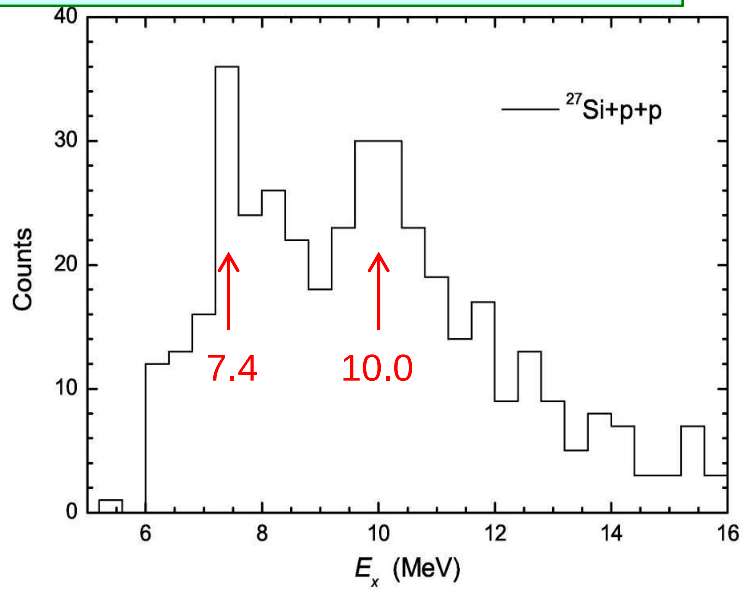
2*p* emission – three extreme decay modes



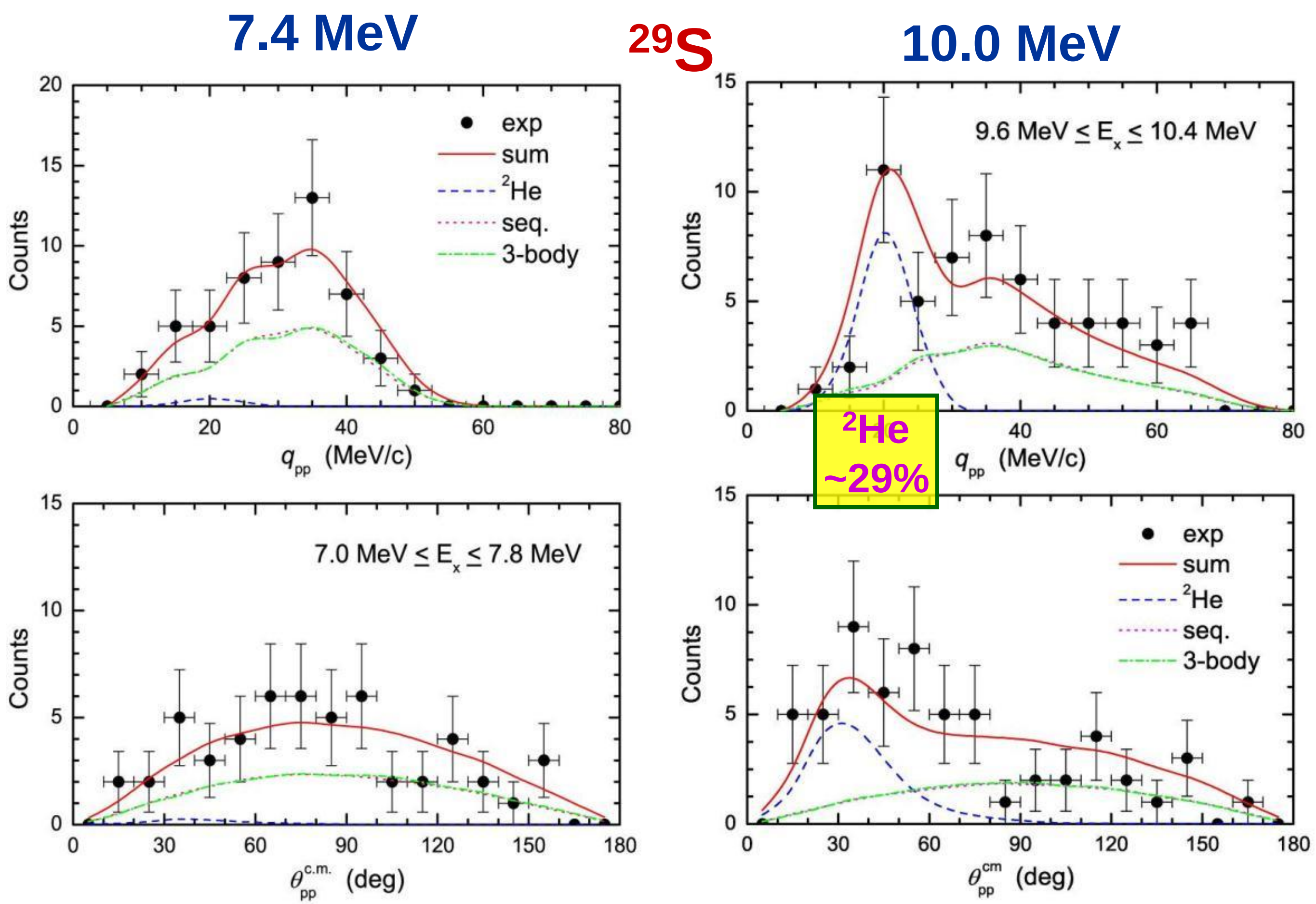
^{2}He decay　　3-body simultaneous decay　　2-body sequential decay

Relativistic-kinematics reconstruction for ^{29}S → ^{27}Si+p+p events





2p emission: ^{29}S/ ^{28}P

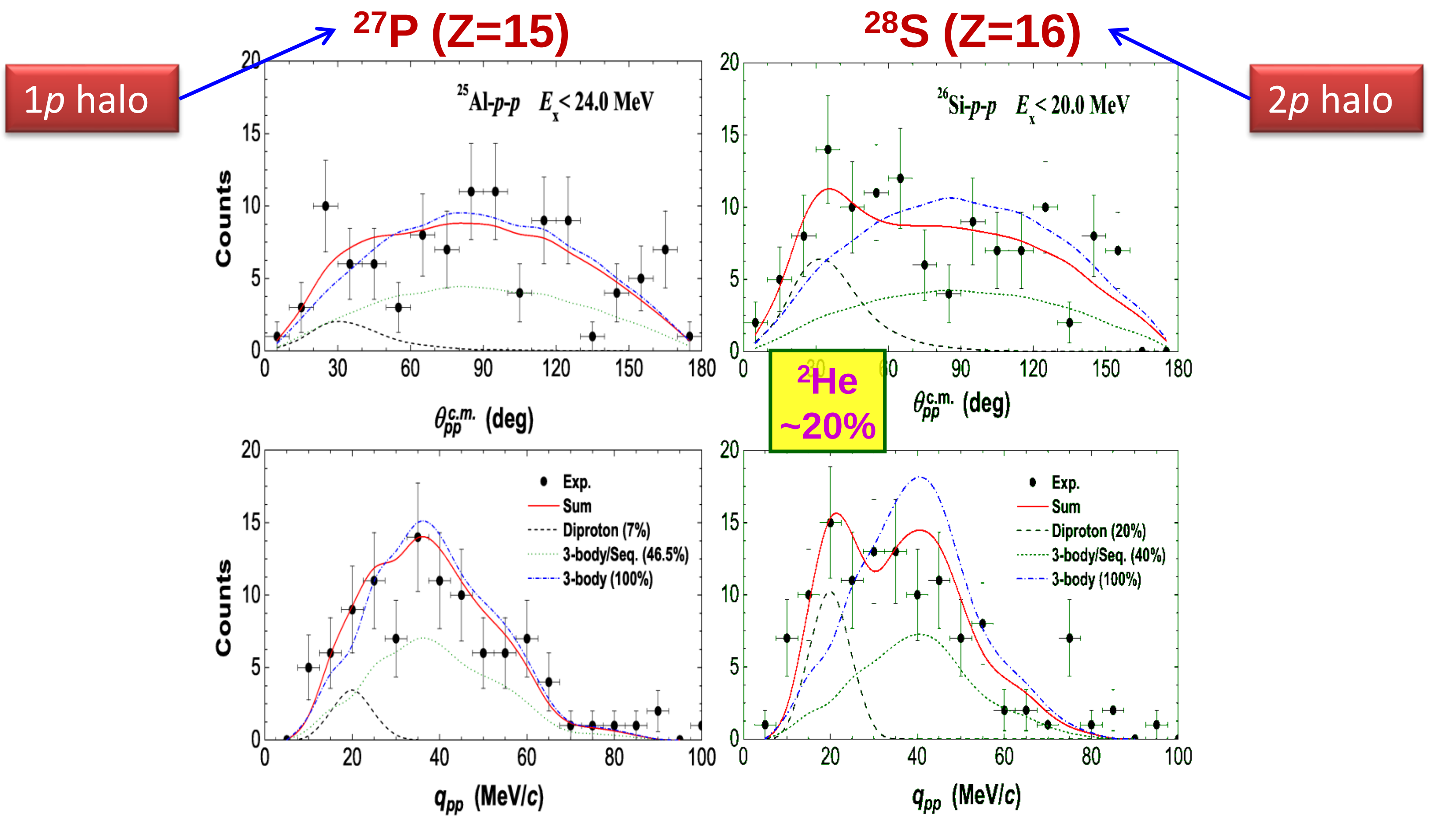


Diproton emissions were observed in ^{29}S but not in ^{28}P.

^{29}S: C.J. Lin, X. X. Xu, H. M. Jia *et al.*, PRC **80**, 014310 (2009);
^{28}P: X. X. Xu, C.J. Lin, H.M. Jia *et al.*, PRC **81**, 054317 (2010).

2p emission: ^{28}S/ ^{27}P

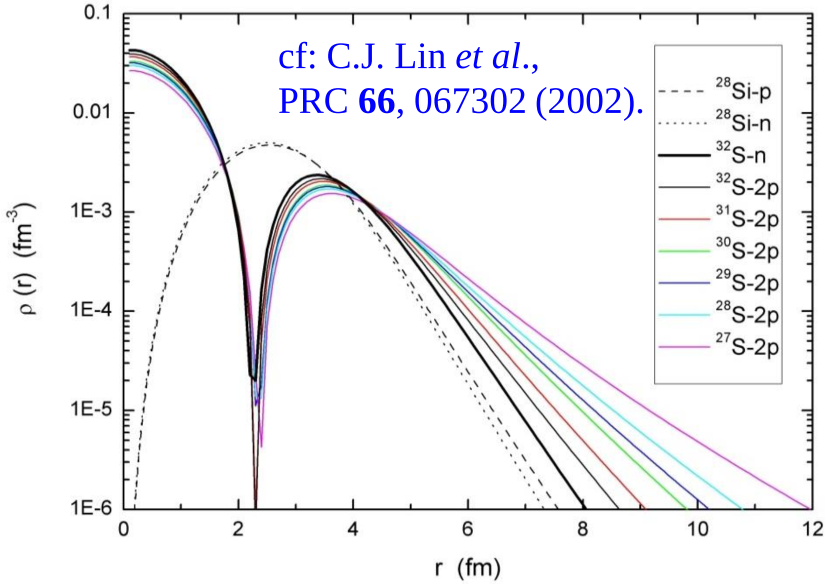
★ **Diproton emission is enhanced by 2*p* halo-like states.**



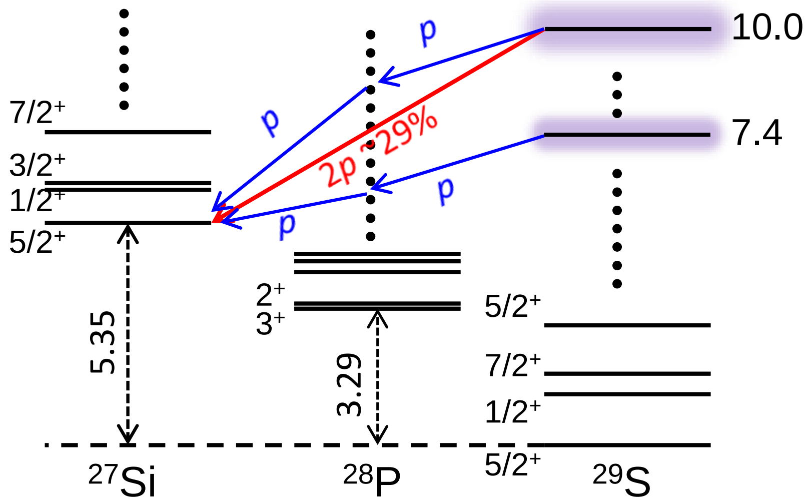
X.X. Xu, C.J. Lin* *et al*., Phys. Lett. B **727**, 126 (2013).

2*p* emission & 2*p* halo

2*p* halo/skin in proton-rich S isotopes



Decay scheme of ^{29}S



2*p* halo/skin → 2*p* valence pair → above 2*p* emission threshold → 2*p* correlated emission

weak link with core (decoupled) → 2*p* valence pair

Beyond 1*p* drip-line → above 2*p* emission threshold

2*p* resonance state → above 2*p* emission threshold

Ground state

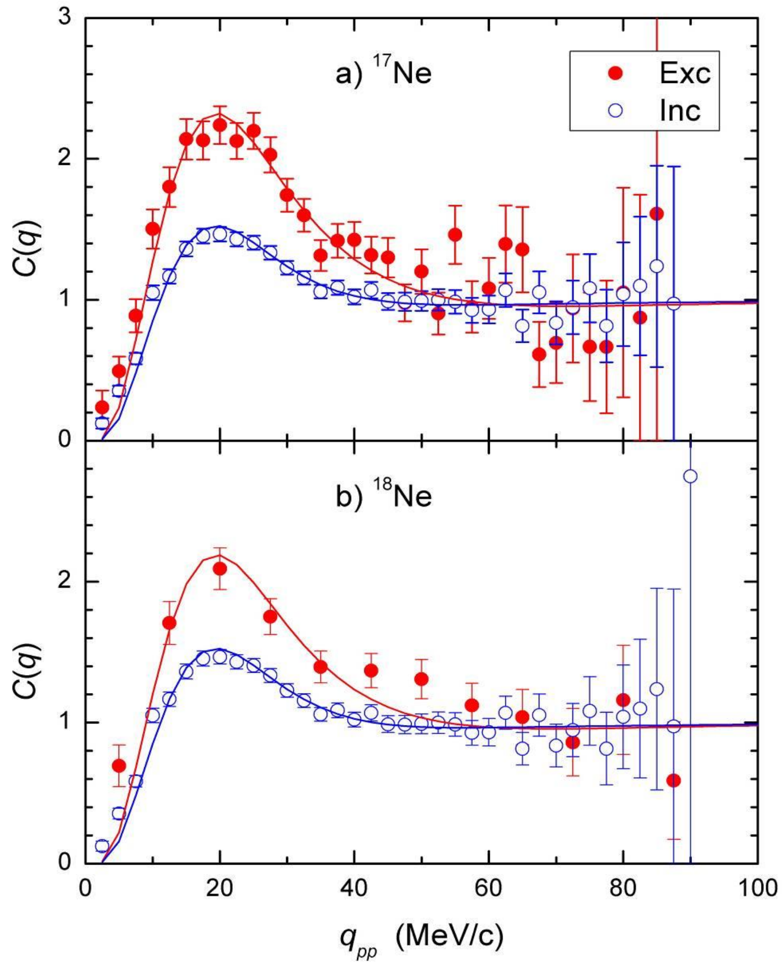
^{6}Be, ^{12}O, ^{16}Ne, ^{19}Mg,
^{45}Fe, ^{48}Ni, ^{54}Zn ……

Excited state:

^{14}O, ^{17,18}Ne,
^{28,29}S, ……

BCS/BEC crossover: ^{17,18}Ne

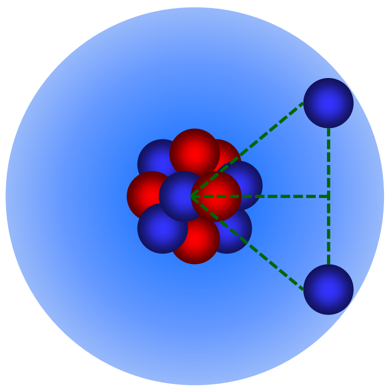
Momentum correlation functions & HBT analyses



^{17}Ne	Exc: $5.17^{+0.09}_{-0.08}$ fm
	Inc: $7.50^{+0.09}_{-0.09}$ fm
^{18}Ne	Exc: $5.44^{+0.19}_{-0.17}$ fm
	Inc: $6.06^{+0.08}_{-0.09}$ fm

J^π	$\langle r^2_{pp}\rangle^{1/2}$	$\langle r^2_{c,pp}\rangle^{1/2}$	$\langle r^2_{cp}\rangle^{1/2}$	$\langle r^2_{p,cp}\rangle^{1/2}$	$\langle \rho^2\rangle^{1/2}$	$\langle r^2\rangle^{1/2}$
$1/2^-$	4.5	3.2	3.9	3.9	5.3	2.8
$3/2^-$	5.3	3.4	4.3	4.4	5.9	2.9
$5/2^-$	5.5	3.5				
$7/2^-$	5.6	3.5				
$9/2^-$	5.7	3.6				

^{17}Ne cf: NPA **733**, 85(2004)



$\langle r_{p\text{-}p}^2\rangle^{1/2}$ = 5.17 fm

$\langle r_{c\text{-}pp}^2\rangle^{1/2}$ = 3.4 fm

⇓

Θ_{pp} = 74.5°

BCS-BEC crossover

Hagino's results (theory): 76.64°

cf: T. Oishi et al., PRC**82**, 024315 (2010).

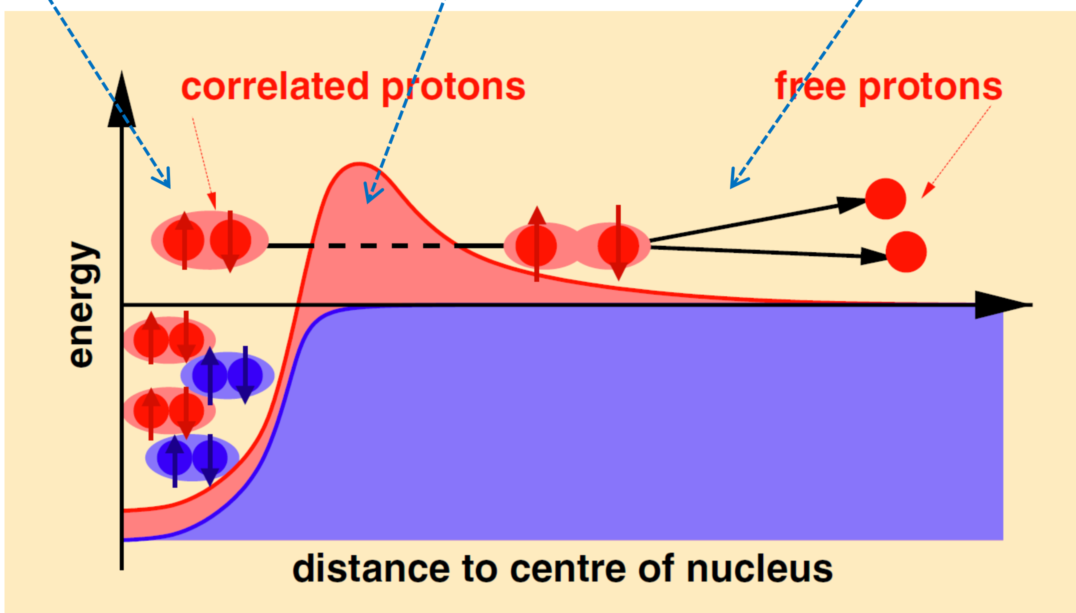
C.J. Lin*, X.X. Xu, H.M. Jia *et al*., JPS Conf. Proc. **1**, 013026 (2014).

Discussions

Question: How to describe 2*p* emission in precise?

Initial state
(3-body model)
[T. Oishi *et al.*, PRC **82**, 024315 (2010).]

→ **Tunneling** → **Propagation** ?



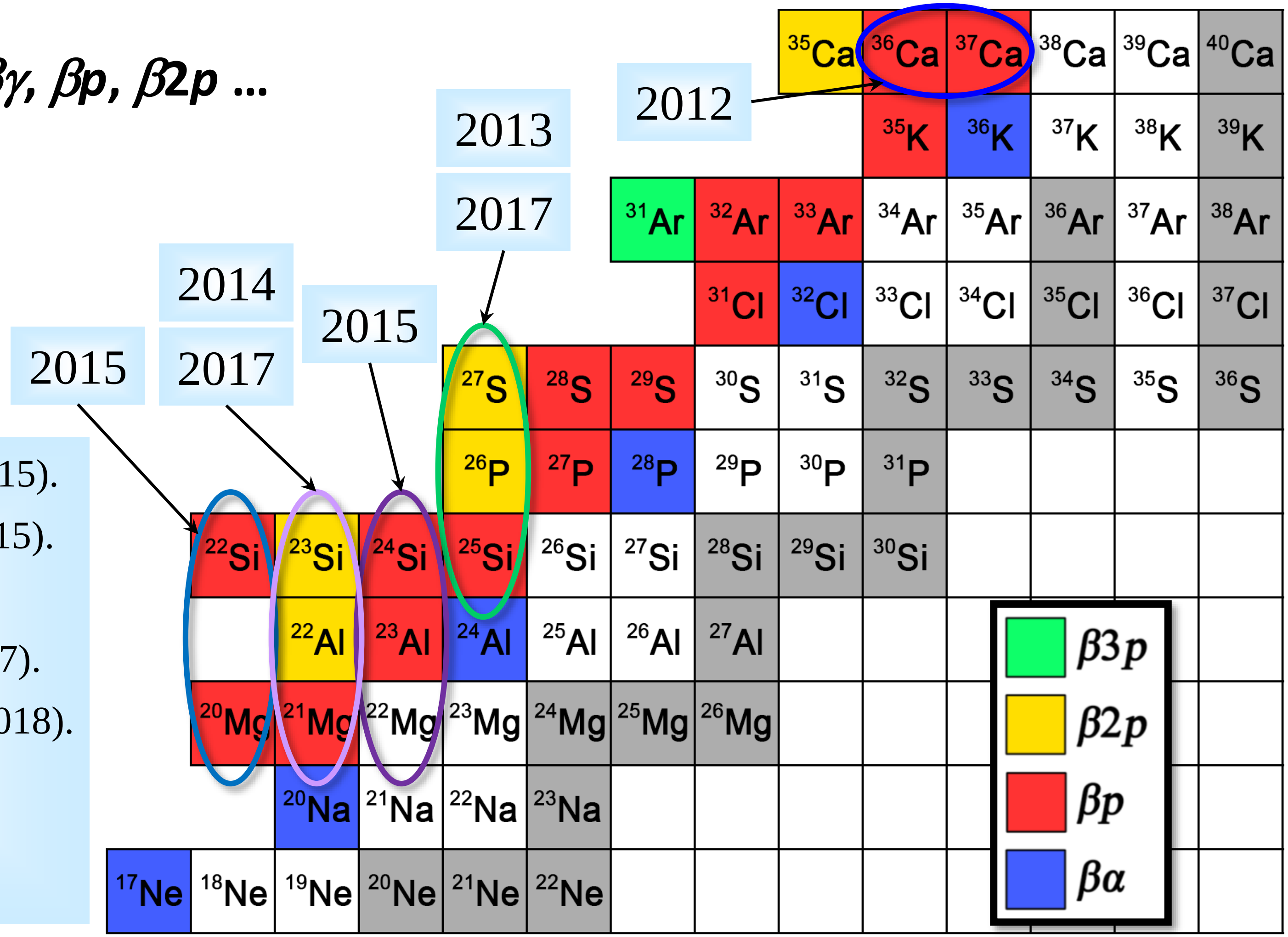
Topics

1. Potentials of exotic nuclear systems
2. Reactions with weakly-bound nuclei
3. 2*p* emissions from excited states
4. **Decays of extremely *p*-rich nuclei**

Implantation decays

β-decay spectroscopy of nuclei close to the proton drip line

Exotic decays： ***βγ, βp, β2p …***



^{36,37}Ca: CPL 32, 012301 (2015).

^{23}Al, ^{24}Si: NIMA 804, 1 (2015).

^{22}Si : PLB 766, 321 (2017).

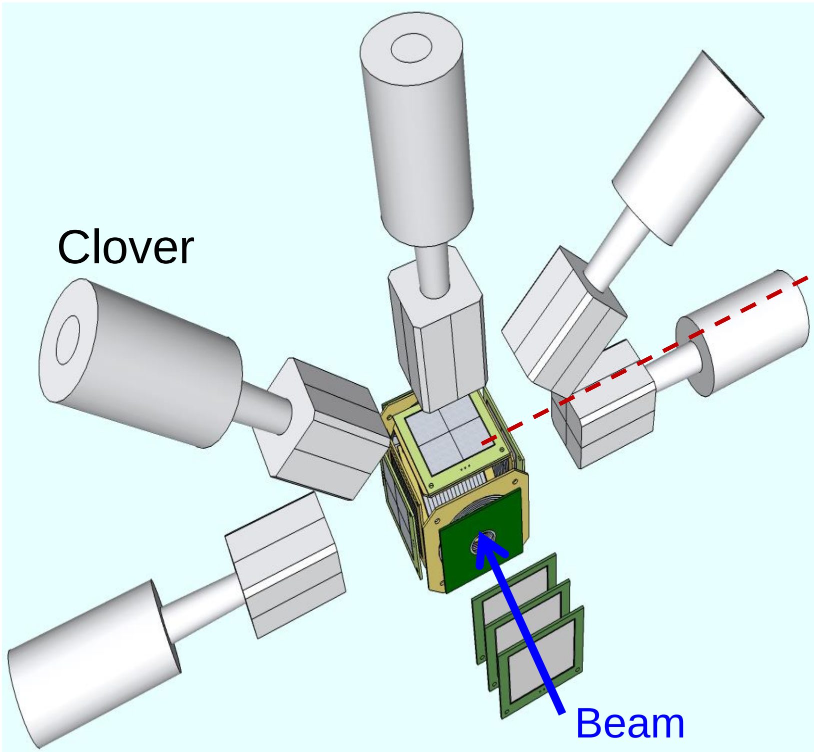
^{20}Mg: PRC 95, 014314 (2017).

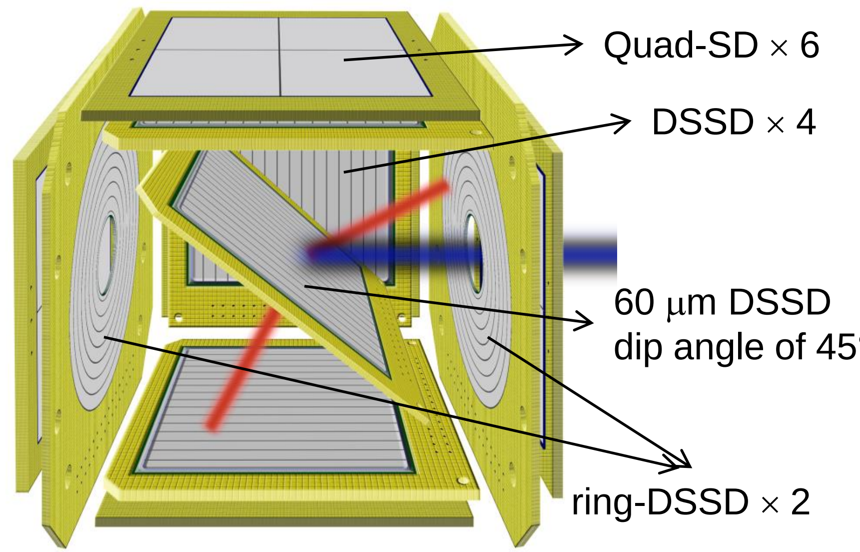
^{23}Si: IJMPE 27, 1850014 (2018).

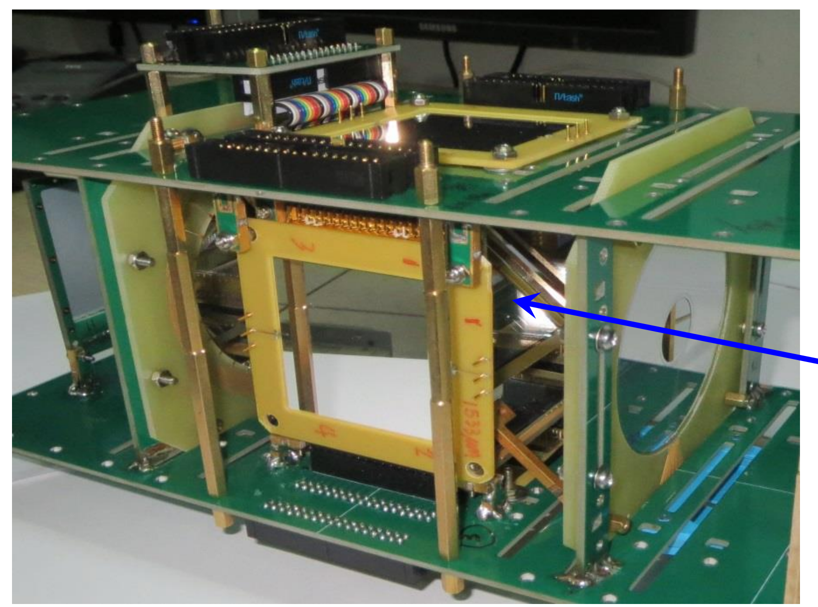
^{22}Al : NST 29, 98 (2018);
PLB 784, 12 (2018).

^{21}Mg: EPJA 54, 107 (2018).

Exp. setup1





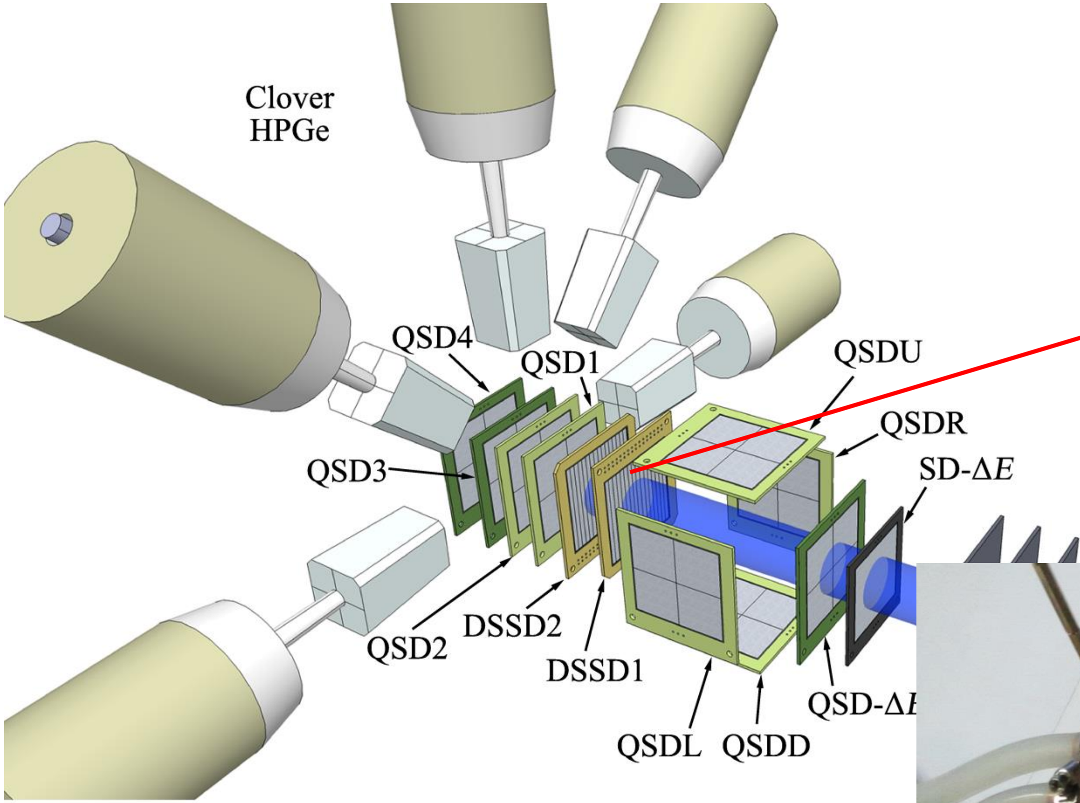


A detector array for 2*p*-decay study by **implantation** method

for lifetime > 10 μs

1p efficiency: 66%; 2p efficiency: 20%

Exp. setup2

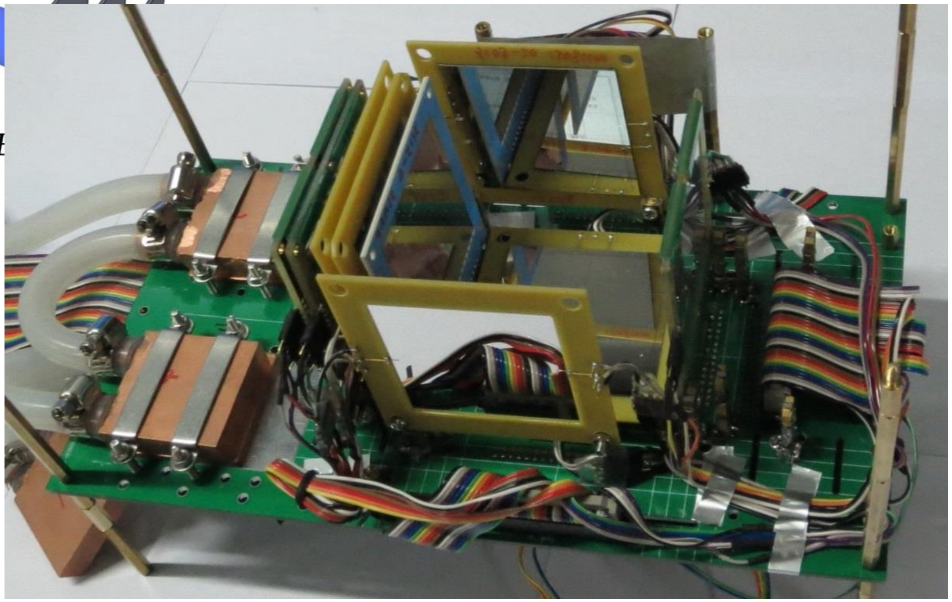


[L.J. Sun et al., NIMA 804, 1 (2005).]

- 150 um + 60 um DSSDs for ion implantations and *p*/2*p*-decay measurements.
- Others for *β*-decay measur. and background rejection.

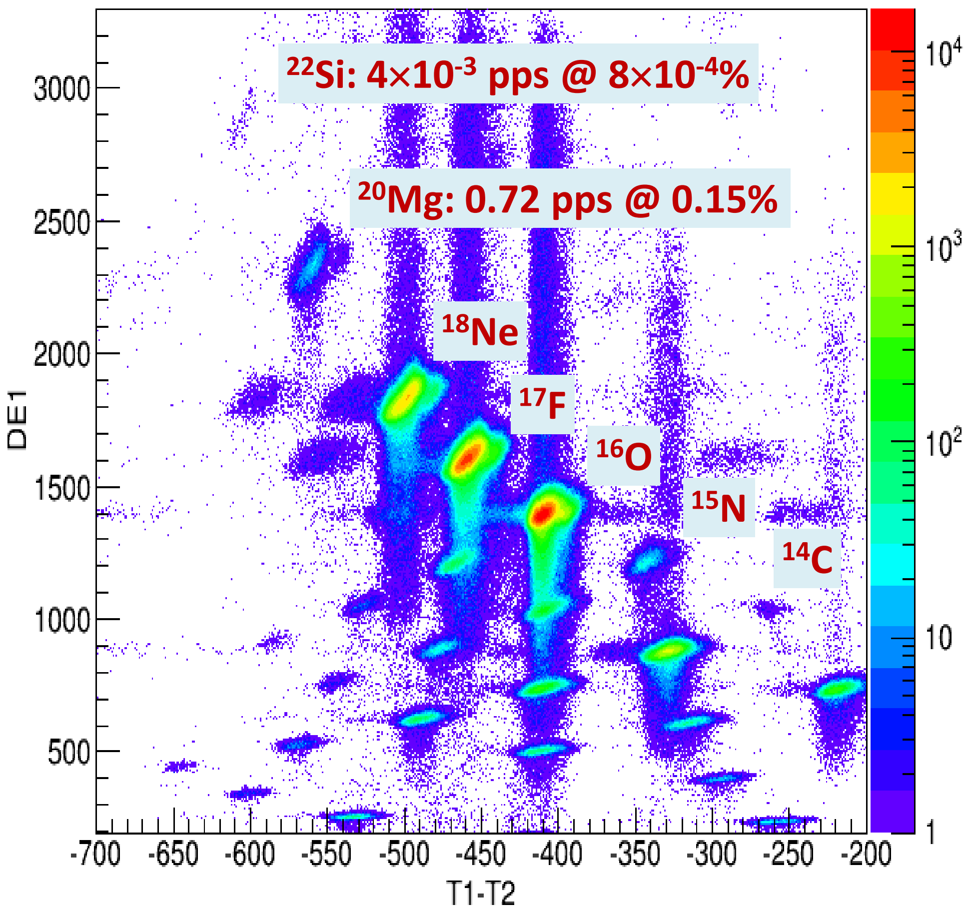
♣ Implanted close to the back edge of the 150 um DSSD.

♣ 1*p* efficiency: >90%;
2p efficiency: 20%

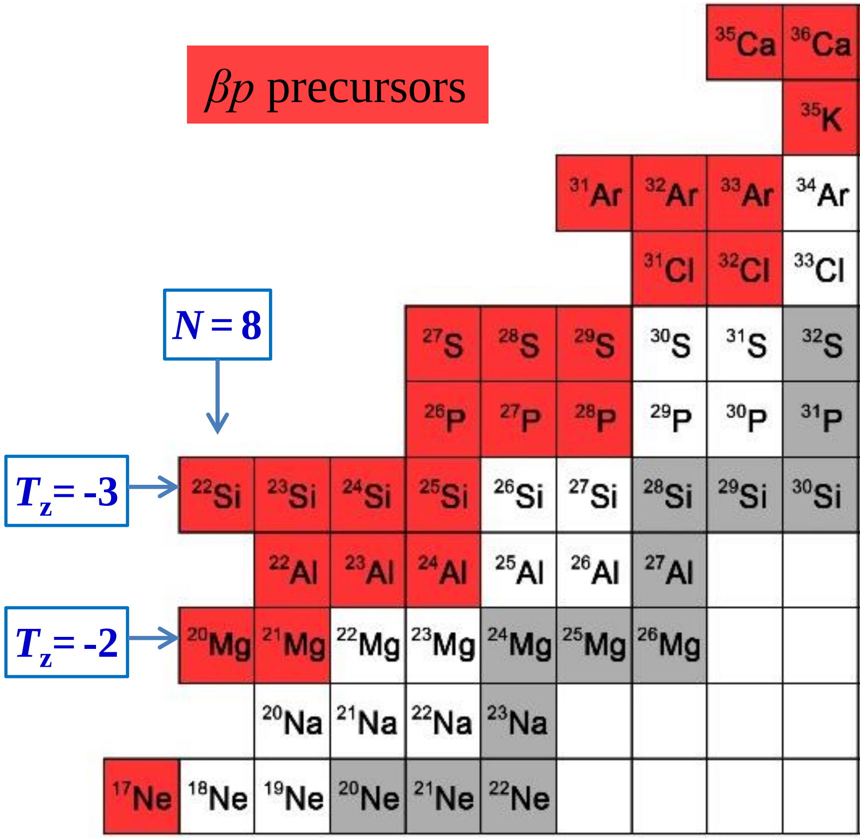


Results 1: $^{22}Si/^{20}Mg$

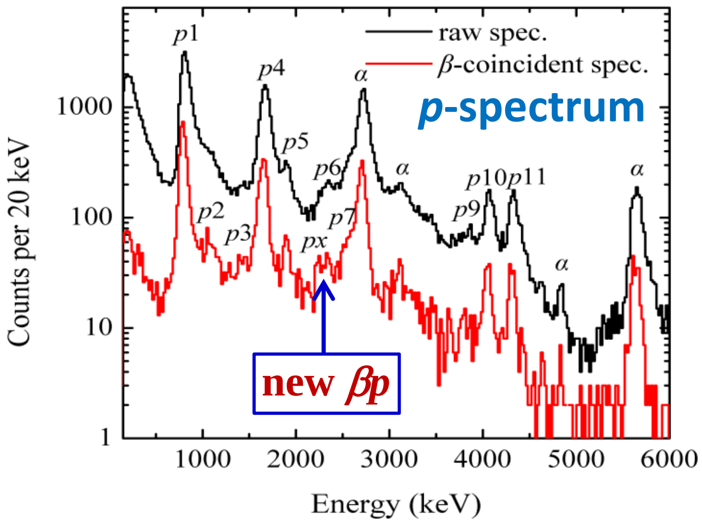
Primary beam: ^{28}Si, 75.3 MeV/u @ 40 enA.

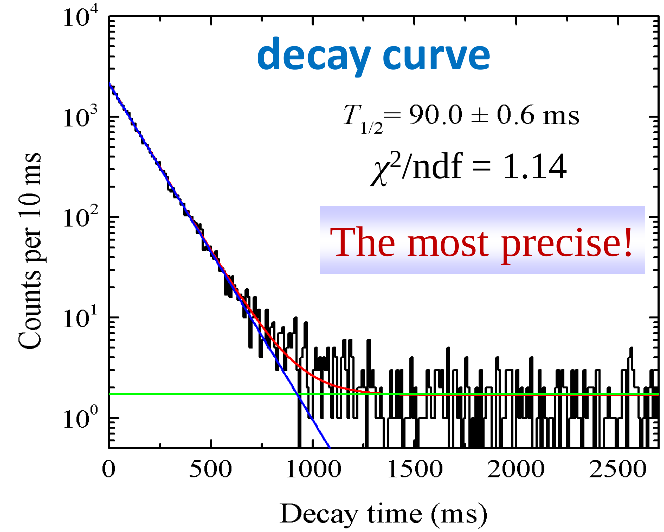


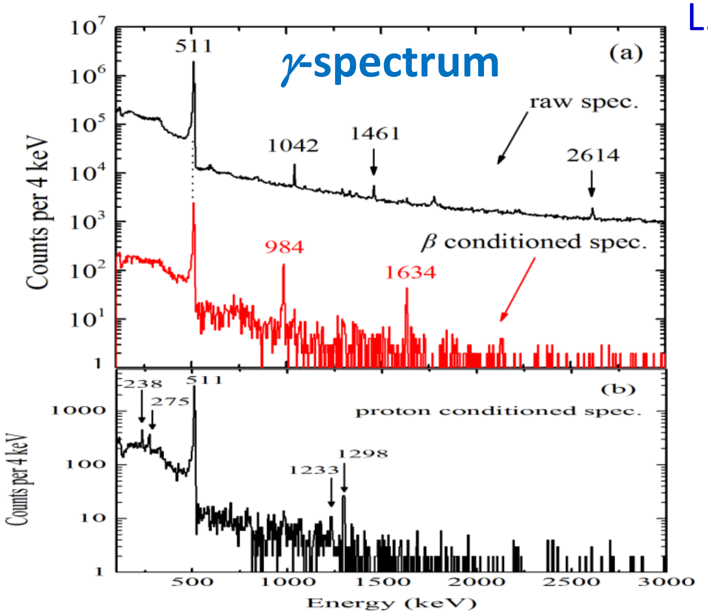
PID of the secondary beam



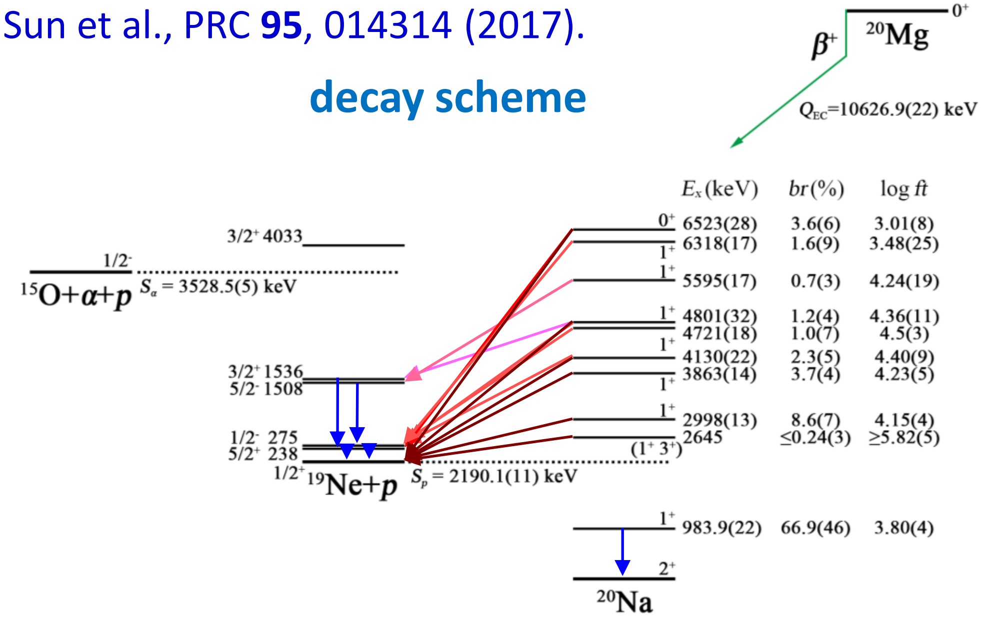
^{20}Mg



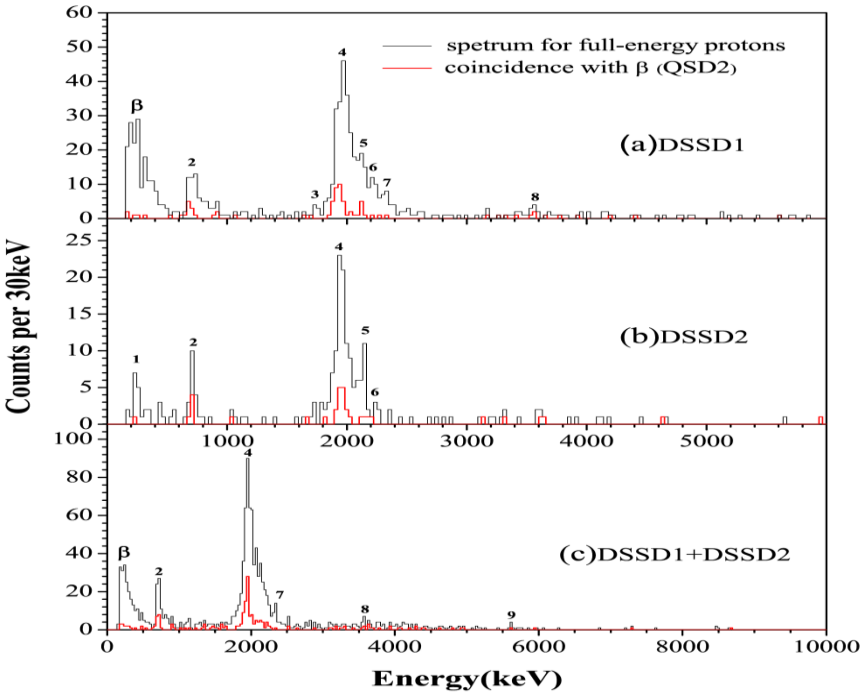




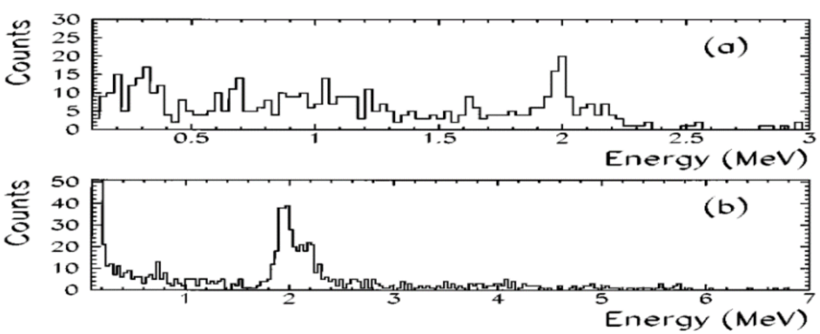
L. J. Sun et al., PRC **95**, 014314 (2017).



^{22}Si



CIAE - Phys. Lett. B **766**, 312 (2017).



GANIL - Phys. Rev. Lett. 59, 33 (1987).
Phys. Rev. C 54, 572 (1996).

Peak	Energy (keV)	BR (%)	Decay Mode
1	230(50)	2.9(10)	$2p$?
2	680(50)	6.8(14)	βp
3	1710(50)	1.9(7)	βp
4	1950(50)	52.0(74)	βp
5	2110(50)	10.9(21)	βp
6	2180(50)	6.5(15)	βp
7	2330(50)	5.1(13)	βp
8	3550(50)	2.5(9)	βp
9	5600(70)	0.7(3)	$\beta 2p$

★ **Mass of ^{22}Si**

- $\Delta(^{22}\text{Si}) = \Delta(^{22}\text{Al IAS}) + \Delta E_C - \Delta_{nH}$
  → S_{2p} **= -108 ± 125 keV;**
- $\Delta(^{22}\text{Si}) = \Delta(^{22}\text{O}) - 2b(A,T)T_Z$
  → S_{2p} **= -15 keV**

The first experimental mass data.
The first $\beta 2p$ precursor found in Asian Lab.

Discussions on ^{22}Si/^{20}Mg

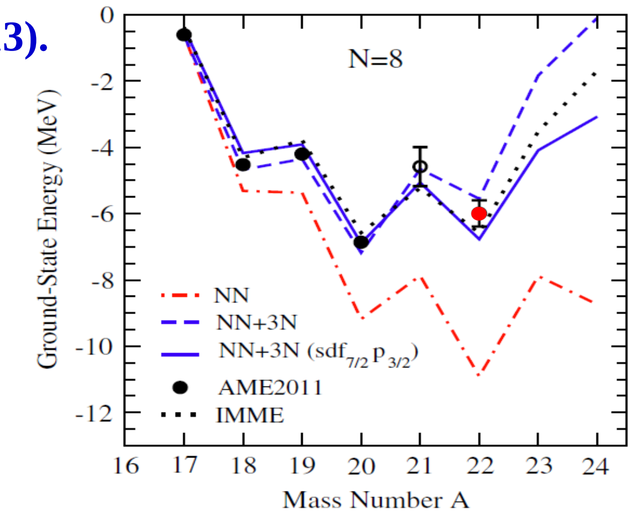
☞ Mirror asymmetry → INC interaction

asymmetry parameter: $\delta = \frac{ft^+}{ft^-} - 1$

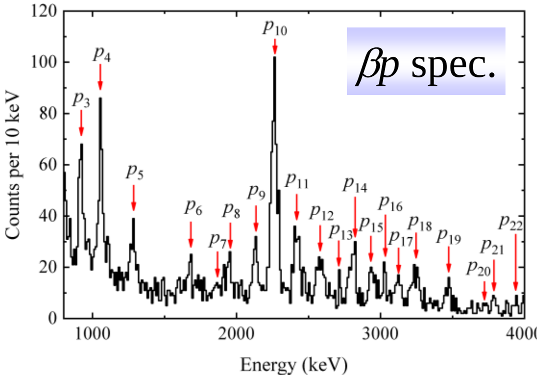
^{20}Mg→^{20}Na				^{20}O→^{20}F			
^{20}Na E^* (keV)	*br* (%)	log *ft*	J^π	^{20}F E^* (keV)	*br* (%)	log *ft*	**δ**
983.9(22)	66.9(46)	3.80(4)	1^+	1056.848(4)	99.973(3)	3.740(6)	**0.148(107)**
2998(13)	8.6(7)	4.15(4)	1^+	3488.54(10)	0.027(3)	3.65(6)	**2.16(53)**
^{22}Si→^{22}Al				**^{22}O→^{22}F**			
^{22}Al E^* (keV)	*br* (%)	log *ft*	J^π	^{22}F E^* (keV)	*br* (%)	log *ft*	δ
1170(50)	5.1(3)	5.10(5)	1^+	1625	29(4)	4.6(1)	**2.16(82)**
2400(50)	60.6(65)	3.79(7)	1^+	2572	68(6)	3.8(1)	**-0.02(28)**

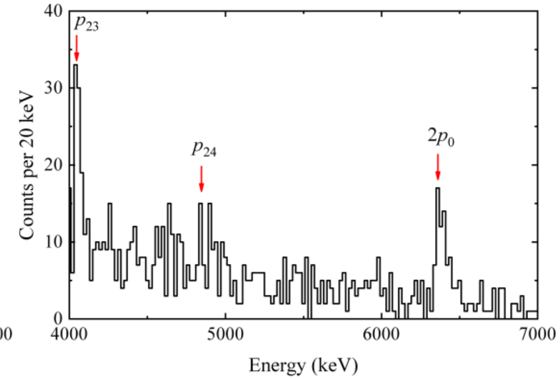
☞ Mass → Three-Body Force **PRL110,022502(2013).**

Nucleus	S_p			S_{2p}		
$N = 8$	Expt. [IMME]	$NN + 3N$ sd	$NN + 3N$ $sdf_{7/2}p_{3/2}$	Expt. [IMME]	$NN + 3N$ sd	$NN + 3N$ $sdf_{7/2}p_{3/2}$
^{18}Ne	3.92	4.05	3.76	4.52	4.67	4.17
^{19}Na	−0.32	−0.32	−0.26	3.60	3.73	3.50
^{20}Mg	2.66	2.83	2.98	2.34	2.51	2.72
^{21}Al	[−1.34]	−2.52	−1.83	[1.45]	0.30	1.15
^{22}Si	[1.35]	0.90	1.71	[0.01]	−1.63	−0.12

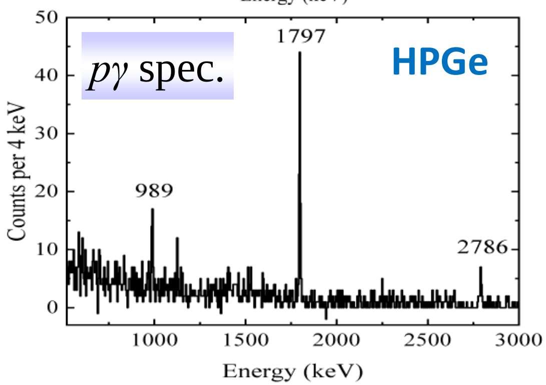


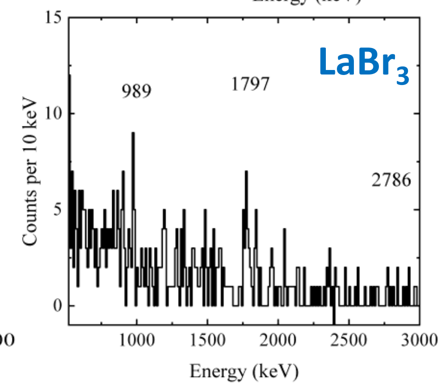
Results 2: ^{27}S

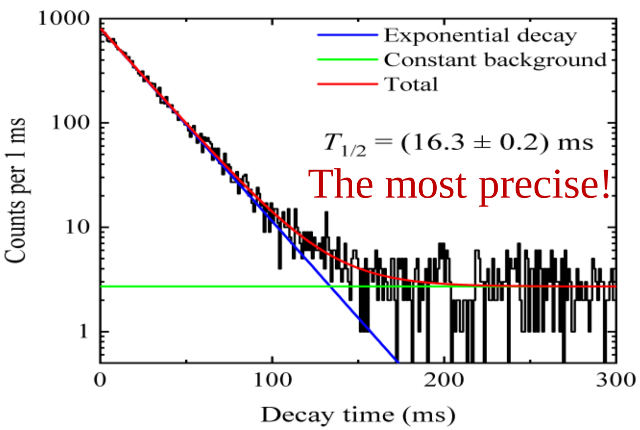




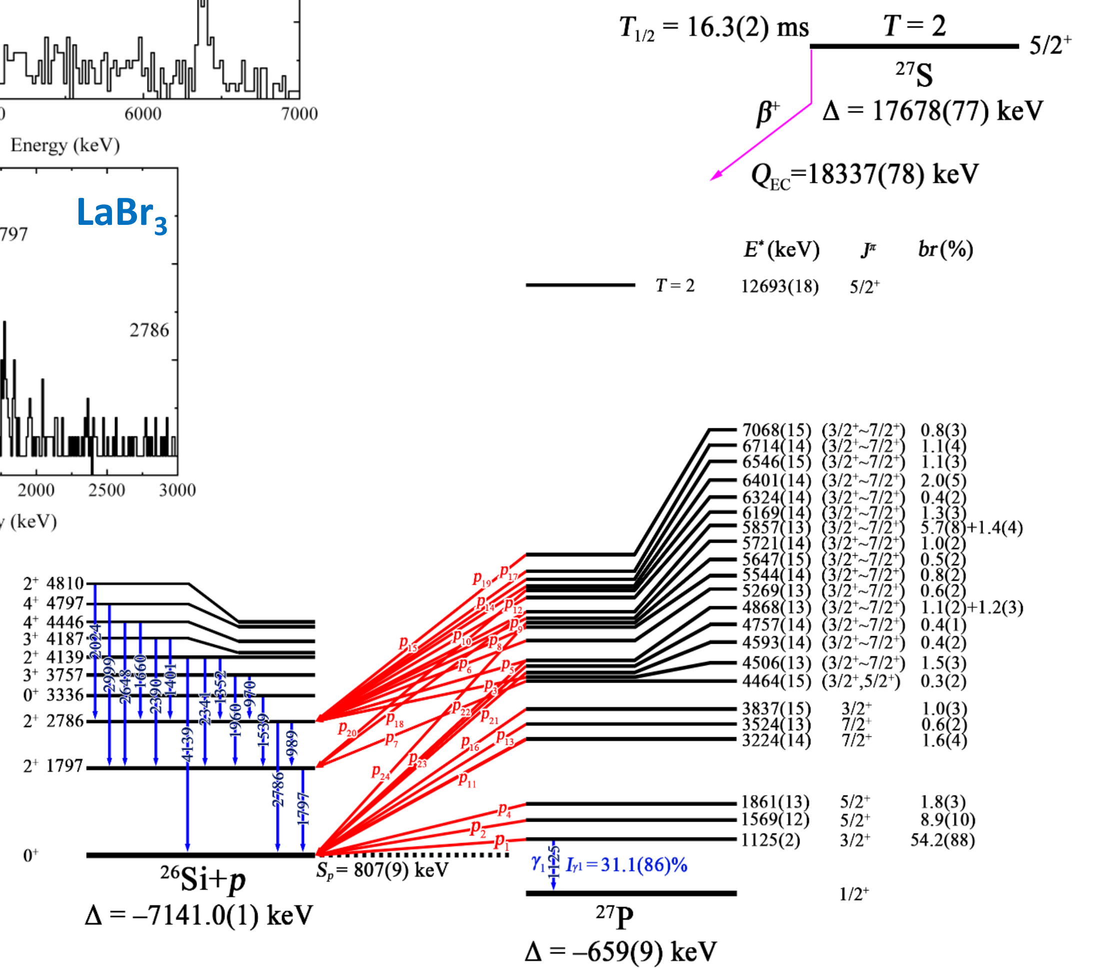
24 *βp* & 1 *β2p* decays







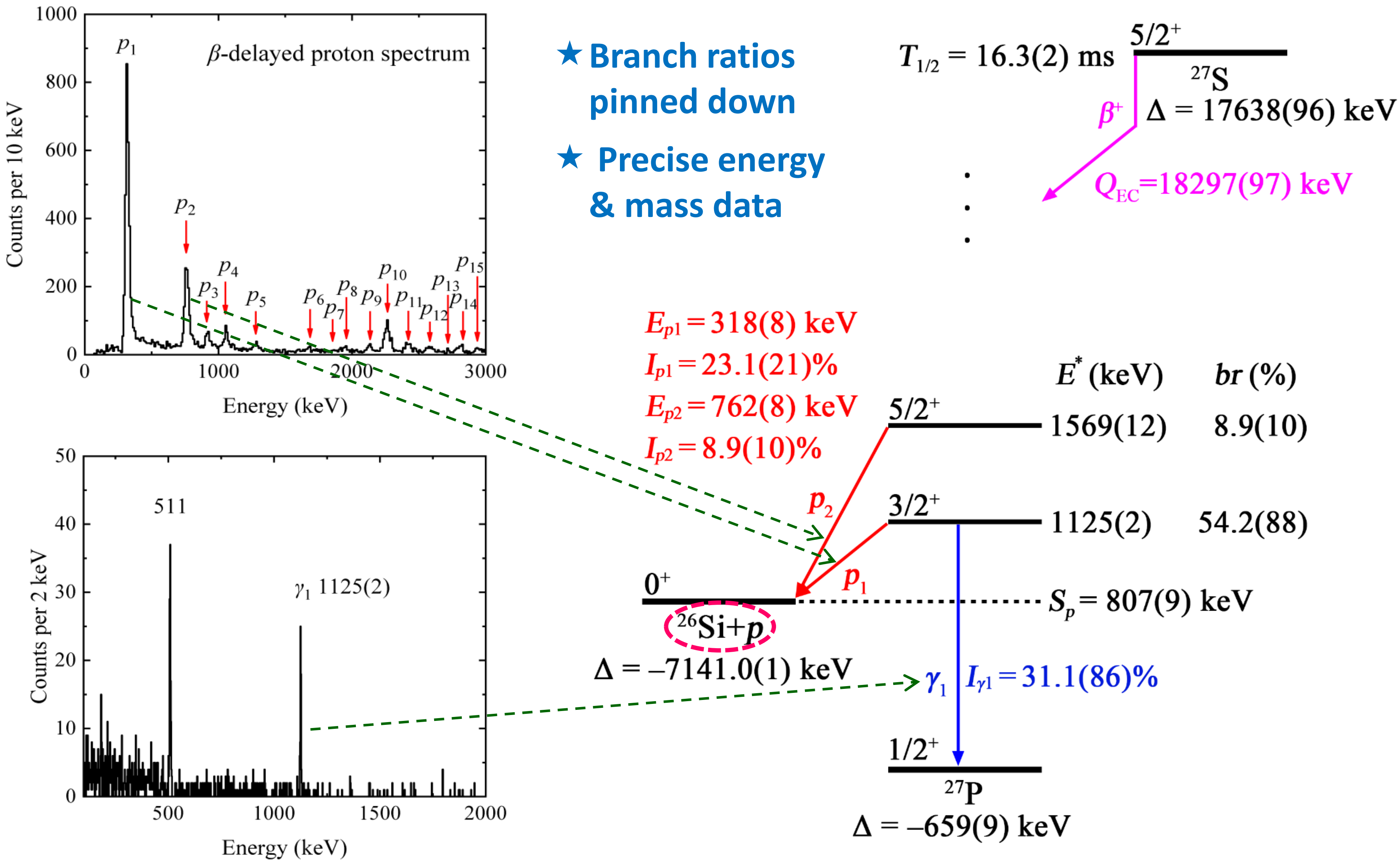
decay scheme



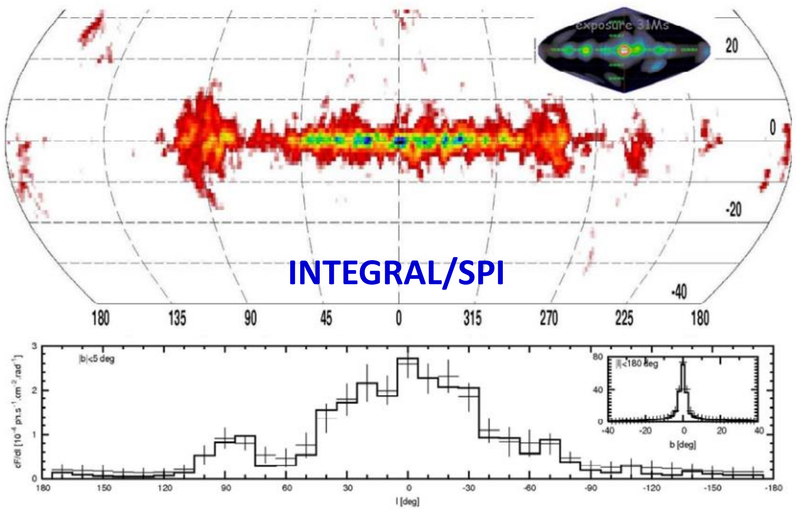
Daughter: ^{27}P

βp & *βγ* were measured simultaneously for the first time.

- ★ Branch ratios pinned down
- ★ Precise energy & mass data

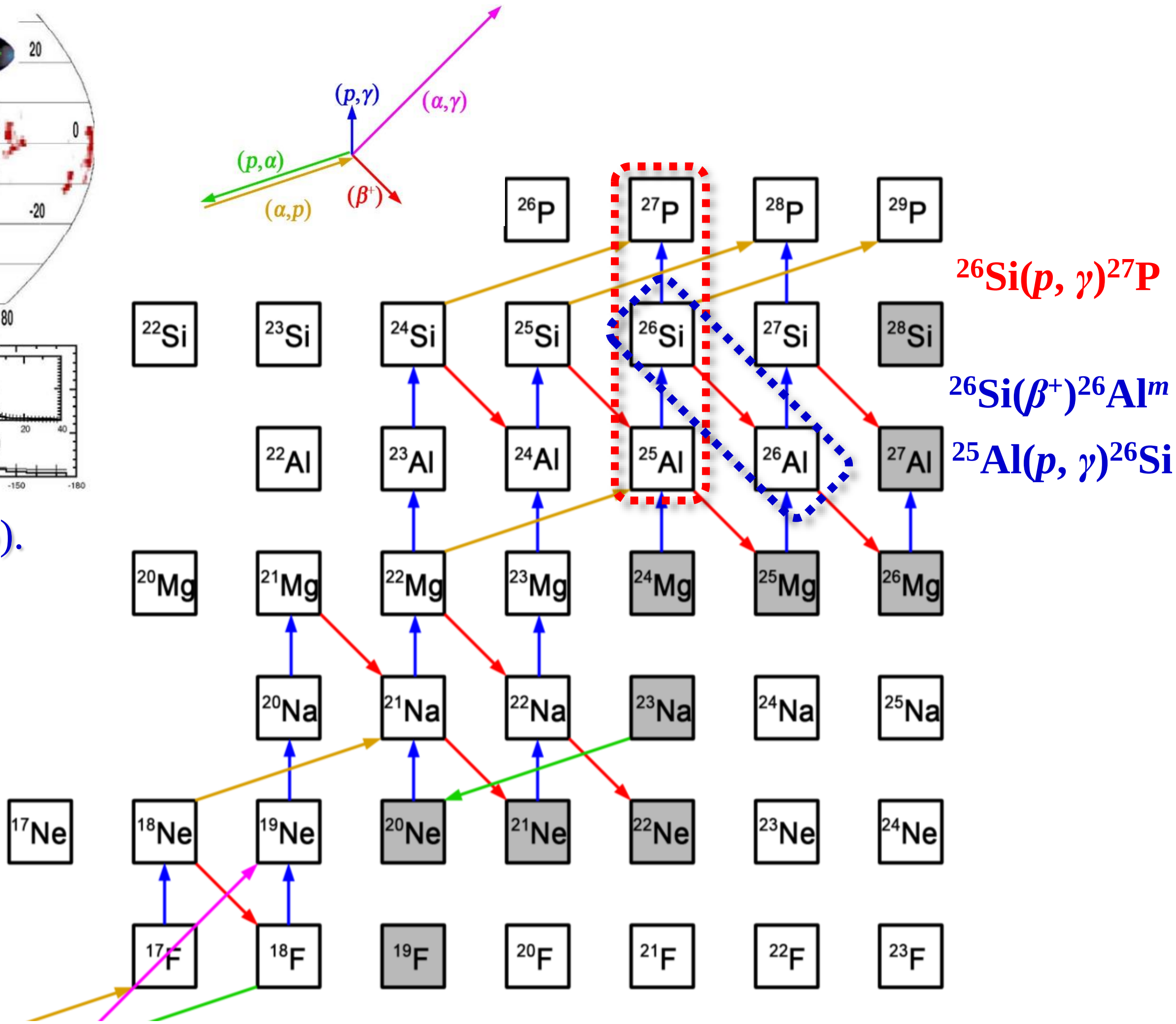


The Galactic ^{26}Al puzzle



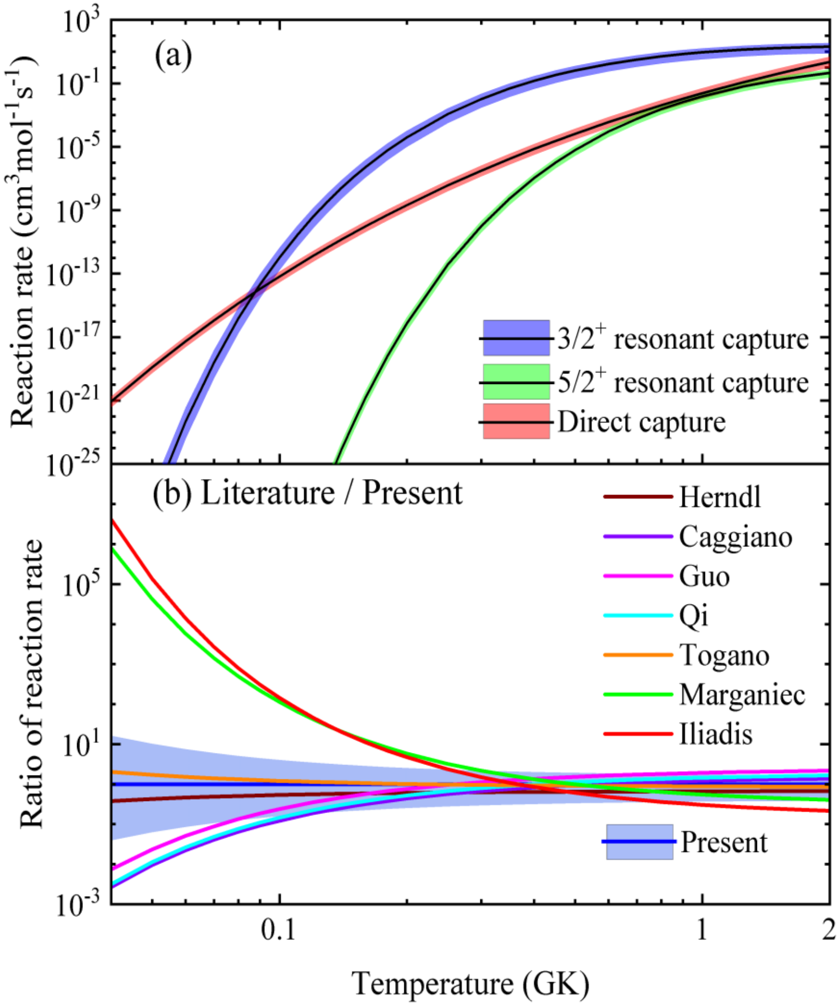
R. Diehl *et al.*, Nature 439, 45 (2006).

The ^{26}Si(p,γ)^{27}P reaction competes with the β decay of ^{26}Si to ^{26}Al^{m}, and the latter can produces ^{26}Al^{g} via thermal excitations. Thus, the production and destruction of ^{26}Si by proton capture should be influential in determining the amount of the ^{26}Al^{m} and ^{26}Al^{g} produced by the equilibrium.

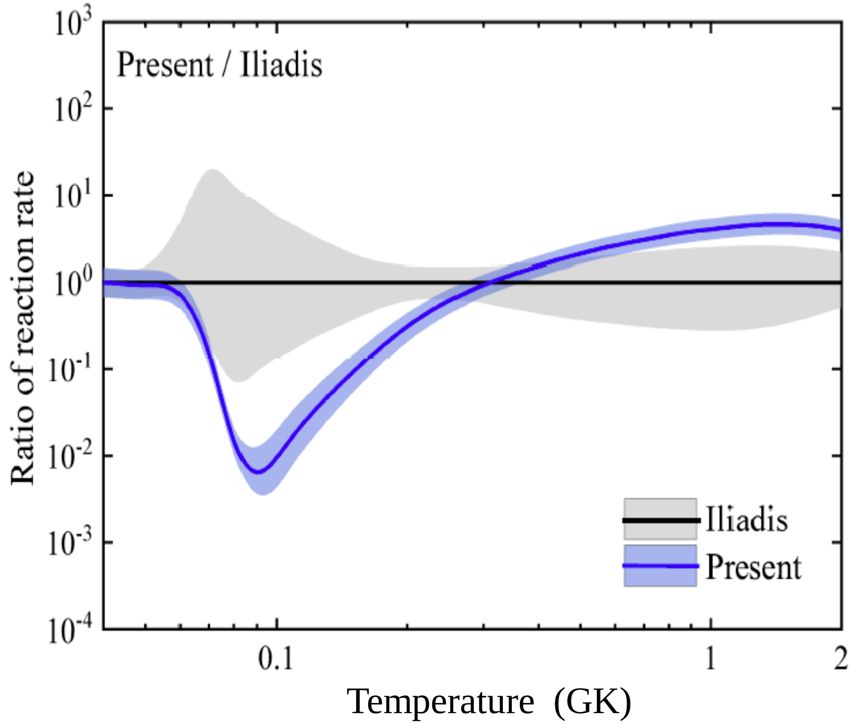


Explosive hydrogen burning scenarios

Thermonuclear $^{26}Si(p,\gamma)^{27}P$ Rate



Comparison of the calculated thermonuclear reaction rates from the 3/2$^+$ resonance contribution.



Comparison of the thermonuclear $^{26}Si(p,\gamma)^{27}P$ reaction rates.

L.J. Sun *et al.*, arXiv:1809.02980v1; arXiv:1809.02987v1.

Collaborators

Thanks to all the collaborators

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17 Department of Physics, University of Napoli "Federico II", Via Cintia, I-80126 Napoli, Italy
18 University of Catania, Sicily, Italy

… …

Thank you for your attention.