JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Gamma-ray spectroscopy employing JUROGAM 3 and MARA – in-beam studies of N ≈ Z nuclei at JYFL

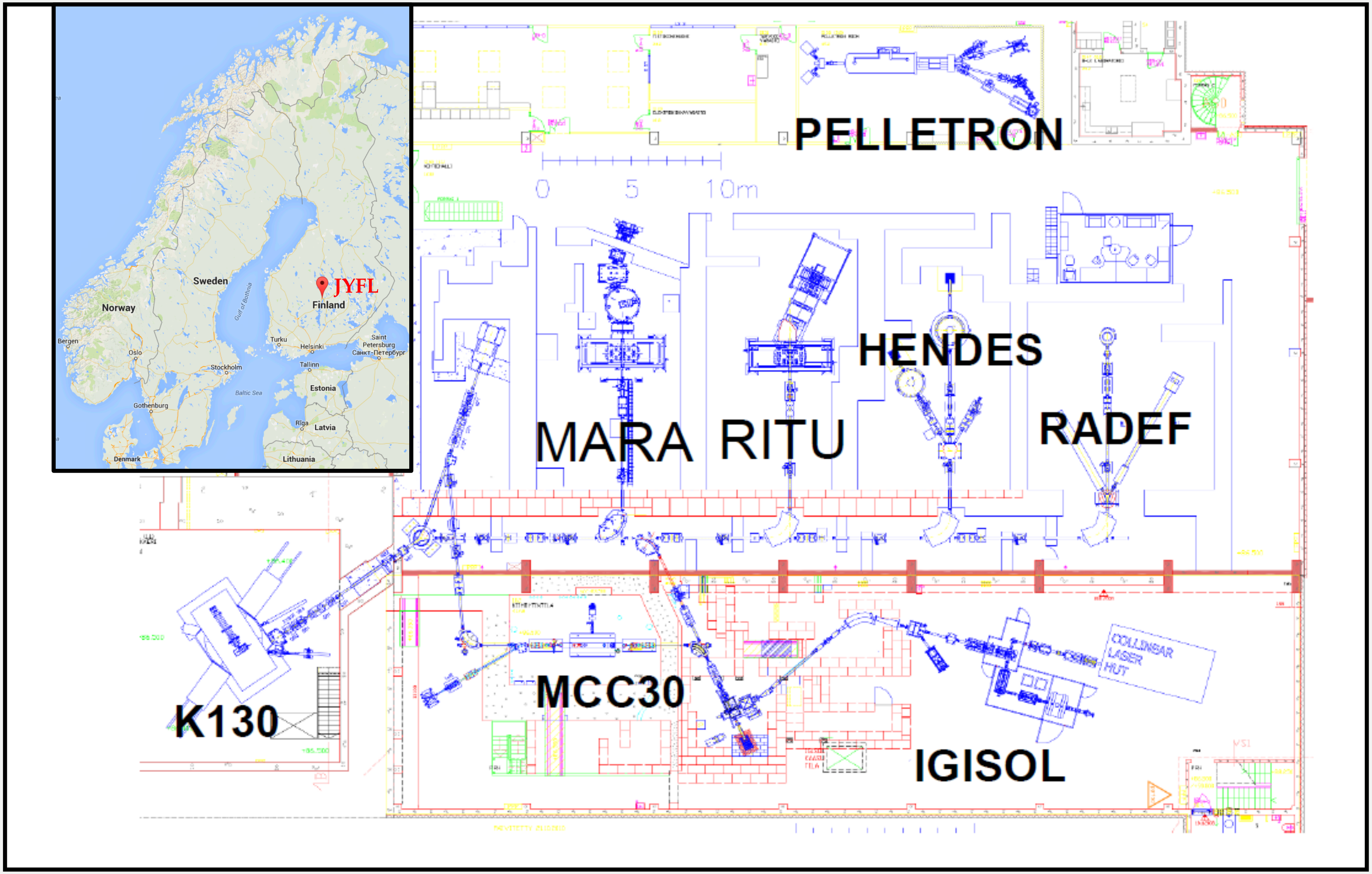
NuSpin 2019, 24.6.2019

Dr. Panu Ruotsalainen, University of Jyväskylä, Department of Physics

Outline

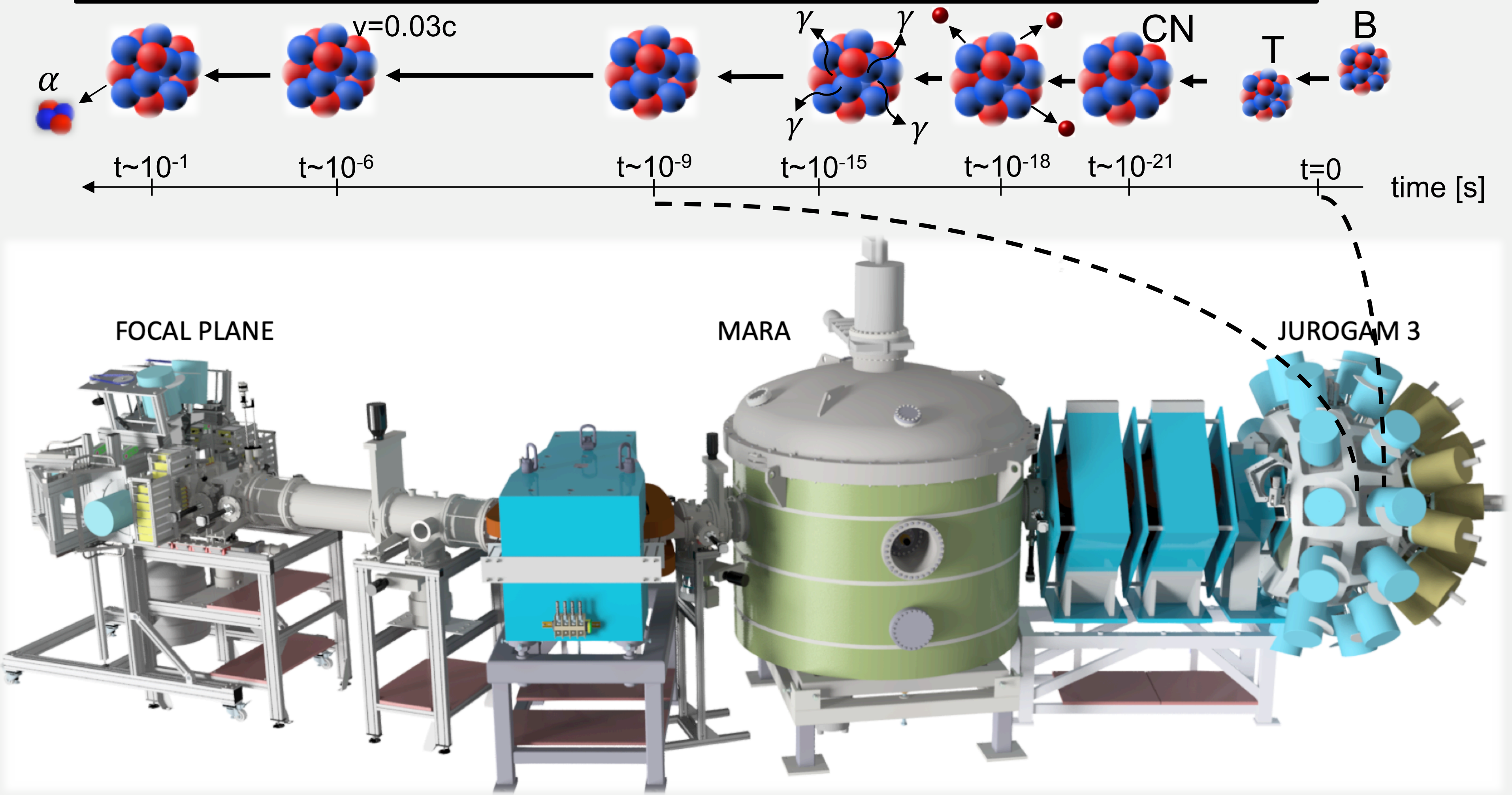
- JYFL
- Recoil-decay tagging
- **M**ass **A**nalysing **R**ecoil **A**pparatus – MARA
- MARA focal plane
- JYtube charged particle (veto) detector
- MARA focal plane spectroscopy
- JUROGAM 3
- JUROGAM 3 scientific program at JYFL
    - *np* pairing correlations
    - Isospin symmetry breaking

JYFL


JYFL
Sweden
Norway
Finland
Bergen
Oslo
Turku
Helsinki
Saint Petersburg
Санкт-Петербург
Tallinn
Stockholm
Estonia
Gothenburg
Baltic Sea
Gulf of Bothnia
Riga
Latvia
Denmark
Lithuania
PELLETRON
0
5
10m
HENDES
MARA
RITU
RADEF
K130
MCC30
IGISOL
COLLINSAR LASER HUT

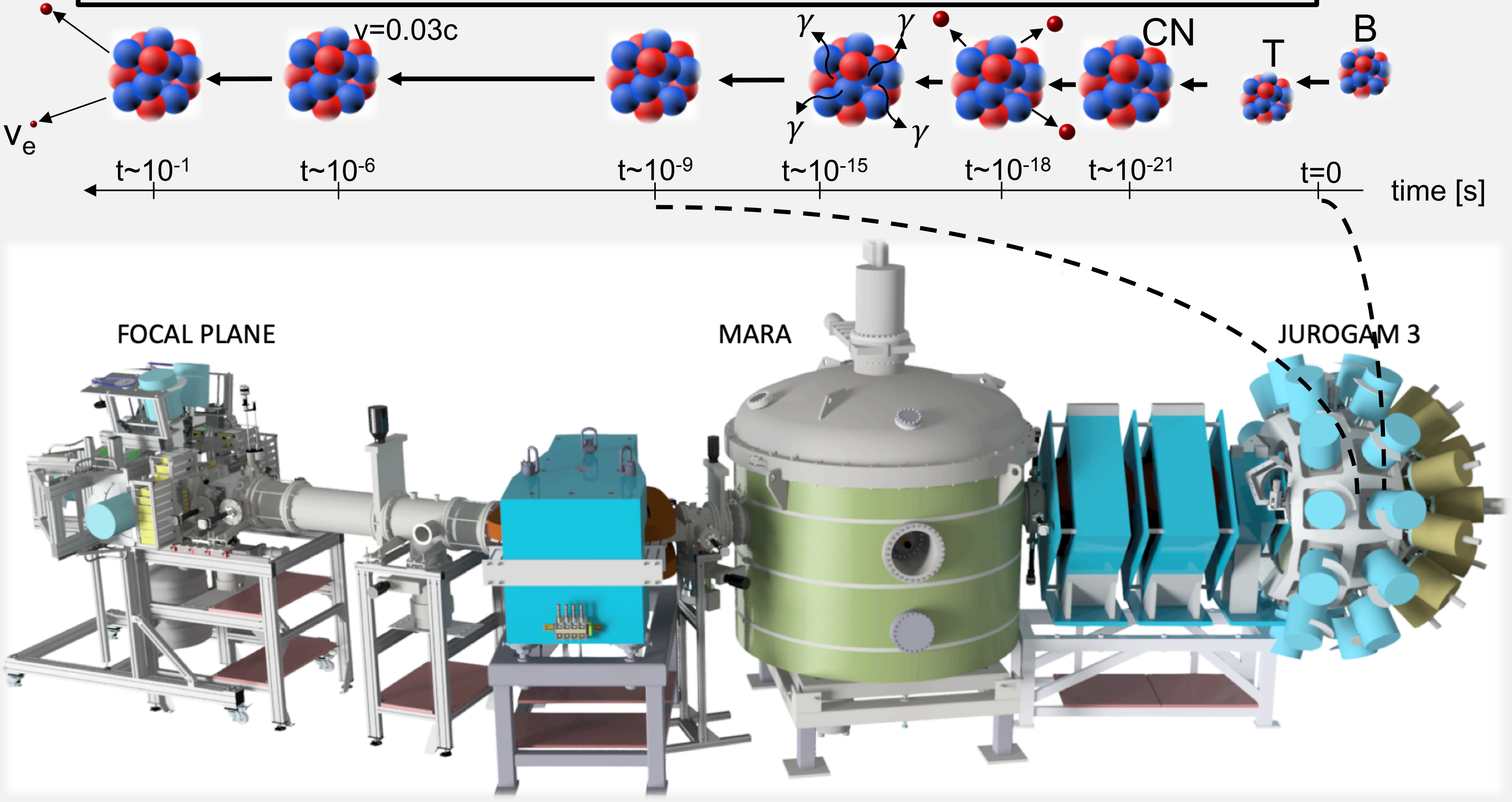
Recoil-decay tagging

1) Identify recoil based on its characteristic α decay (A > 110).
2) Tag prompt (or delayed) γ-ray transitions originating from the recoil.



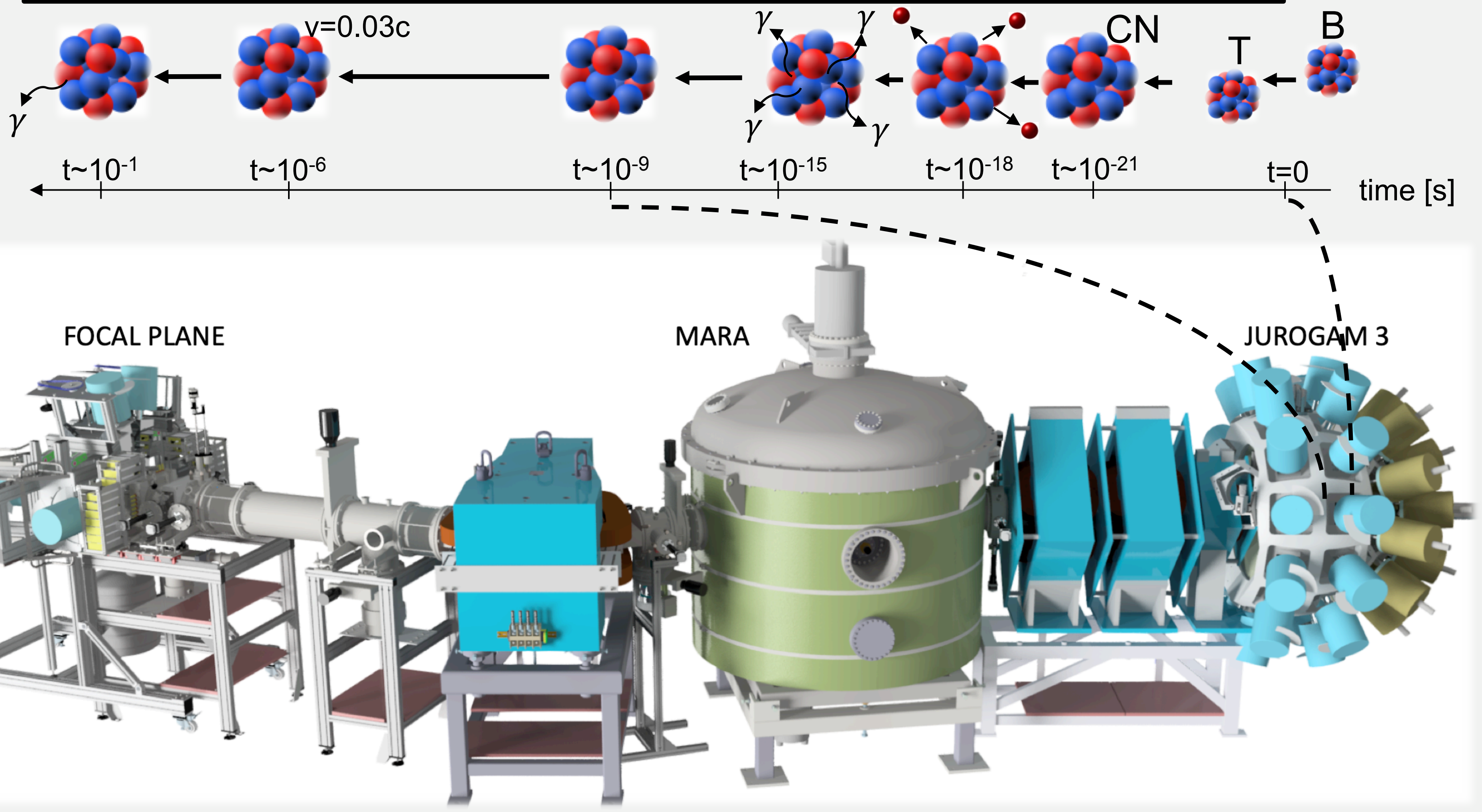
Recoil-decay tagging

1) Identify recoil based on its β decay (A < 110).
2) Tag prompt (or delayed) γ-ray transitions originating from the recoil.



Recoil-decay tagging

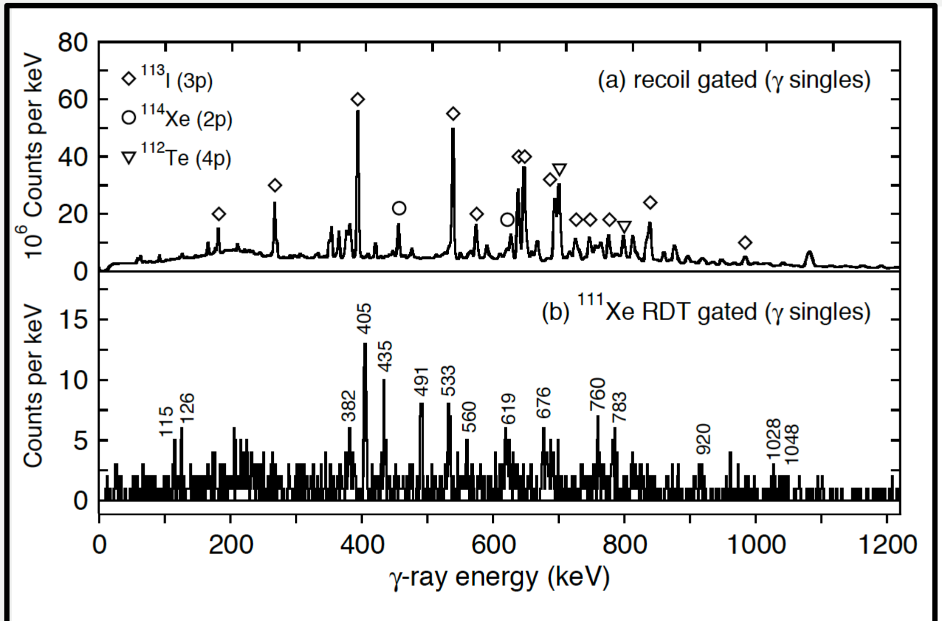
1) Identify recoil based on isomeric γ-ray transition.
2) Tag prompt (or delayed) γ-ray transitions originating from the recoil.



Recoil-decay tagging

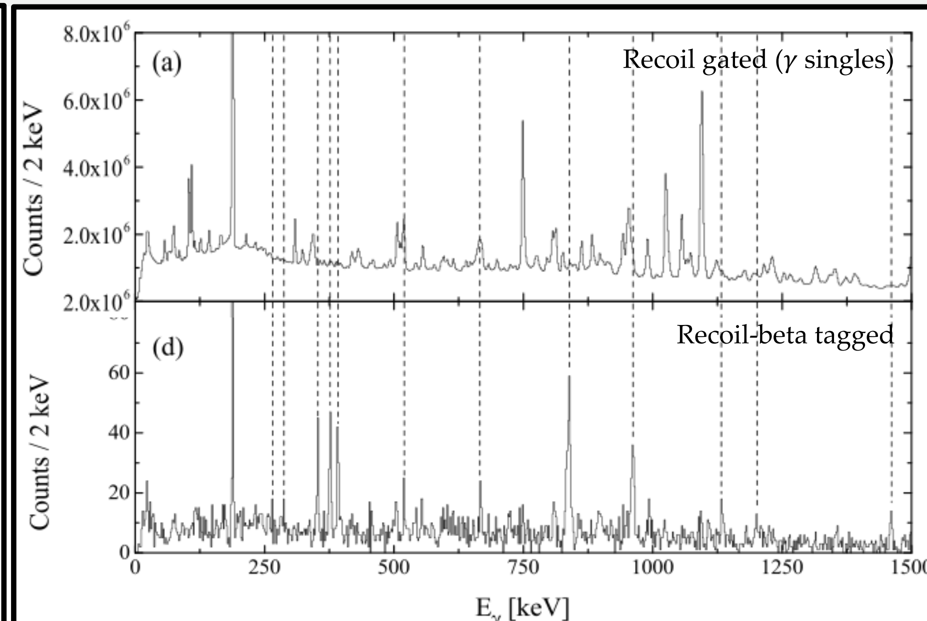
^{111}Xe

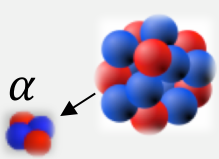
$^{58}Ni + ^{58}Ni$ @ 210 MeV, JUROGAM II + RITU



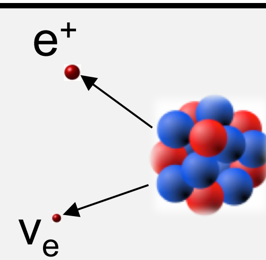
^{66}As

$^{28}Si + ^{40}Ca$ @ 75 MeV, JUROGAM II + RITU





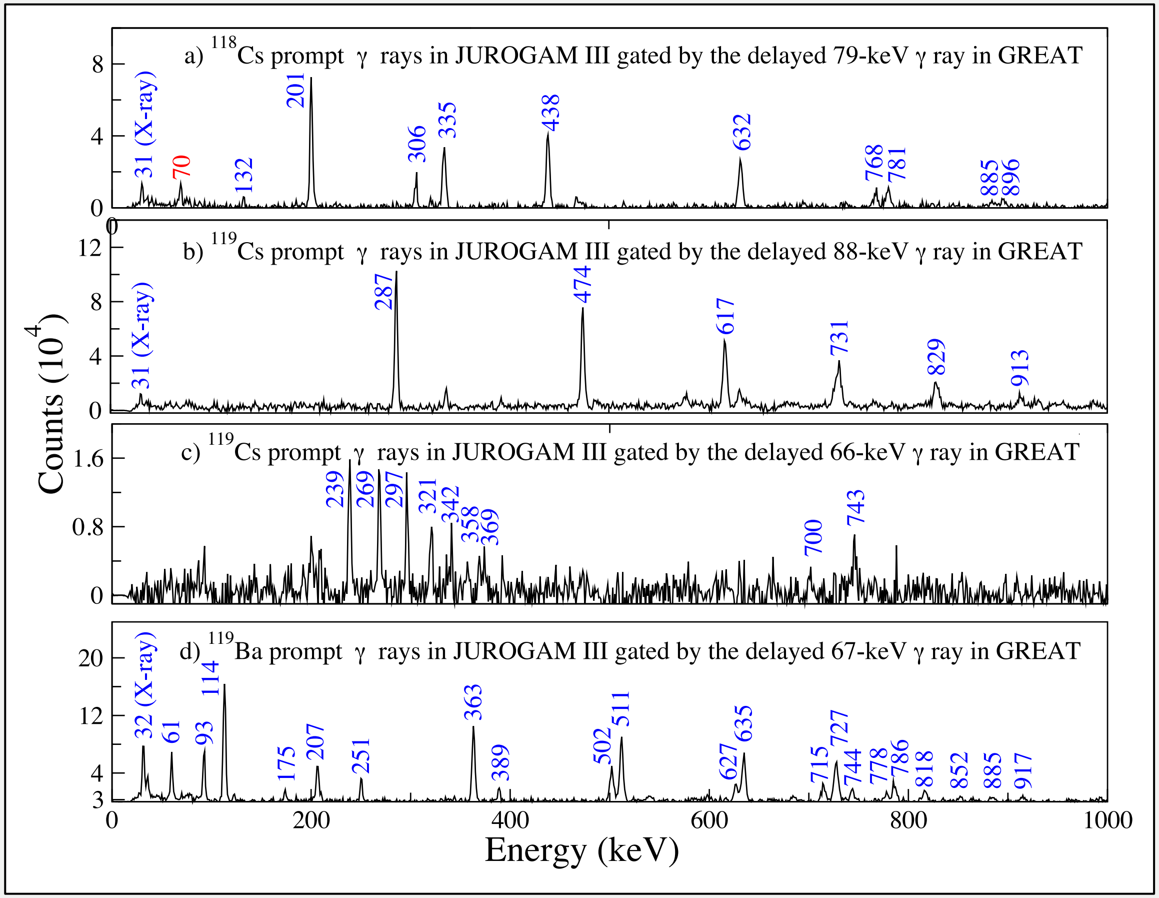
"Recoil-alpha tagging"



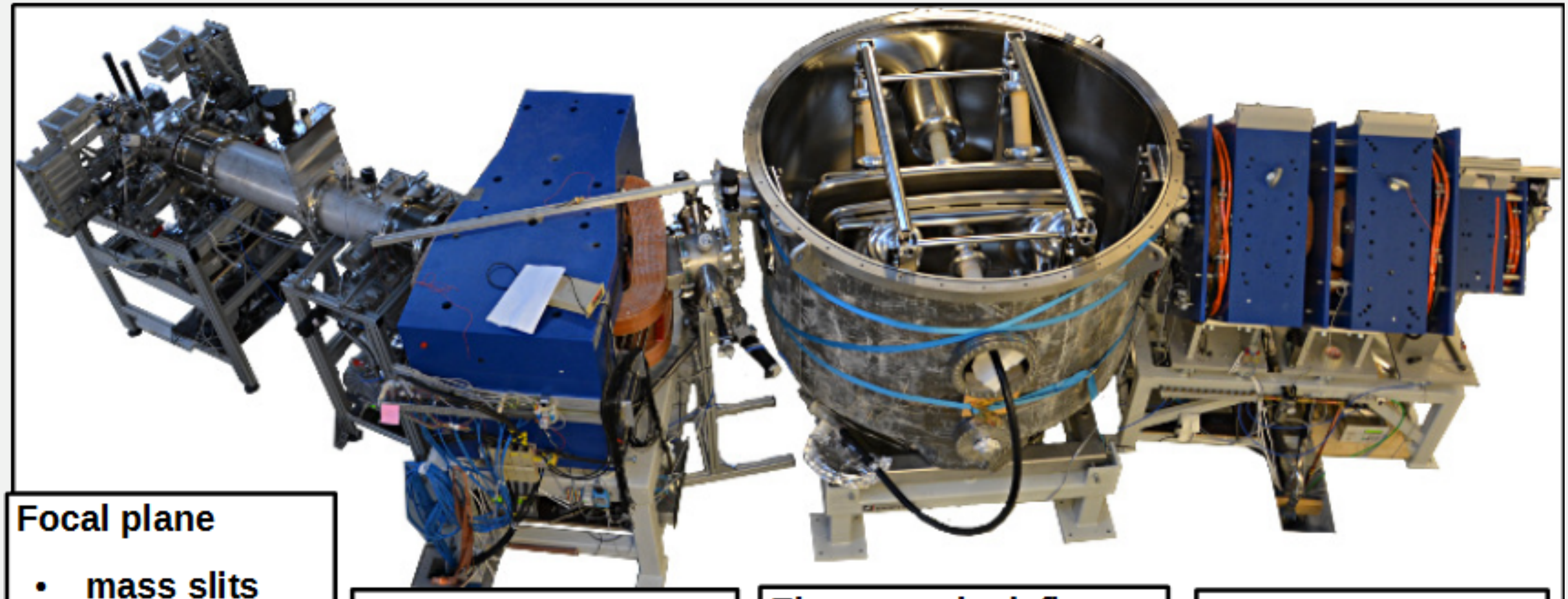
"Recoil-beta tagging"

Isomer tagging

C. Petrache
J3+MARA experiment in May 2019



MARA – Mass Analysing Recoil Apparatus



Focal plane

- mass slits
- MWPC, DSSD, Box detector and Ge array

Magnetic dipole

- 1 T, 1 m radius
- adjustable surface coils to change focal plane position

Electrostatic deflector

- beam separation
- +- 230 kV, 4 m radius
- split anode and a beam dump

Quadrupole triplet

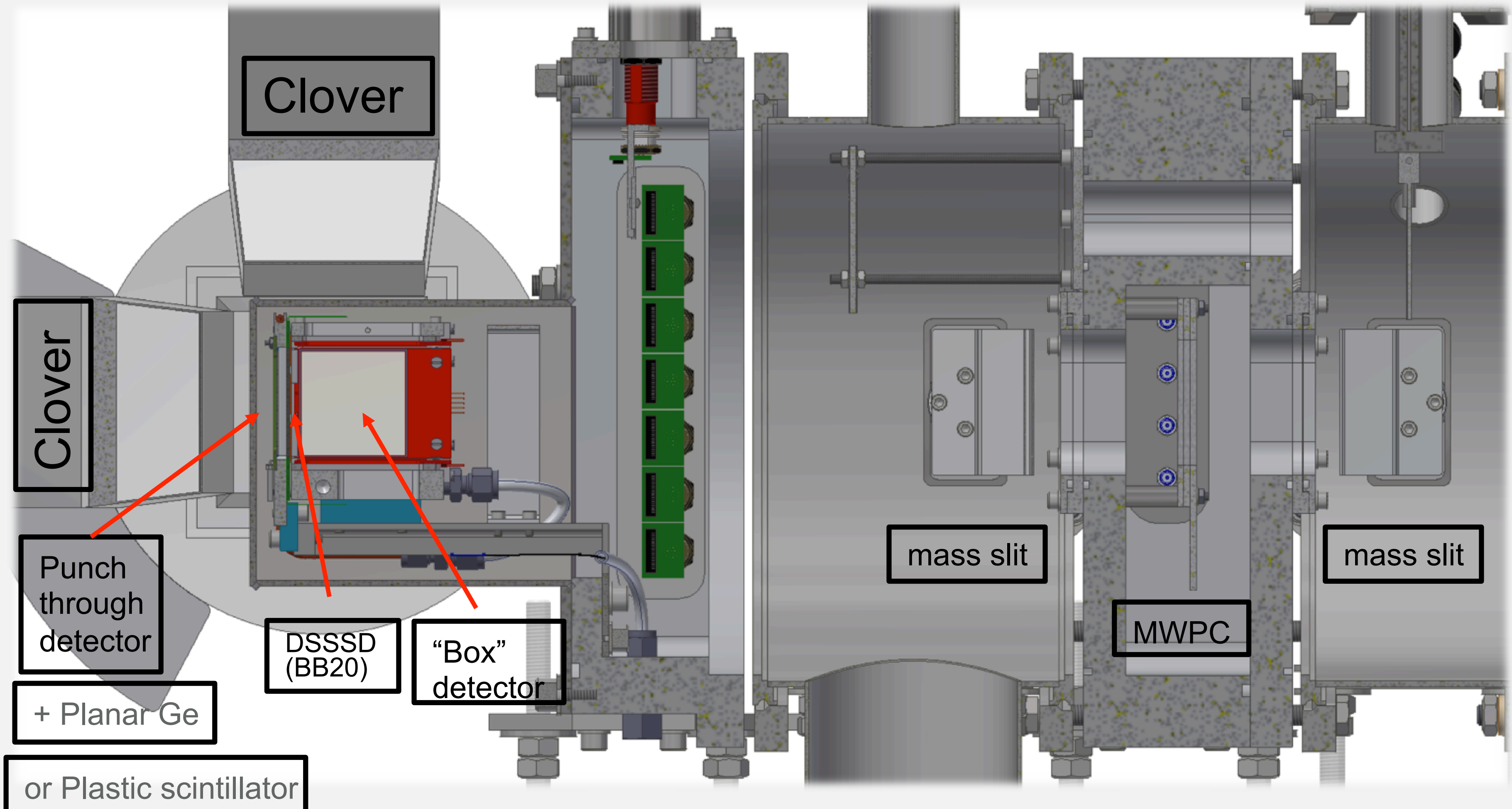
- scalable first order resolving power

MARA – Mass Analysing Recoil Apparatus

Main properties of the MARA separator @ JYFL in comparison to FMA @ ANL:

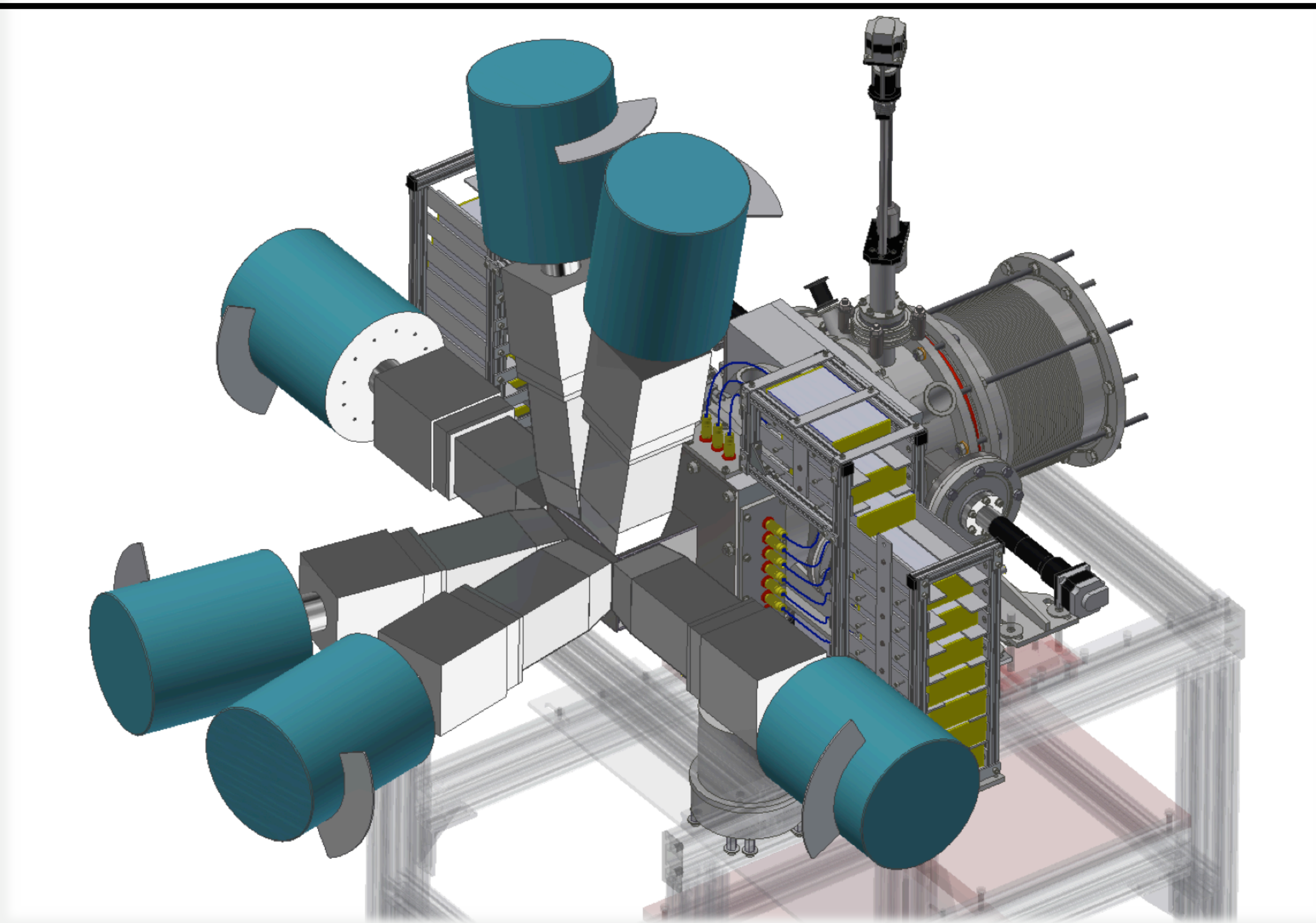
	FMA	MARA
Configuration	Q-Q-ED-MD-ED-Q-Q	Q-Q-Q-ED-MD
Horizontal magnification	-1.93	-1.55
Vertical magnification	0.98	-4.48
m/q dispersion	10 mm/(1 % in m/q)	8.0 mm/(1 % in m/q)
1^{st} order resolving power with 2 mm beam spot	259	259
Solid angle acceptance for central m/q and E	8 msr	10 msr
Energy acceptance for central M and angle	-15% – +20%	-15% – +20%
M/Q acceptance	±4%	±7%

MARA focal plane



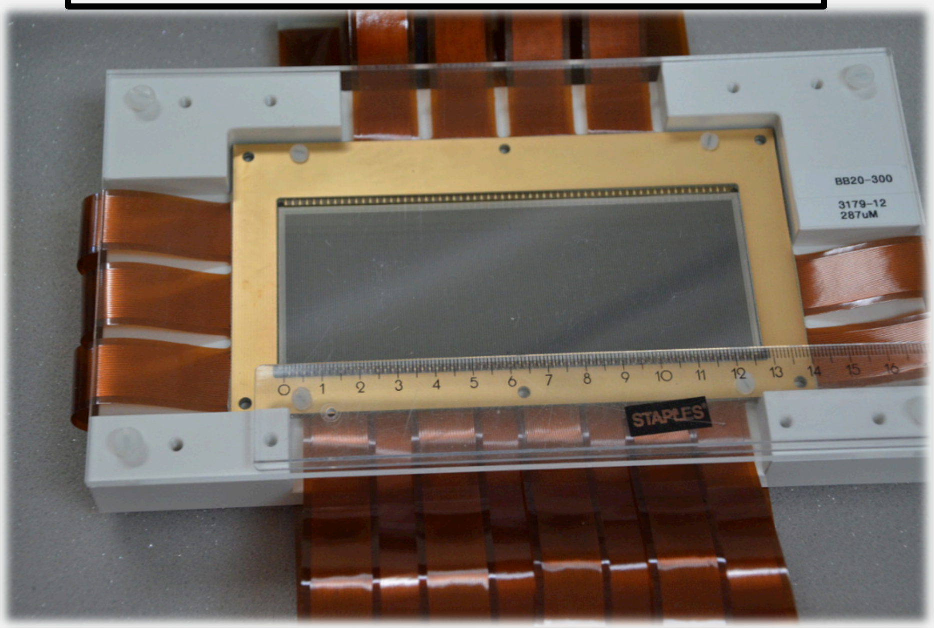
MARA focal plane

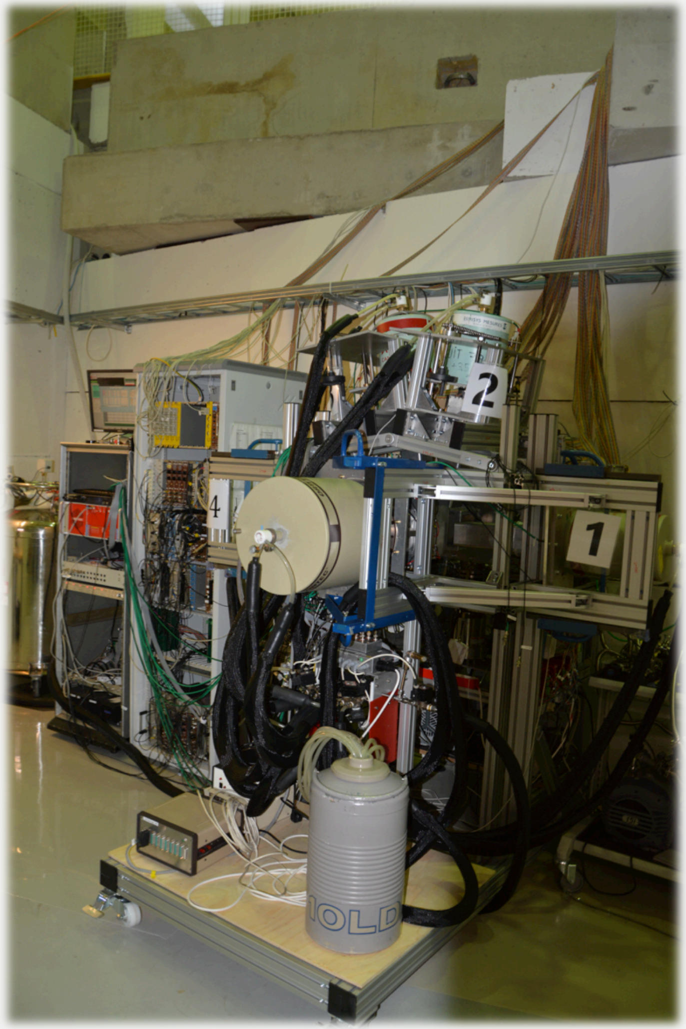
Ge-detector frame houses 6 or 4 Clovers (GAMMAPOOL + one JYFL Ge) and a large GREAT clover. Three new BeGes will be available in fall 2019.



MARA focal plane

Micron BB20 DSSSD
Area: 128x48 mm^2
Strip pitch: 0.67 mm
Thicknesses: 300, 150 and 700 um

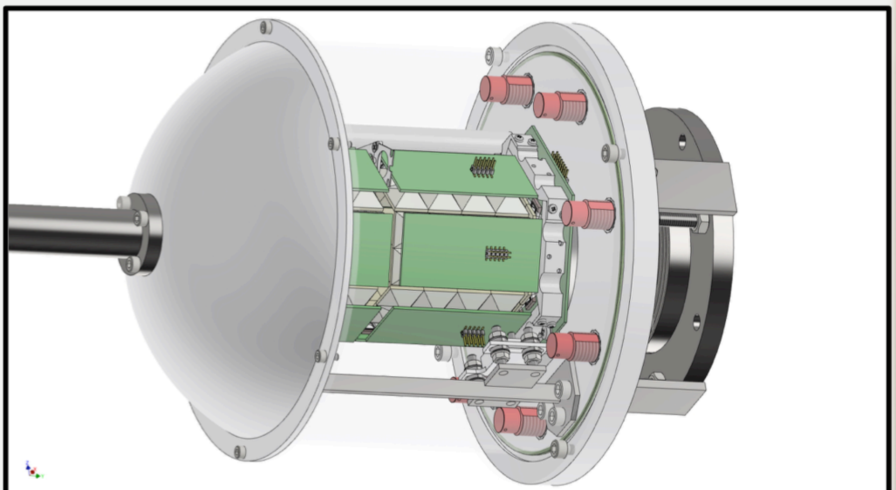


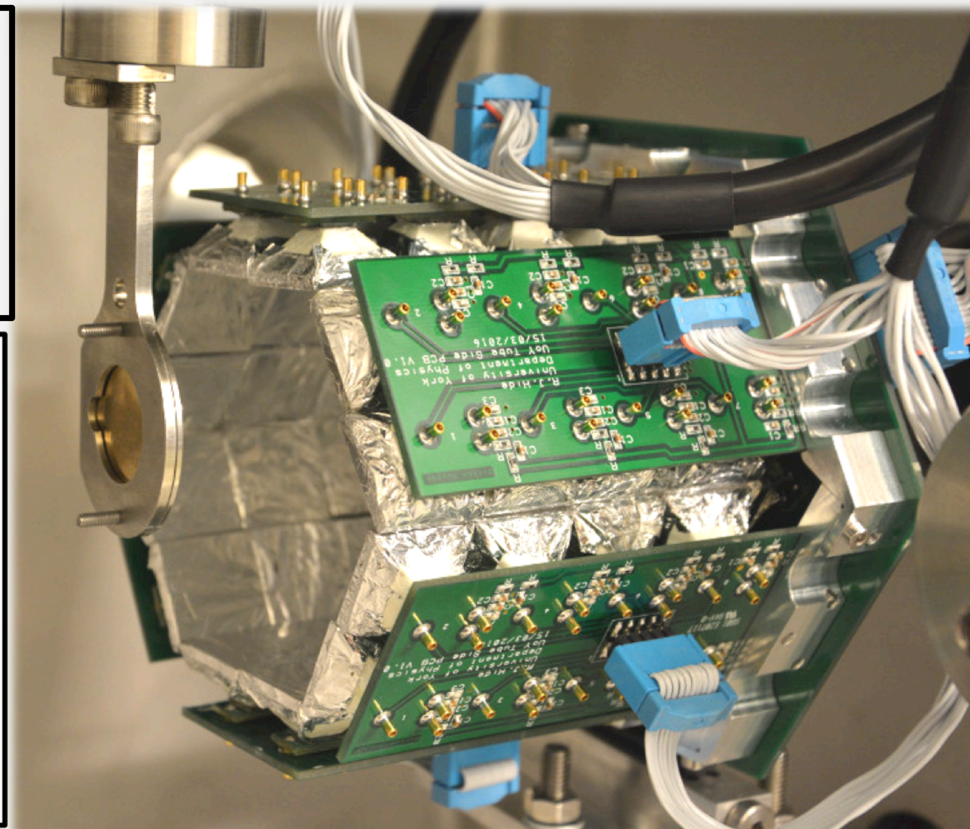


JYtube charged particle detector

120 plastic scintillator elements read out by SiPMs

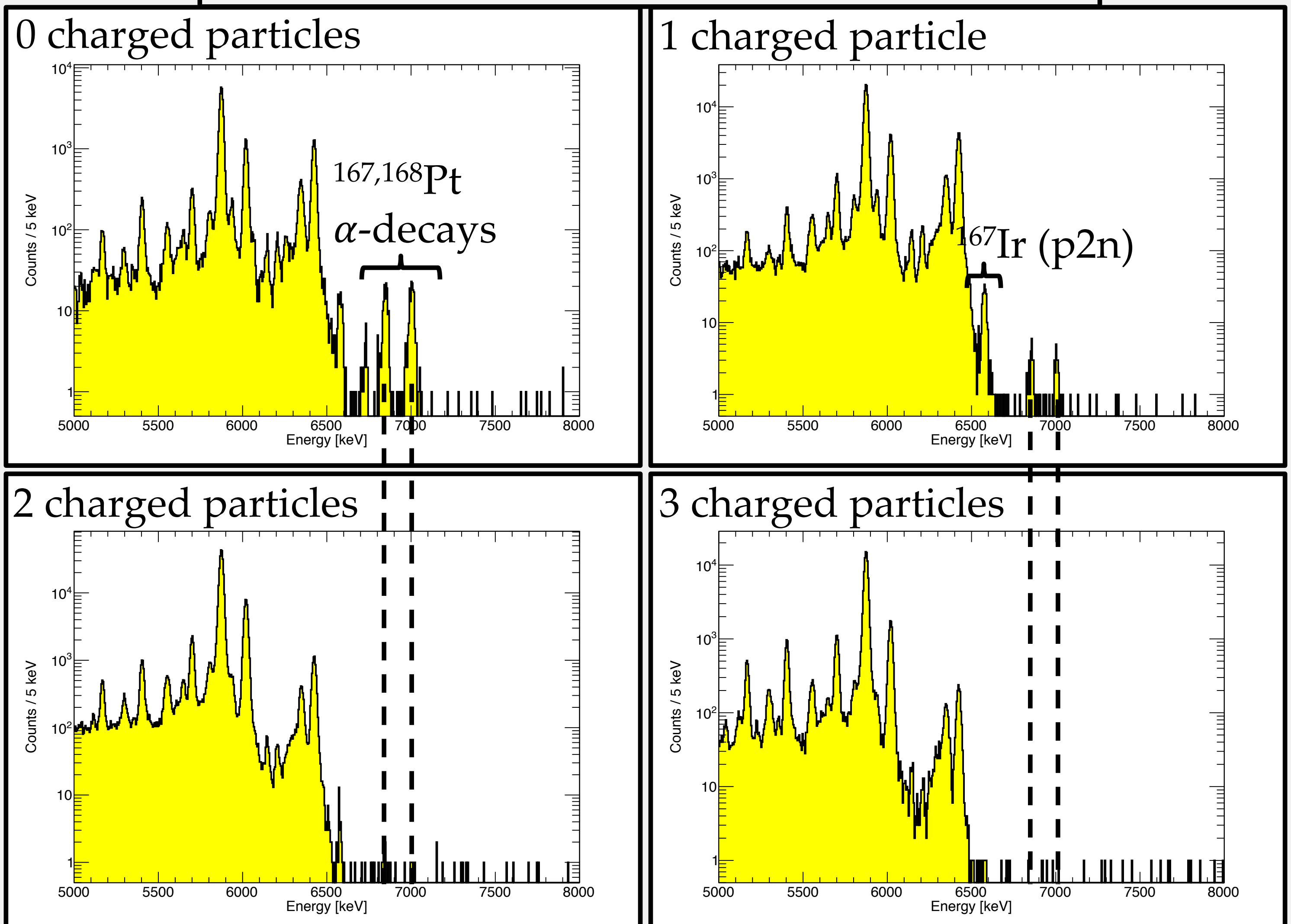
Detect evaporated charged particles
- → 65% cp detection eff.
- → cp veto to suppress *xp* channels
- → 97% veto efficiency for 3p
- → evaporation channel selection





JYtube charged particle detector

$^{78}\mathrm{Kr} + {}^{92}\mathrm{Mo} \rightarrow {}^{170}\mathrm{Pt}^{*} \rightarrow {}^{167}\mathrm{Pt} + 3n,\ {}^{168}\mathrm{Pt} + 2n$



MARA focal plane spectroscopy

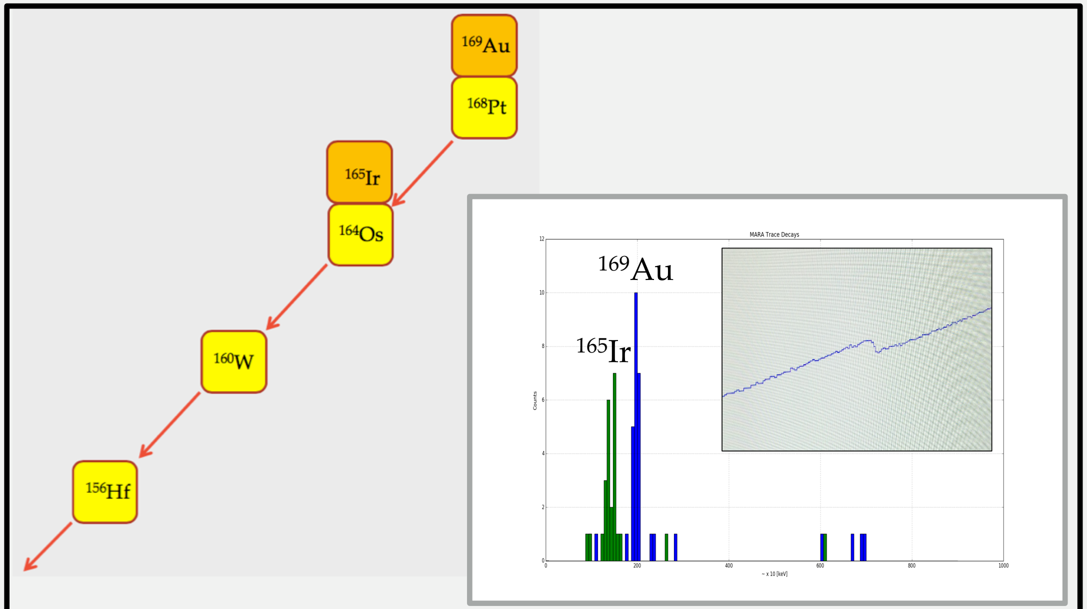
During the first two years of running MARA, discoveries of:

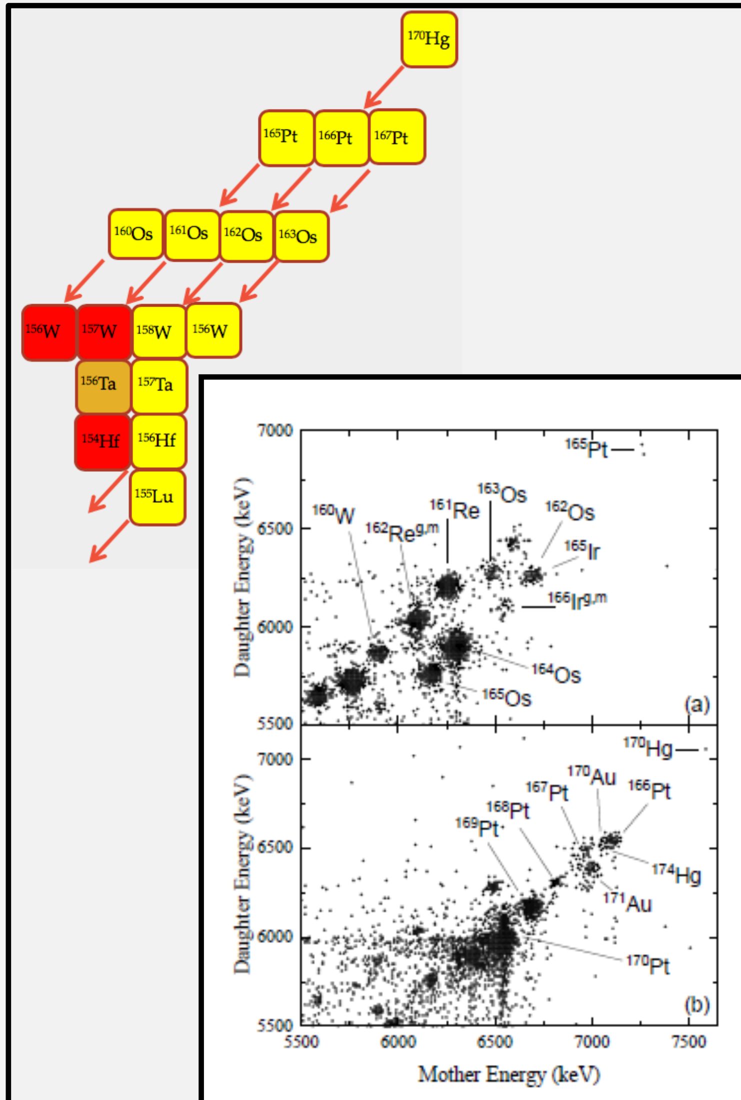
1) ^{160}Os
2) ^{156}W
in ^{58}Ni + ^{106}Cd -> ^{164}Os*, A. Briscoe, R. Page, J. Uusitalo et. al.

3) ^{170}Hg
4) ^{169}Au
in ^{78}Kr + ^{96}Ru -> ^{174}Hg*, J. Hilton and J. Uusitalo et. al.

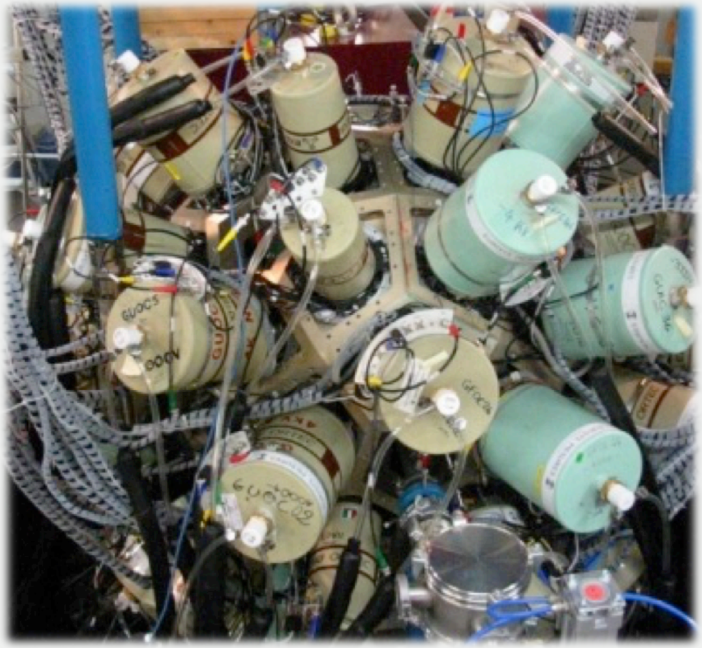
5) ^{165}Pt
in ^{78}Kr + ^{92}Mo -> ^{170}Pt*, J. Hilton and J. Uusitalo et. al.

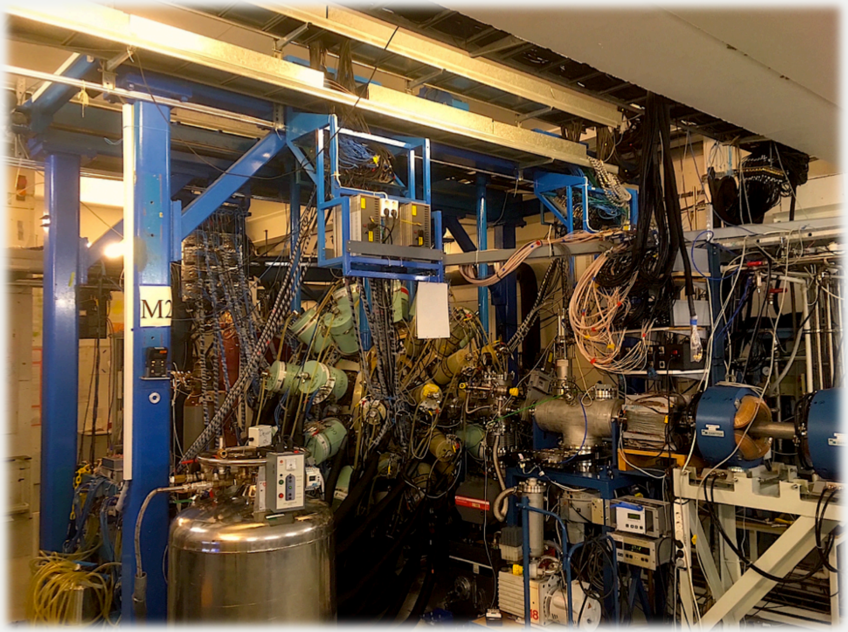
isotopes and several new excited isomeric states in Ba, Cs, I and Te isotopes (B. Cederwall, J. Uusitalo et. al.).





JUROGAM I & II

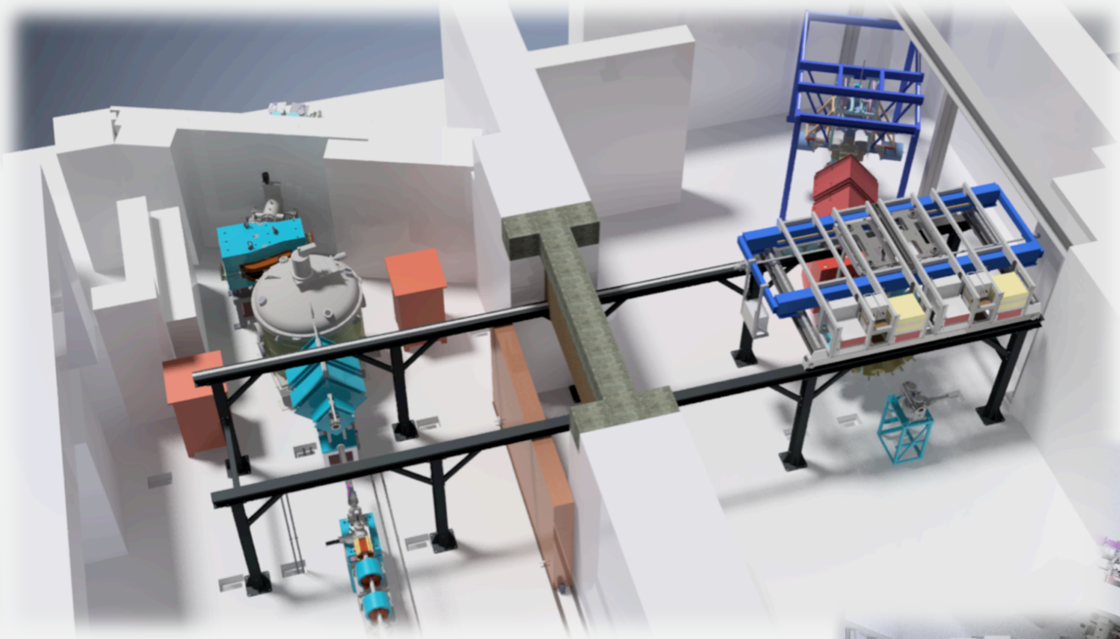


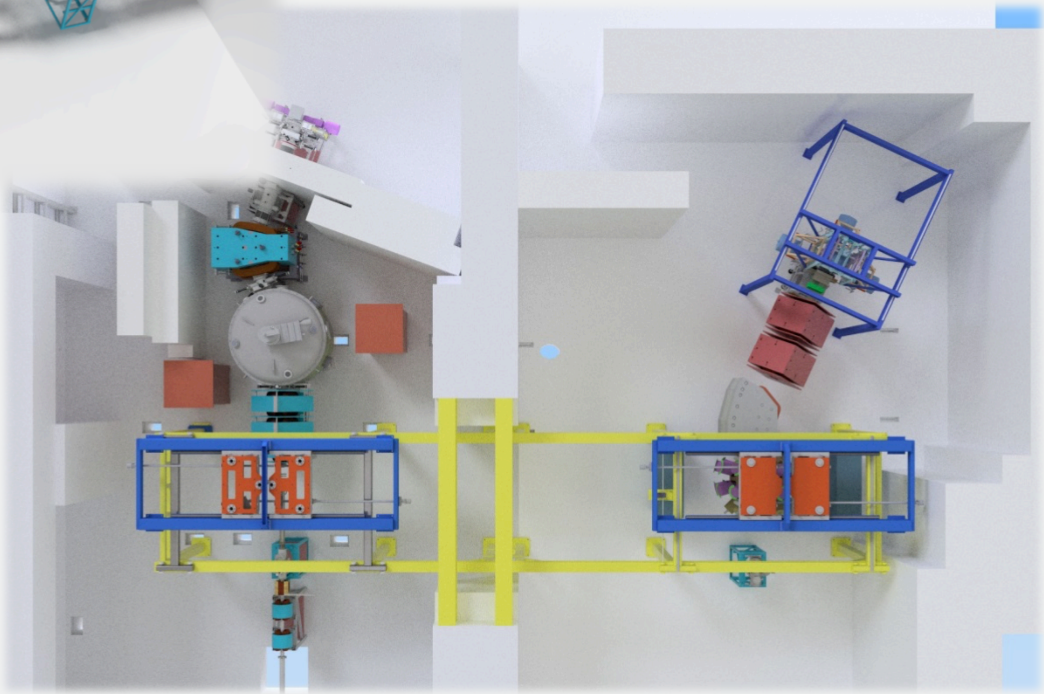


	JUROGAM I	JUROGAM II
Number of detectors	43 Eurogam Phase 1	15 Eurogam Phase1 24 Eurogam Clover
Efficiency @ 1.3MeV	4.3%	5.2%
Operational	Years 2003-2008	Years 2008-2017
Number of experiments	85	97
Peer reviewed publications	60	70
Beam time hours	13700+	18450+

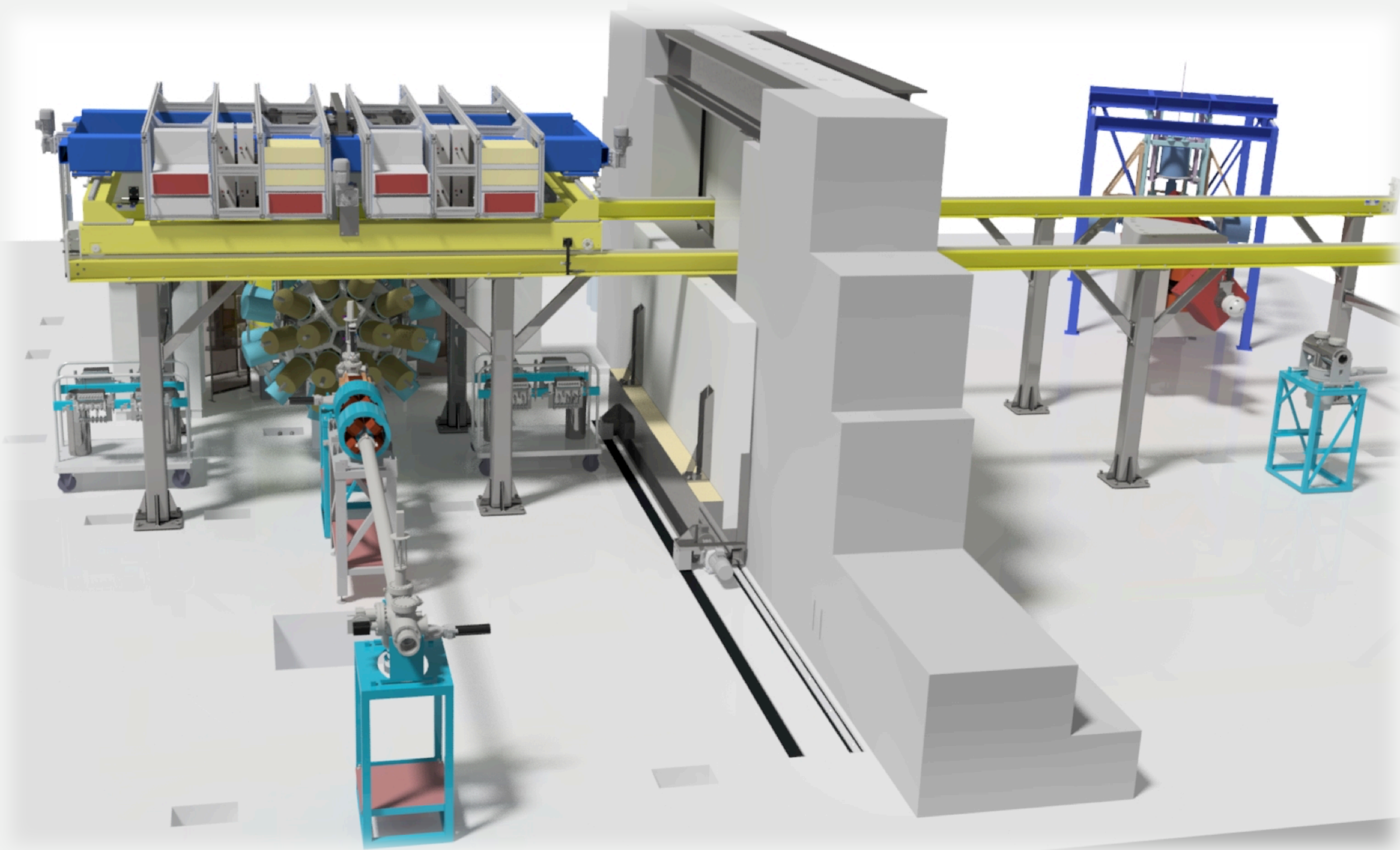
JUROGAM 3

JUROGAM 3





JUROGAM 3



JUROGAM 3 scientific program at JYFL

List of pending proposals as of 6th of June 2019:

No.	Title	Spokesperson	Remaining beam time	Submission deadline
1	**In-beam study of excited states of ^{107}Te using recoil-decay tagging with JurogamIII and MARA**	B. Cederwall J. Smith	14	15.03.2017
2	**Identification of excited states in ^{78}Zr**	D. Jenkins	9	15.03.2017
4	**T=0 neutron-proton correlations in ^{94}Ag**	M. Bentley R. Wadsworth	12	15.03.2017
5	**Isoscalar neutron-proton pairing in N=Z nuclei ^{84}Mo and ^{88}Ru**	P. Ruotsalainen	16	15.03.2017
7	**Feasibility test of a lifetime measurement in ^{74}Rb using the plunger and recoil-β tagging technique**	B.S. Nara Singh P. Ruotsalainen	4	15.03.2017
8	**Isospin Symmetry and Shape Coexistence in Mirror Nuclei ^{71}Kr-^{71}Br**	A. Boso D. Jenkins	14	15.03.2017
9	**Search for the isoscalar spin-aligned pairing scheme in self-conjugate ^{96}Cd**	B. Cederwall B.S. Nara Singh	10	15.03.2017
10	**Isospin-breaking effect in the A=62 isobaric triplet: In-beam recoil-beta tagging study of ^{62}Ge and ^{62}Ga employing MARA**	P. Ruotsalainen J. Uusitalo	12	15.09.2017
11	**Mirror energy differences in A=43: a tool to pin down the nature of cross-shell excitations**	S.M. Lenzi A. Boso	7	15.09.2017
12	**Disentangling proton-neutron pairing modes in heavy N~Z nuclei**	F. Recchia	16	15.09.2017
13	**Simultaneous lifetime measurements in ^{50}Fe, ^{50}Mn nad ^{50}Cr isobaric analogue nuclei using DPUNS and recoil-beta tagging technique to probe isospin symmetry breaking**	B.S. Nara Singh M. Giles	14	15.09.2017
14	**Oblate-deformed proton emitter ^{149}Lu**	K. Auranen J. Uusitalo	7	15.03.2018
19	**Prompt proton- and gamma-ray spectroscopy of ^{57}Cu**	M. Bentley U. Forsberg	7	15.09.2018
20	**Nuclear reaction dynamics study at MARA**	J. Khuyagbaatar J. Uusitalo	7	15.09.2018
22	**Towards understanding of isospin-breaking effects in isobaric multiplets: In-beam recoil-β tagging study of ^{66}Se and ^{66}As**	P. Ruotsalainen G. Zimba	7	15.03.2019
23	**Octupole correlations in the N=56 neutron-deficient ^{110}Xe**	A. Illana J.J. Valiente-Dobón	8	15.03.2019
24	**RDDS measurement of lifetimes in ^{107,108}Te using recoil-decay tagging with JurogamIII and MARA: Probing the emergence of collectivity above ^{100}Sn**	B. Cederwall T. Grahn	11	15.03.2019

<u>175 days</u> of beam time for JUROGAM 3 + MARA experiments:

- *np* interaction
- isospin symmetry, CED

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- *np* interaction (30%)
- isospin symmetry, CED

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175 days of beam time for JUROGAM 3 + MARA experiments:

- *np* interaction (30%)
- isospin symmetry, CED (42%)

JUROGAM 3 scientific program at JYFL

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150	Prompt and delayed spectroscopy of neutron deficient trans-lead nuclei ^{211,213}Ac	K. Auranen	14	15.03.2017
151	Investigation of the high-spin isomeric states and collective structures in the very neutron-deficient ^{191,192}Bi nuclei	A. Herzan S. Juutinen	15	15.09.2017
152	Understanding Proton-, gamma- and alpha-emission within a simultaneous theoretical approach: Lifetime measurements in ^{161}Re	M. Giles T. Grahn	9	15.09.2018
153	First lifetime measurements of excited states in the triaxial three-dimensional proton emitter ^{147}Tm	D. Cullen L. Barber	9	15.09.2018

<u>47 days</u> of beam time for
JUROGAM 3 + RITU experiments:

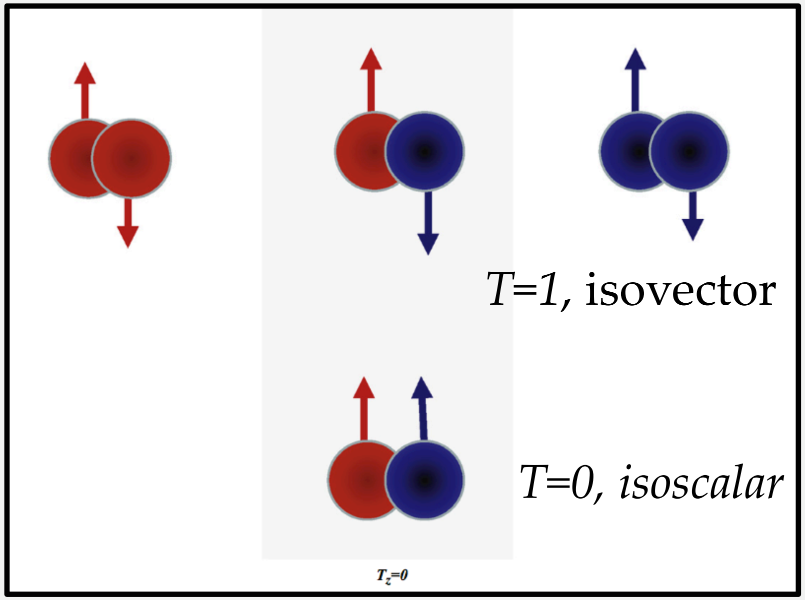
24	In-beam spectroscopy of ^{190}Pb using the SAGE spectrometer at the MARA separator	J. Pakarinen	14	15.09.2017
25	Probing shape coexistence via E0 transitions in the mass A~70-80 region using the SAGE spectrometer at the MARA separator	M. Sandzelius	7	15.09.2018
26	Identification and study of parity-doublet bands in ^{225}U using recoil-decay tagging with SAGE and RITU	J. Smith	14	15.03.2019

<u>35 days</u> of beam time for
SAGE + MARA experiments:

<u>257 days</u> of beam time for
JUROGAM 3 + MARA/RITU experiments.

np pairing correlations

- For almost all known nuclei, i.e. those with *N>Z* ,the pair correlated state consists of neutron and/or proton pairs coupled to angular momentum *J=0* and isospin *T=1*.
- Charge independence of the nuclear force implies that for *N*=Z nuclei, *J=0, T=1 np* pairing should exist on an equal footing with *J=0, T=1 nn* and *pp* pairing.
- However, it is still an open question whether strongly correlated *J=1, T=0 np* pairs also exist <-> deuteron-like pair condensate.



np pairing correlations

<u>Experimental and theoretical efforts to find "fingerprints" of *np* pairing:</u>

1. Binding energies
2. Low-lying states of odd-odd self-conjugate nuclei
3. Rotational response
4. Gamow-Teller **β**-decay
5. Pairing vibrations
6. …

Progress in Particle and Nuclear Physics 78 (2014) 24–90

Contents lists available at ScienceDirect

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

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Overview of neutron–proton pairing

S. Frauendorf[a], A.O. Macchiavelli[b,*]

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[b] Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, United States

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Nuclear Physics A 957 (2017) 144–153

NUCLEAR PHYSICS A

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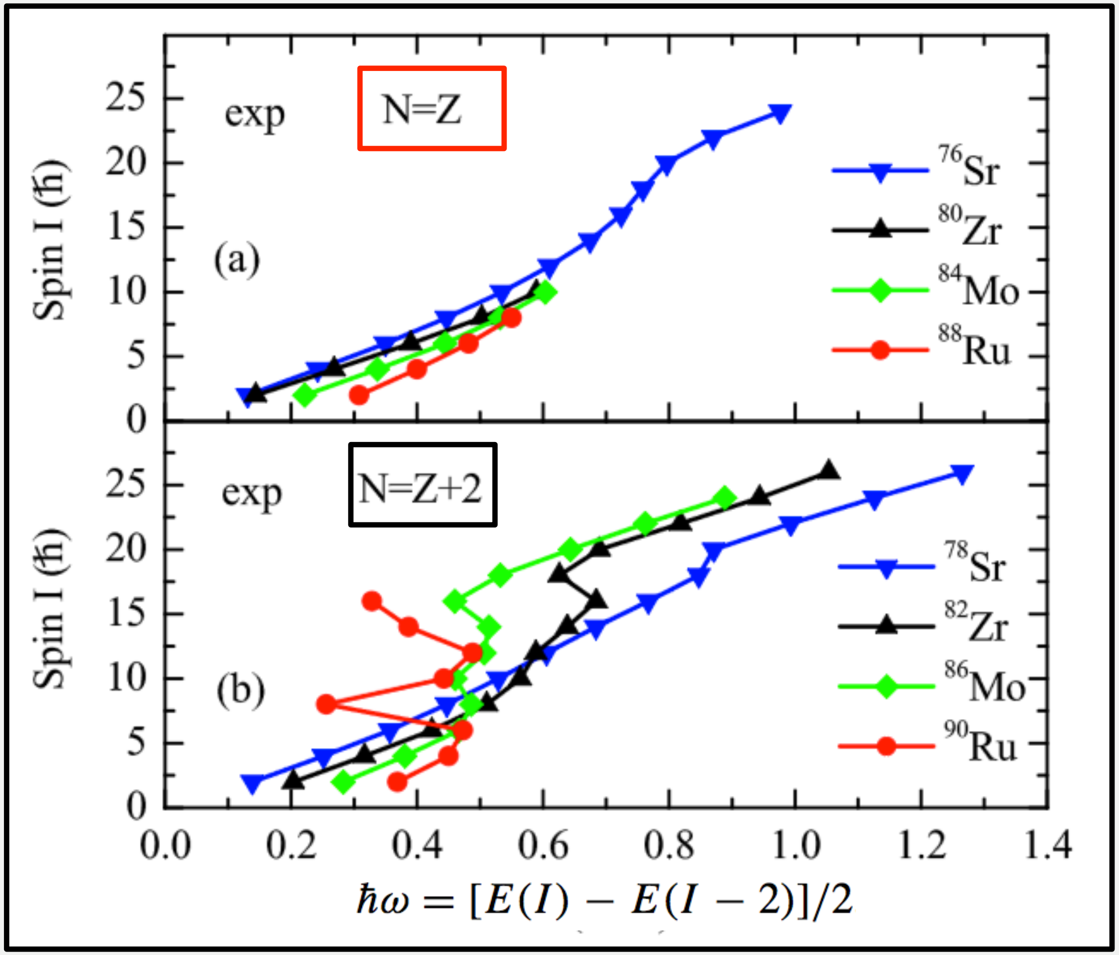
Enhancement of high-spin collectivity in $N = Z$ nuclei by the isoscalar neutron–proton pairing

K. Kaneko[a], Y. Sun[b,c,d,*], G. de Angelis[e]

np pairing correlations

Experimental $I - \omega$ plots for yrast bands



- In rotating nucleus, Coriolis force breaks nucleon pairs causing sudden increase of MoI.
- Very smooth $I - \omega$ behavior observed in the case of *N*=*Z* nuclei.
- *N*=Z+2 nuclei ^{82}Zr, ^{86}Mo and ^{90}Ru show sharp backbending, while ^{78}Sr show upbending.
- *np* pairing more robust against rotation?

np pairing correlations

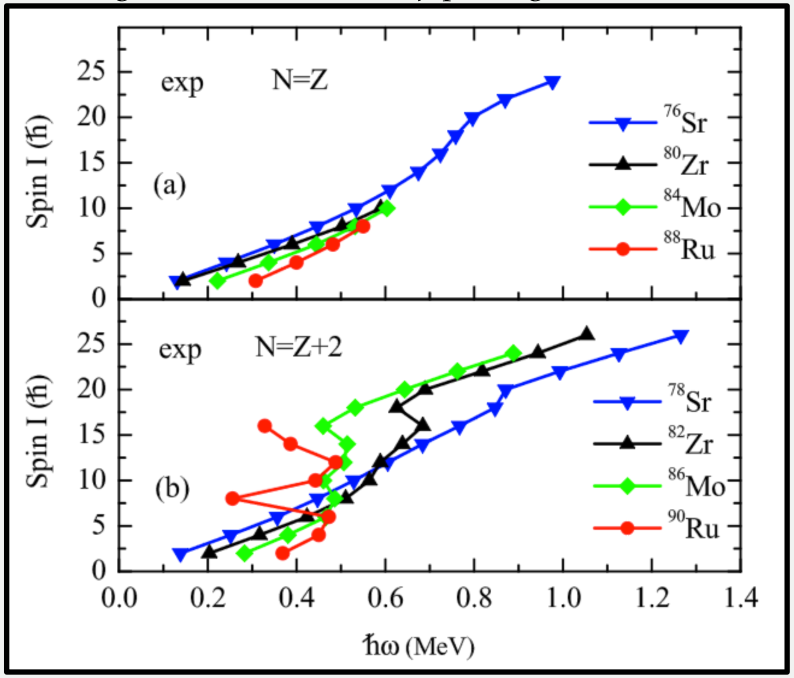
JUROGAM 3 + MARA experiments:

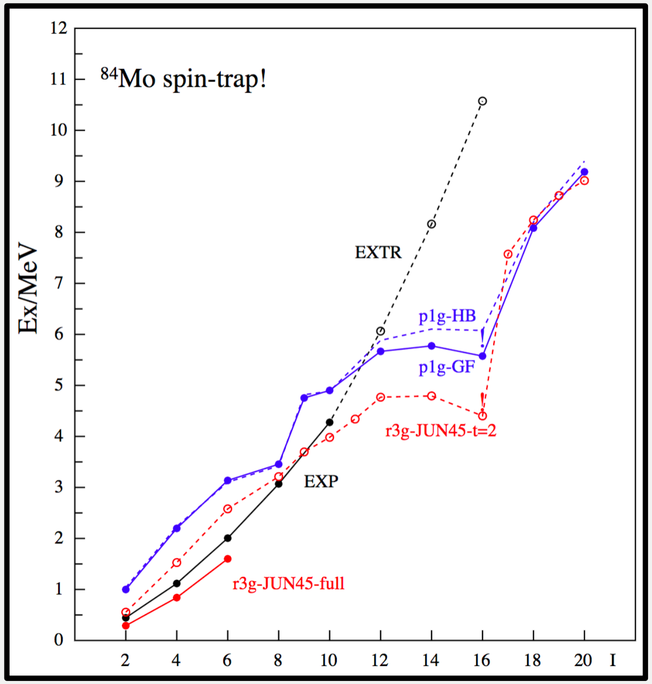
$^{58}Ni + ^{28}Si \rightarrow ^{84}Mo + 2n$:

- Extend level scheme in ^{84}Mo to higher angular momentum.
- Investigate excistence of 16^{+} spin trap isomer.
- Investigate the role of T=0, *np* pairing.

$^{32}S + ^{58}Ni \rightarrow ^{88}Ru + 2n$:

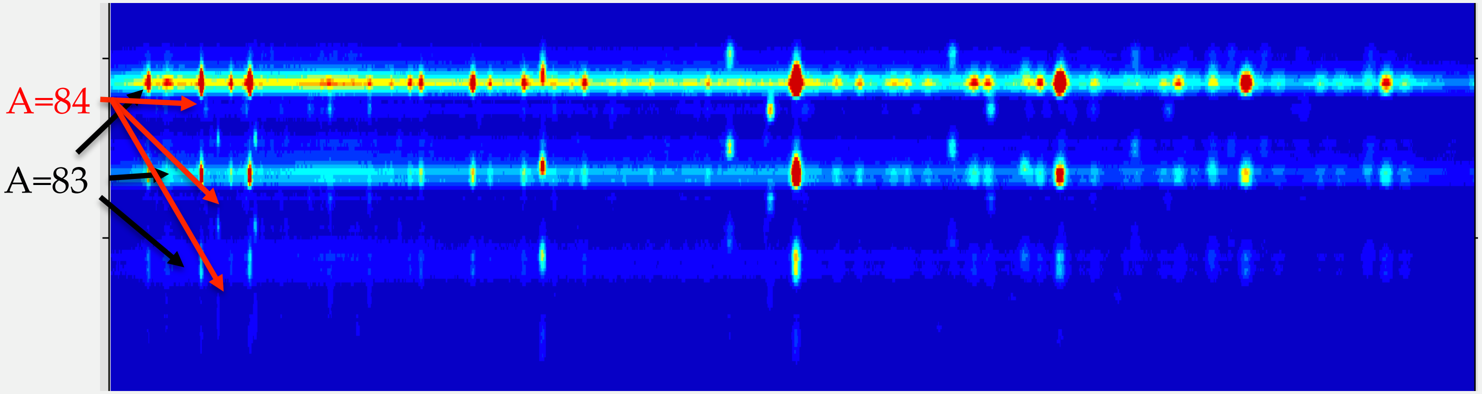
- Extend level scheme in ^{88}Ru to higher angular momentum.
- Investigate the role of T=0, *np* pairing.



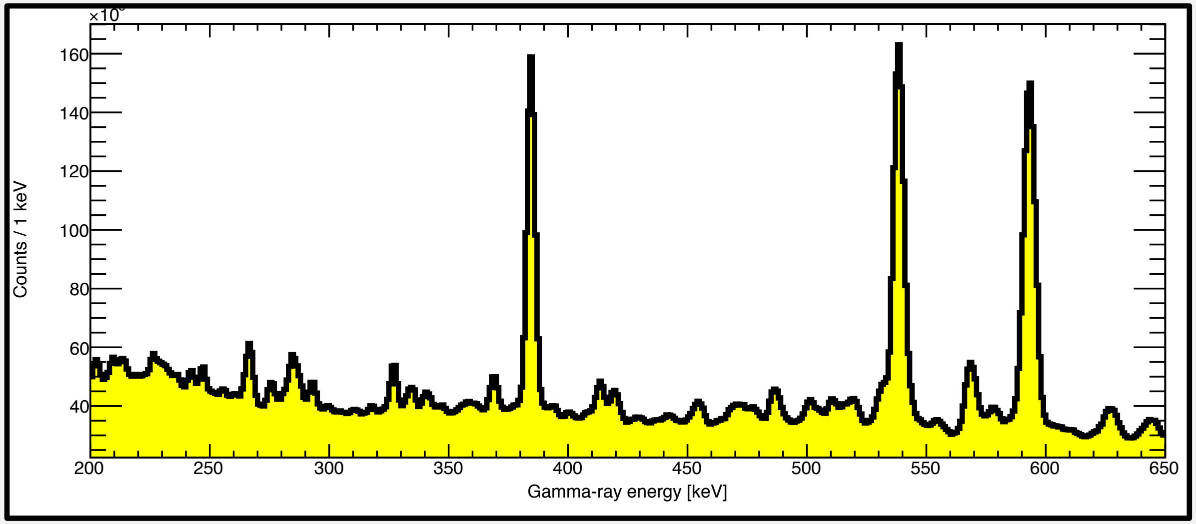


^{84}Mo

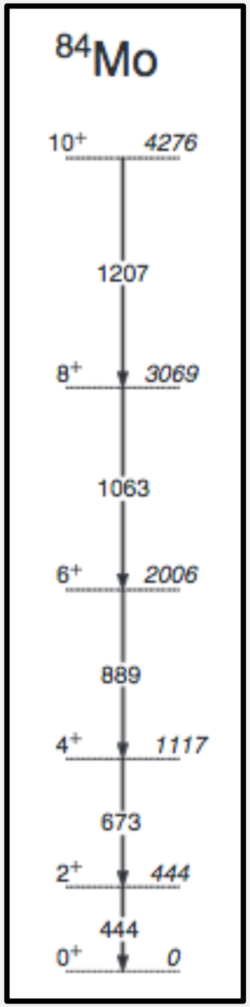
$^{58}Ni + ^{28}Si \rightarrow ^{84}Mo + 2n$ @ $E_b = 201$ MeV



Gamma-ray energy

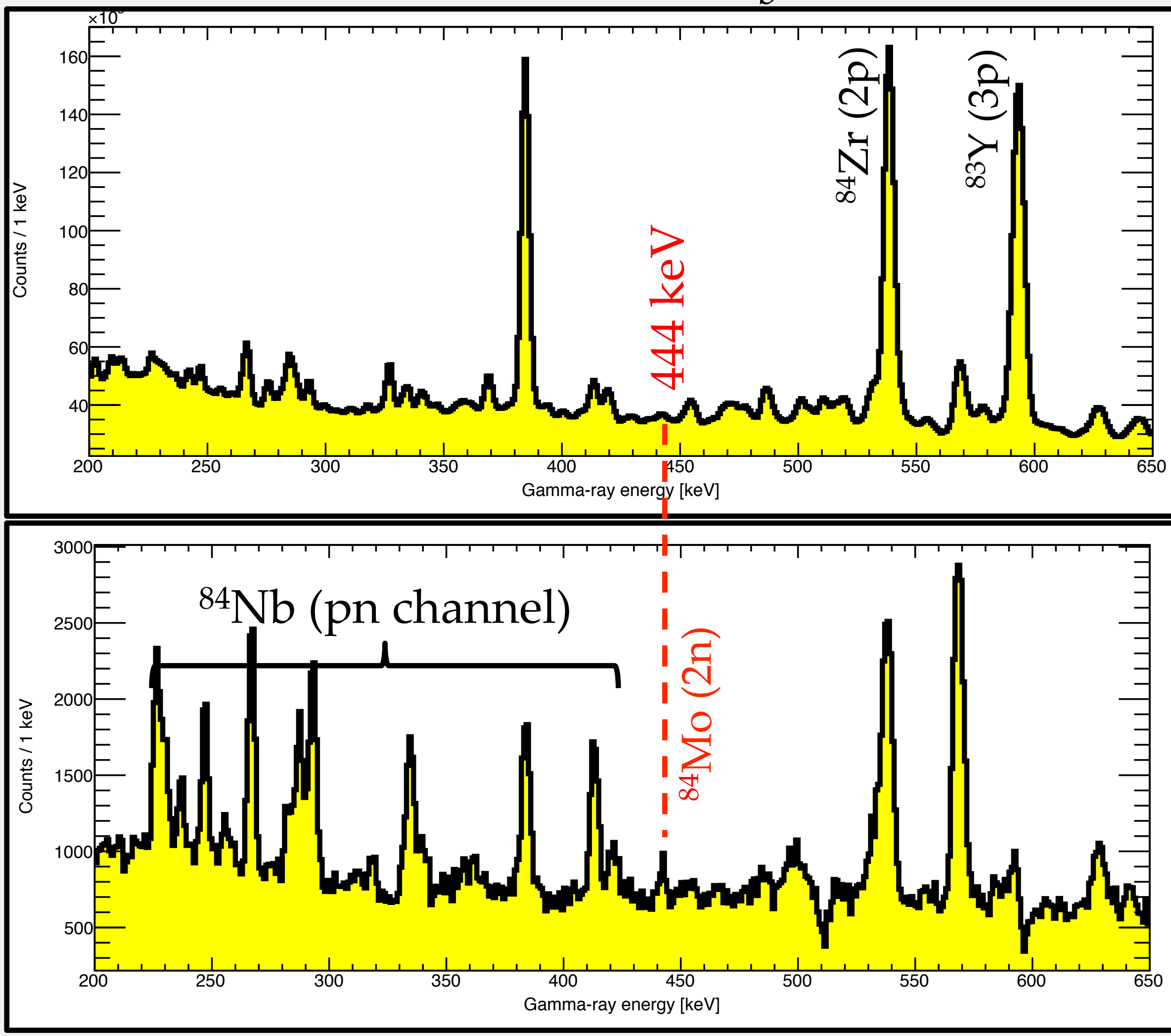


JUROGAM 3
gamma-ray singles



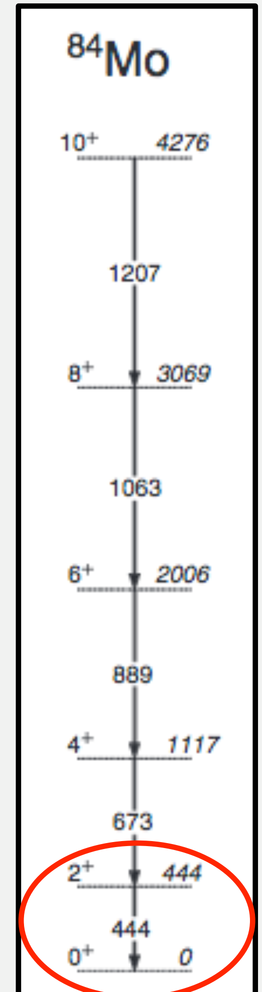
^{84}Mo

$^{58}Ni + {}^{28}Si \rightarrow {}^{84}Mo + 2n$ @ E_b = 201 MeV



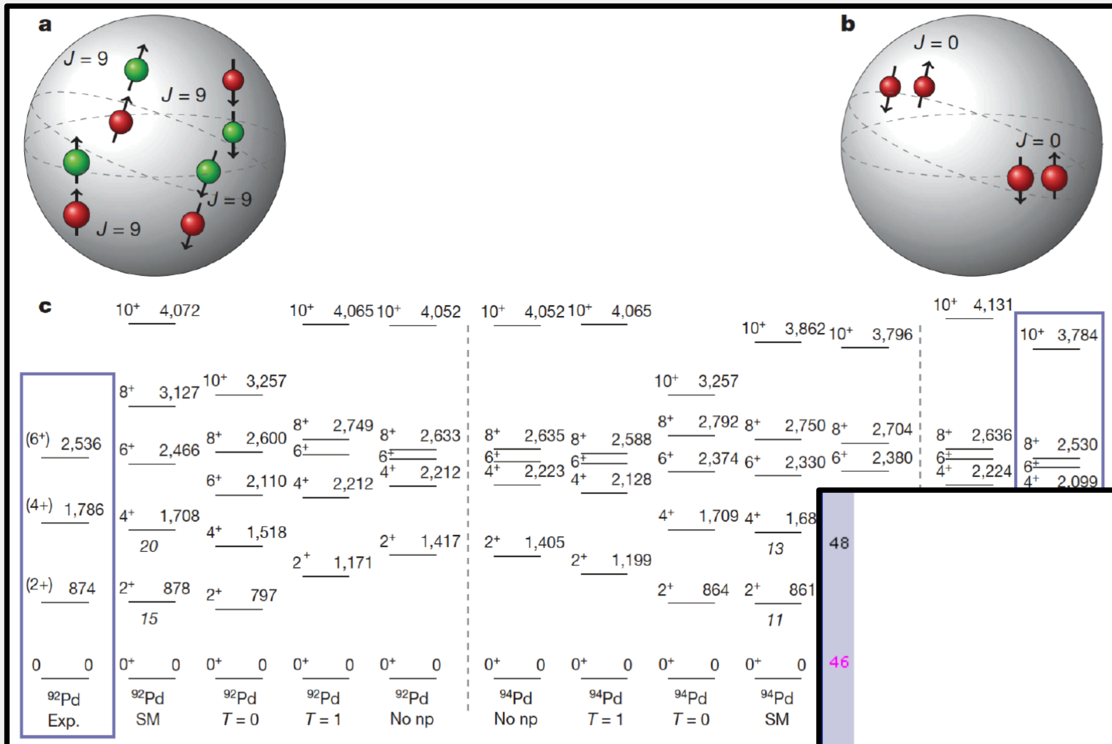
JUROIGAM 3 gamma-ray singles

…with cp veto and mass gate



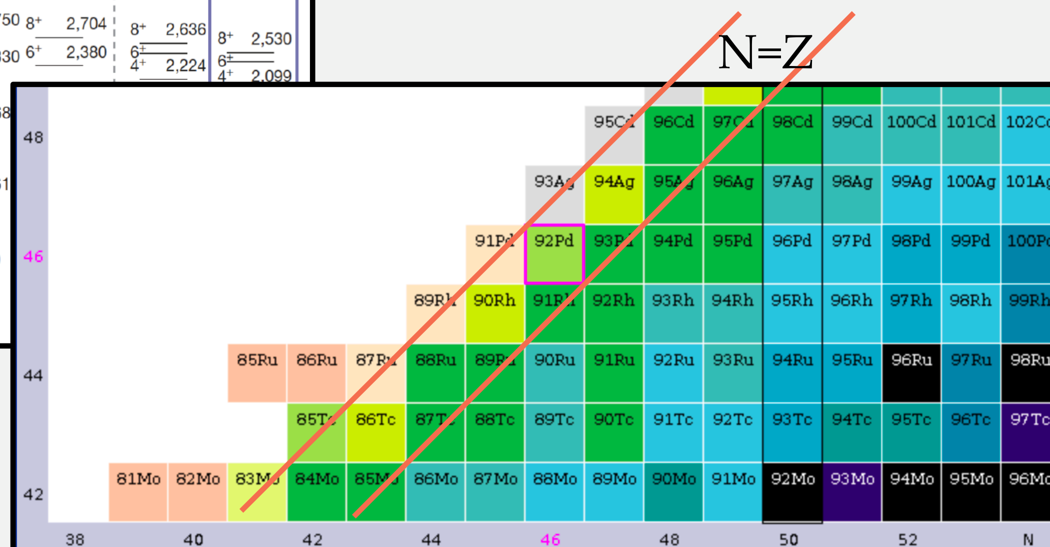
np pairing correlations

Spin-aligned, T=0 *np*-coupling scheme in ^{92}Pd



B. Cederwall et. al., Nature (2011)

"The calculated wavefunctions for the ground state and low-lying yrast states in ^{92}Pd are completely dominated by the isoscalar np pairs in the spin-aligned $J^{\pi} = 9^{+}$ coupling."

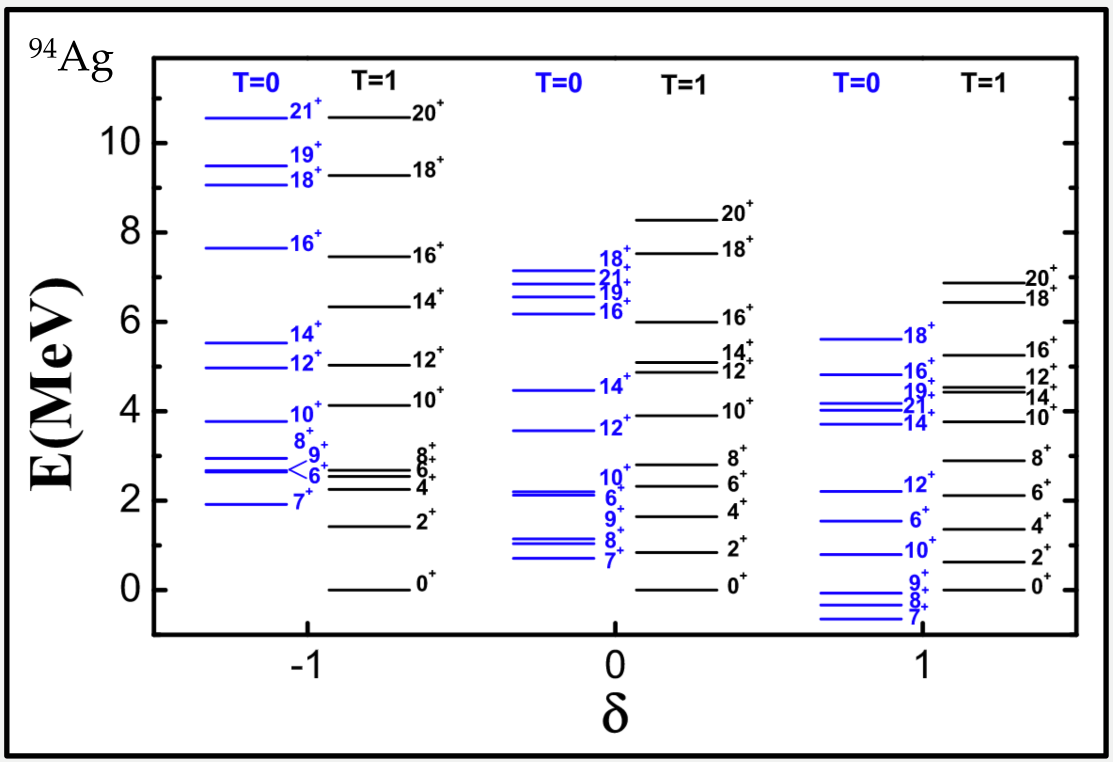


np pairing correlations

<u>JUROGAM 3 + MARA experiments:</u>

^{58}Ni + ^{40}Ca → ^{94}Ag + p3n:

- Identify low-lying T=0 and T=1 states in ^{94}Ag
- Investigate the effect of the possible T=0 spin-aligned *np*-pairing schemes.



δ = strength of the T=0 $g_{9/2}$ np-spin-aligned matrix element.

δ = -1 → interaction off

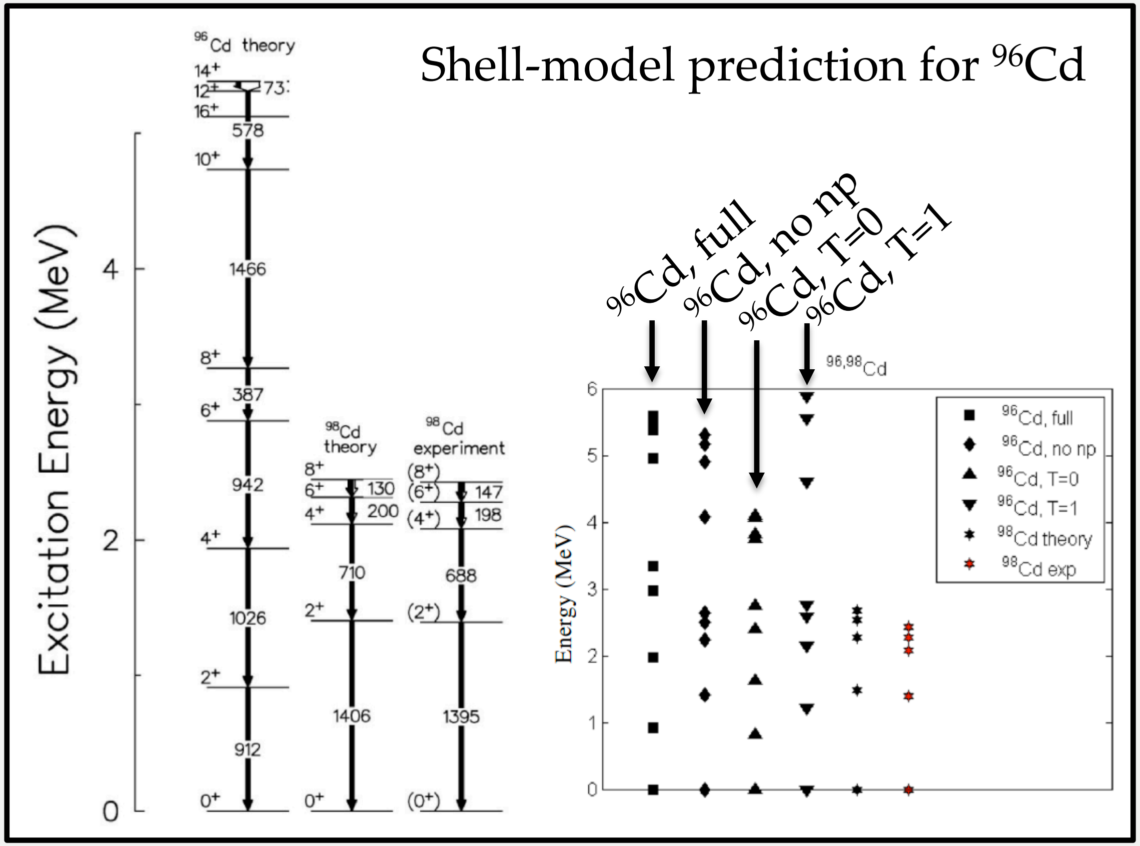
δ = 2 → twice the strength

np pairing correlations

JUROGAM 3 + MARA experiments:

$^{58}Ni + ^{40}Ca \rightarrow ^{96}Cd + 2n$:

- Identify low-lying excited states in ^{96}Cd.
- Investigate the effect of the possible T=0 spin-aligned *np*-pairing schemes.



np pairing correlations

JUROGAM 3 + MARA experiments:

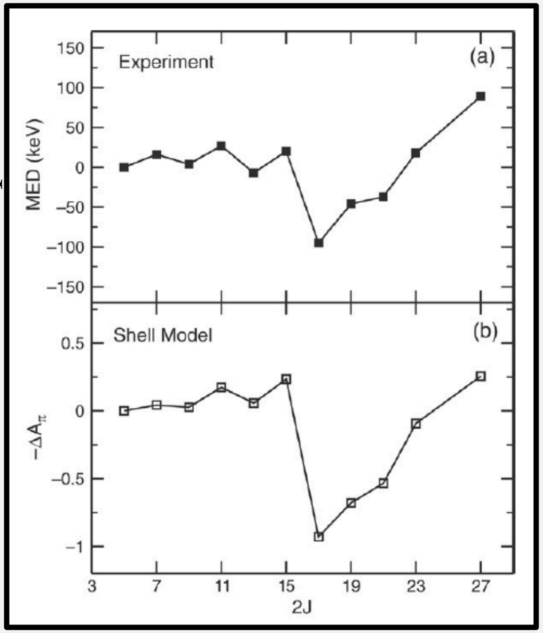
^{58}Ni + ^{40}Ca → ^{96}Cd + 2n:

- Identify low-lying excited states in ^{96}Cd.
- Investigate the effect of the possible T=0 spin-aligned *np*-pairing schemes.

^{36}Ar + ^{58}Ni → ^{91}Pd + 3n:

- Identify states up to $25/2^{+}$ state.
- Extract MED between A=91 mirror pair.
- Investigate the type of nucleons aligning angular momenta.

51Fe – 51Mn mirror pair

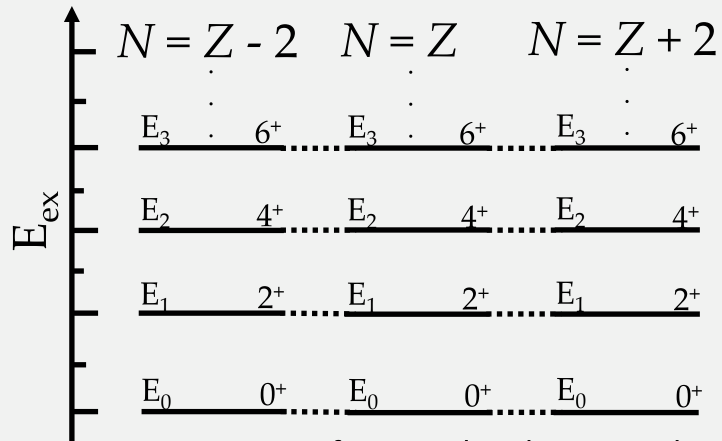


Experimental MED

”quasi-alignment - measure of the type of nucleons aligning”

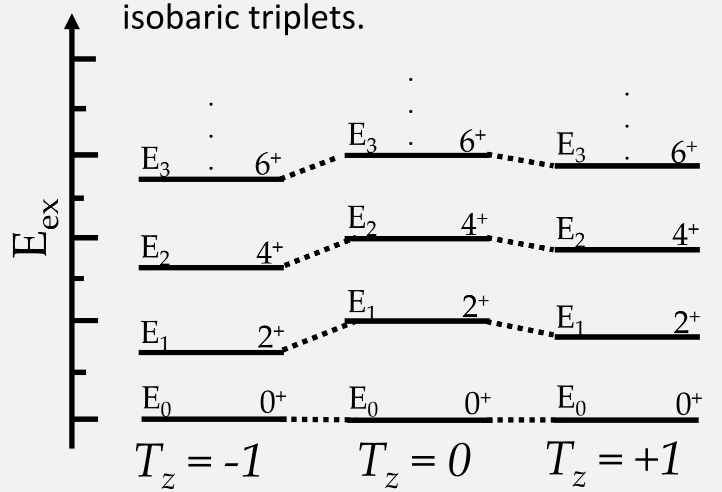
Isospin symmetry breaking

Nuclear interaction is:
a) charge symmetric
b) charge independent



Degeneracy of energy levels across the isobaric triplets.

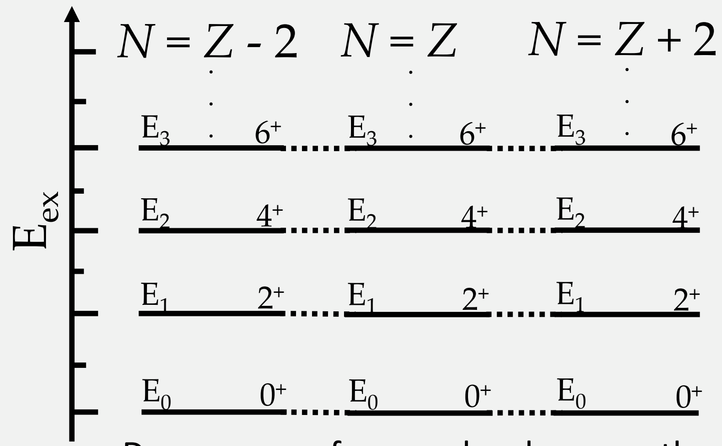
Isospin symmetry is broken mainly due to the Coulomb interaction.



Energy differences between excited states, CED (~10 – 100 keV)

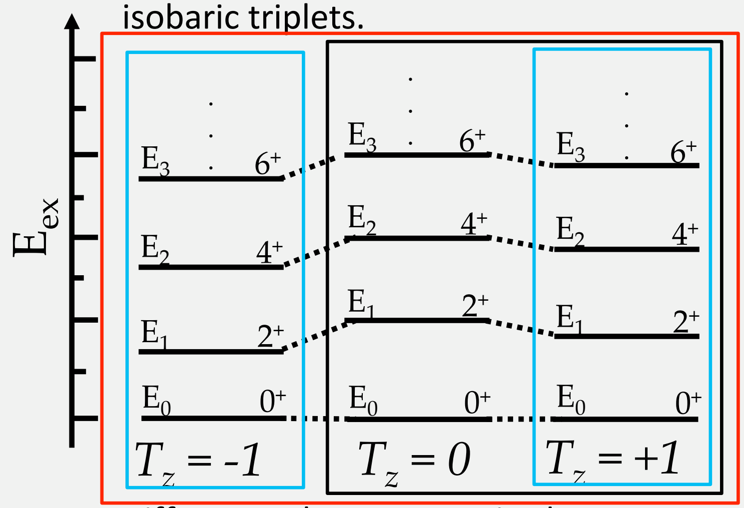
Isospin symmetry breaking

Nuclear interaction is:
- a) charge symmetric
- b) charge independent



Degeneracy of energy levels across the isobaric triplets.

Isospin symmetry is broken mainly due to the Coulomb interaction.



Differences between excited states, CED (~10 – 100 keV)

"Coulomb energy differences"

$$CED_{J,T} = E_{J,\,Tz=0} - E_{J,\,Tz=+1}$$

"Mirror energy differences"

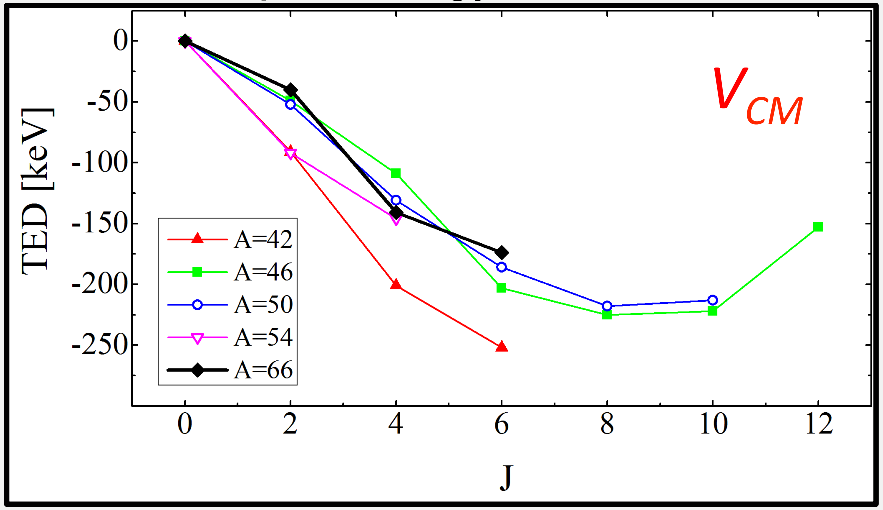
$$MED_{J,T} = E_{J,\,Tz=-1} - E_{J,\,Tz=+1}$$

"Triplet energy differences"

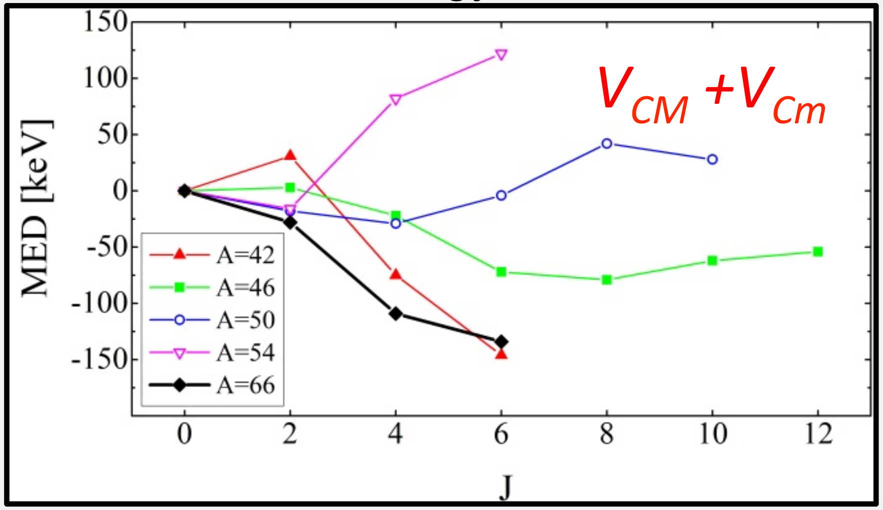
$$TED_{J,T} = E_{J,\,Tz=-1} + E_{J,\,Tz=+1} - 2 * E_{J,\,Tz=0}$$

Isospin symmetry breaking

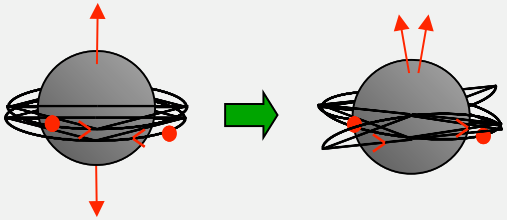
“Triplet energy differences”

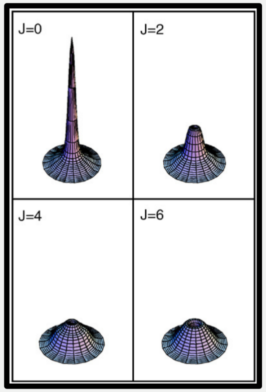


“Mirror energy differences”



Multipole component V_{CM} : Coulomb contributions resulting from angular momentum recoupling of the valence protons.





Monopole component V_{Cm} : single-particle effects and bulk properties. This is further divided into:

$$E_{ls} \simeq (g_s - g_l) \frac{1}{2m_N^2 c^2} \left(-\frac{Ze^2}{R_C^3} \right) \langle \vec{l} \cdot \vec{s} \rangle$$

el.m. spin-orbit potential (effects both protons and neutrons).

$$V_{Cr}(J) = -\frac{3}{5} Z(Z-1)e^2 \frac{\Delta R(J)}{R_C^2}$$

Radial term, nuclear radius changes as a function J.

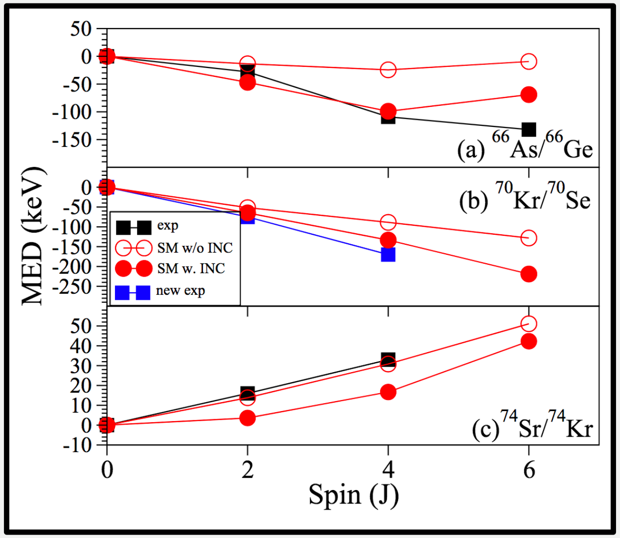
$$E_{ll} = \frac{-4.5 Z_{\mathrm{cs}}^{13/12} [2l(l+1) - N(N+3)]}{A^{1/3} \left(N + \frac{3}{2} \right)} \mathrm{keV}$$

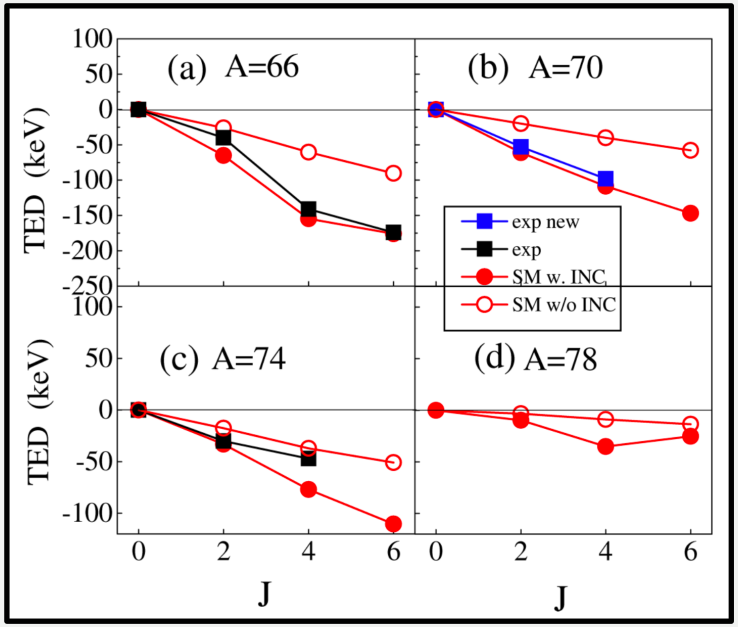
Single-particle shift for protons.

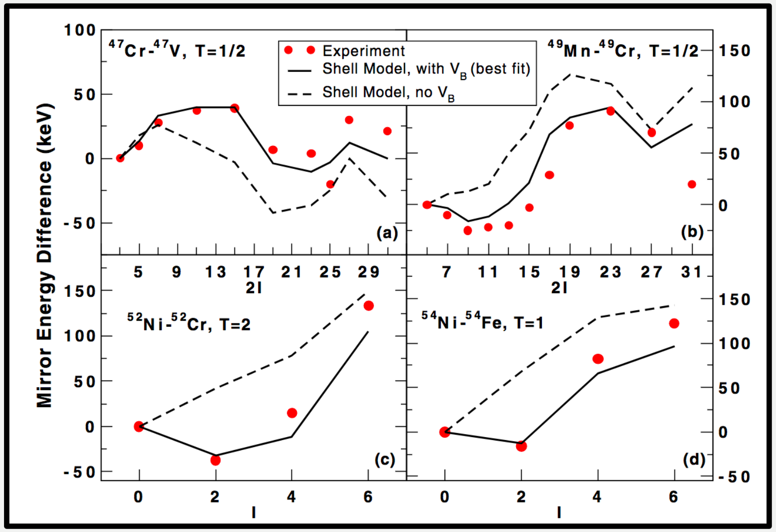
Isospin symmetry breaking

Coulomb multipole interaction (V_{CM}) is not sufficient to reproduce experimental TED/MED within shell model.

Additional isospin non-conserving (INC) interaction required.







Isospin symmetry breaking

Accepted Paper

Isospin-symmetry breaking corrections for the description of triplet energy differences

Phys. Rev. C

S. M. Lenzi, M. A. Bentley, R. Lau, and C. Aa. Diget

Accepted 5 November 2018

ABSTRACT

The charge-independence breaking of the nuclear interaction is analyzed by means of energy differences among analogue states in $T = 1$ isobaric multiplets. Data on triplet energy differences in the sd, pf and pfg shells, i.e. $18 \leq A \leq 66$, are reproduced with very good accuracy by large-scale shell model calculations taking into account, aside from the Coulomb interaction, a single isotensor schematic interaction of monopole-pairing type. It is shown that the effect on the triplet energy differences of this isospin-breaking interaction is of the same magnitude as the Coulomb one. Moreover, its strength is the same for every single-particle orbital of the considered model space.

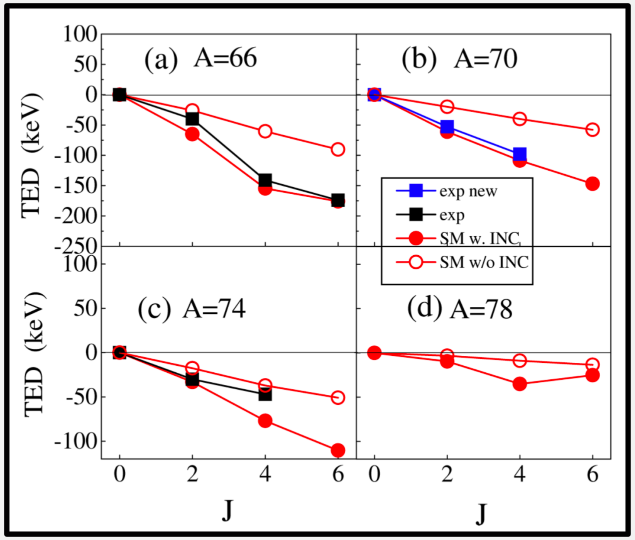
Isospin symmetry breaking

<u>JUROGAM 3 + MARA experiments:</u>

$^{40}Ca + ^{28}Si \rightarrow ^{66}As$ + pn, ^{66}Se + 2n:
- Confirm excitation energies of the T=1, 2+, 4^+ and 6^+ states and extend level scheme in ^{66}Se and ^{66}As

$^{40}Ca + ^{40}Ca \rightarrow ^{78}Zr$ + 2n:
- Identification of the excited T=1 states in ^{78}Zr employing RBT.
- Extract TED and MED across A=78 isobaric triplet.

$^{33}S + ^{40}Ca \rightarrow ^{71}Kr$ + 2n:
- Identification of the excited T=1/2 states in ^{71}Kr employing RBT.
- Extract MED for A=71 mirror pair.



$^{24}Mg + ^{40}Ca \rightarrow ^{62}Ge$ + 2n, ^{62}Ga + pn:
- Identification of the excited T=1 states in ^{62}Ge employing RBT.
- Resolve ambiguity in the excitation energy of the T=0, 2^+ state in ^{62}Ga.
- Extract TED and MED across A=62 isobaric triplet.

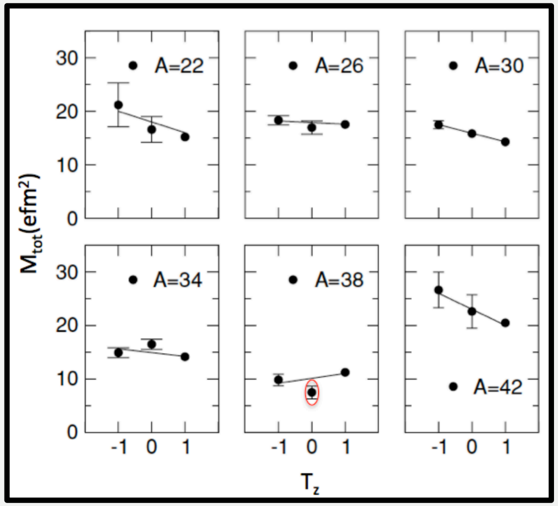
$^{33}S + ^{12}C \rightarrow ^{43}Ti$ + 2n:
- Extend the level scheme of ^{43}Ti up to $27/2^+$ employing isomer decay tagging.
- Extract MED for A=43 mirror pair.

$^{36}Ar + ^{24}Mg \rightarrow ^{57}Cu$ + p2n:
- Identify prompt proton decay in ^{57}Cu.
- First experiment of the planned in-beam proton-γ coincidence spectroscopy campaign.
- Study competition between γ- and proton emission in weakly-bound systems.
- Extract MED for A=57 mirror pair.

Isospin symmetry breaking

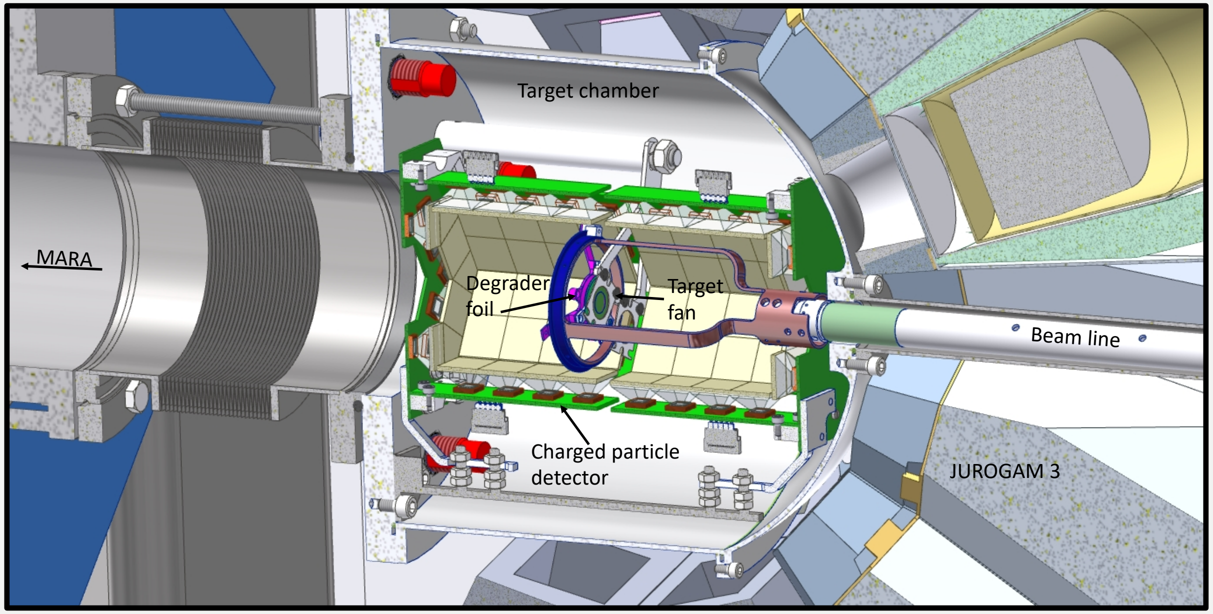
JUROGAM 3 + MARA experiments:

$^{36}Ar + ^{40}Ca \rightarrow ^{74}Rb + pn$:
- DPUNS + RBT proof-of-principle experiment.
- measure excited state lifetimes in ^{74}Rb.



$^{40}Ca + ^{12}C \rightarrow ^{50}Fe + 2p$, $^{50}Mn + pn$, $^{50}Cr + 2n$:
- Simultaneous DPUNS (+ RBT) measurement of 2^+ state lifetimes in ^{50}Fe, ^{50}Mn and ^{50}Cr.
- Investigate linearity of transition matrix elements as a function of T_z.

Plan to develop lifetime measurement technique around the *N*=*Z* line by building an **A**dvanced **P**lunger – **P**article detector **A**rray (APPA).



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Men behind MARA

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Thank you!