Gamma-ray spectroscopy employing JUROGAM 3 and MARA – in-beam studies of $N \approx Z$ nuclei at JYFL
Outline

- JYFL
- Recoil-decay tagging
- Mass Analysing Recoil Apparatus – 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
Recoil-decay tagging

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

$\alpha \rightarrow \nu = 0.03c \rightarrow \gamma \rightarrow \gamma \rightarrow \gamma \rightarrow B$

$t \sim 10^{-1}$ $t \sim 10^{-6}$ $t \sim 10^{-9}$ $t \sim 10^{-15}$ $t \sim 10^{-18}$ $t \sim 10^{-21}$

FOCAL PLANE

MARA

JUROGAM 3
Recoil-decay tagging

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

- $e^+ \rightarrow v_e$
- $v = 0.03c$
- $t \sim 10^{-1}$
- $t \sim 10^{-6}$
- $t \sim 10^{-9}$
- $t \sim 10^{-15}$
- $t \sim 10^{-18}$
- $t \sim 10^{-21}$
- $t = 0$
- $\nu_e$
Recoil-decay tagging

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

\[ \text{CN} \]

\[ \text{B}  \]

\[ \text{FOCAL PLANE} \]

\[ \text{MARA} \]

\[ \text{JUROGAM 3} \]
Recoil-decay tagging

$^{111}$Xe

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

(a) recoil gated (γ singles)

(b) $^{111}$Xe RDT gated (γ singles)

$^{66}$As

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

Recoil gated (γ singles)

Recoil-beta tagged

"Recoil-alpha tagging"

"Recoil-beta tagging"
Isomer tagging

C. Petrache
J3+MARA experiment in May 2019

a) $^{118}$Cs prompt $\gamma$ rays in JUROGAM III gated by the delayed 79-keV $\gamma$ ray in GREAT

b) $^{119}$Cs prompt $\gamma$ rays in JUROGAM III gated by the delayed 88-keV $\gamma$ ray in GREAT

c) $^{119}$Cs prompt $\gamma$ rays in JUROGAM III gated by the delayed 66-keV $\gamma$ ray in GREAT

d) $^{119}$Ba prompt $\gamma$ rays in JUROGAM III gated by the delayed 67-keV $\gamma$ ray in GREAT
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:

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

- Clover
- Punch through detector
- DSSSD (BB20)
- "Box" detector
- + Planar Ge
- or Plastic scintillator

- mass slit
- MWPC
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: 128\times 48 \text{ mm}^2
Strip pitch: 0.67 \text{ mm}
Thicknesses: 300, 150 and 700 \text{ 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

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

0 charged particles

1 charged particle

2 charged particles

3 charged particles

$^{167,168}\text{Pt} \alpha$-decays

$^{167}\text{Ir} (p2n)$
MARA focal plane spectroscopy

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

1) $^{160}\text{Os}$ in $^{58}\text{Ni} + ^{106}\text{Cd} \rightarrow ^{164}\text{Os}^*$, A. Briscoe, R. Page, J. Uusitalo et. al.
2) $^{156}\text{W}$
3) $^{170}\text{Hg}$
4) $^{169}\text{Au}$
5) $^{165}\text{Pt}$

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

<table>
<thead>
<tr>
<th></th>
<th>JUROGAM I</th>
<th>JUROGAM II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of detectors</td>
<td>43 Eurogam Phase 1</td>
<td>15 Eurogam Phase 1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24 Eurogam Clover</td>
</tr>
<tr>
<td>Efficiency @ 1.3MeV</td>
<td>4.3%</td>
<td>5.2%</td>
</tr>
<tr>
<td>Operational</td>
<td>Years 2003-2008</td>
<td>Years 2008-2017</td>
</tr>
<tr>
<td>Number of experiments</td>
<td>85</td>
<td>97</td>
</tr>
<tr>
<td>Peer reviewed publications</td>
<td>60</td>
<td>70</td>
</tr>
<tr>
<td>Beam time hours</td>
<td>13700+</td>
<td>18450+</td>
</tr>
</tbody>
</table>
JUROGAM 3
**JUROGAM 3 scientific program at JYFL**

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

<table>
<thead>
<tr>
<th>No.</th>
<th>Title</th>
<th>Spokesperson</th>
<th>Remaining beam time</th>
<th>Submission deadline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>In-beam study of excited states of $^{169}$Te using recoil-decay tagging with JurogamIII and MARA</td>
<td>B. Cederwall, J. Smith</td>
<td>14</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>2</td>
<td>Identification of excited states in $^{79}$Zr</td>
<td>D. Jenkins</td>
<td>9</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>4</td>
<td>T=0 neutron-proton correlations in $^{116}$Ag</td>
<td>M. Bentley, R. Wadsworth</td>
<td>12</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>5</td>
<td>Isoscalar neutron-proton pairing in N=Z nuclei $^{99}$Mo and $^{99}$Ru</td>
<td>P. Ruotsalainen</td>
<td>16</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>7</td>
<td>Feasibility test of a lifetime measurement in $^{85}$Rb using the plunger and recoil-β tagging technique</td>
<td>B.S. Nara Singh, P. Ruotsalainen</td>
<td>4</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>8</td>
<td>Isospin Symmetry and Shape Coexistence in Mirror Nuclei $^{79}$Kr-$^{81}$Br</td>
<td>A. Boso, D. Jenkins</td>
<td>14</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>9</td>
<td>Search for the isoscalar spin-aligned pairing scheme in self-conjugate $^{97}$Cd</td>
<td>B. Cederwall, B.S. Nara Singh</td>
<td>10</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>10</td>
<td>Isospin-breaking effect in the A=62 isobaric triplet: In-beam recoil-beta tagging study of $^{40}$Ge and $^{40}$Ga employing MARA</td>
<td>P. Ruotsalainen, J. Uusitalo</td>
<td>12</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>11</td>
<td>Mirror energy differences in A=43: a tool to pin down the nature of cross-shell excitations</td>
<td>S.M. Lenz, A. Boso</td>
<td>7</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>12</td>
<td>Disentangling proton-neutron pairing modes in heavy N-Z nuclei</td>
<td>F. Recchia</td>
<td>16</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>13</td>
<td>Simultaneous lifetime measurements in $^{58}$Fe, $^{58}$Mn and $^{58}$Cr isobaric analogue nuclei using DPUNS and recoil-beta tagging technique to probe isospin symmetry breaking</td>
<td>B.S. Nara Singh, M. Giles</td>
<td>14</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>14</td>
<td>Oblate-deformed proton emitter $^{138}$Lu</td>
<td>K. Auranen, J. Uusitalo</td>
<td>7</td>
<td>15.03.2018</td>
</tr>
<tr>
<td>19</td>
<td>Prompt proton- and gamma-ray spectroscopy of $^{75}$Cu</td>
<td>M. Bentley, U. Forsberg</td>
<td>7</td>
<td>15.09.2018</td>
</tr>
<tr>
<td>20</td>
<td>Nuclear reaction dynamics study at MARA</td>
<td>J. Khuyagbaatar, J. Uusitalo</td>
<td>7</td>
<td>15.09.2018</td>
</tr>
<tr>
<td>22</td>
<td>Towards understanding of isospin-breaking effects in isobaric multiplets: In-beam recoil-β tagging study of $^{48}$Se and $^{48}$As</td>
<td>P. Ruotsalainen, G. Zimba</td>
<td>7</td>
<td>15.03.2019</td>
</tr>
<tr>
<td>23</td>
<td>Octupole correlations in the N=56 neutron-deficient $^{130}$Xe</td>
<td>A. Illana, J.J. Valiente-Dobón</td>
<td>8</td>
<td>15.03.2019</td>
</tr>
<tr>
<td>24</td>
<td>RDDS measurement of lifetimes in $^{107}$,109$^{10}$Te using recoil-decay tagging with JurogamIII and MARA: Probing the emergence of collectivity above $^{108}$Sn</td>
<td>B. Cederwall, T. Grahn</td>
<td>11</td>
<td>15.03.2019</td>
</tr>
</tbody>
</table>

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

- $np$ interaction

- isospin symmetry, CED
JYU. Since 1863.

JYU. Since 1863.

JYU. Since 1863.

JYU. Since 1863.

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

<table>
<thead>
<tr>
<th>No.</th>
<th>Title</th>
<th>Spokesperson</th>
<th>Remaining beam time</th>
<th>Submission deadline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>In-beam study of excited states of $^{169}$Te using recoil-decay tagging with JurogamIII and MARA</td>
<td>B. Cederwall, J. Smith</td>
<td>14</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>2</td>
<td>Identification of excited states in $^{79}$Zr</td>
<td>D. Jenkins</td>
<td>9</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>4</td>
<td>T=0 neutron-proton correlations in $^{119}$Ag</td>
<td>M. Bentley, R. Wadsworth</td>
<td>12</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>5</td>
<td>Isoscalar neutron-proton pairing in N=Z nuclei $^{150}$Mo and $^{189}$Ru</td>
<td>P. Ruotsalainen</td>
<td>16</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>7</td>
<td>Feasibility test of a lifetime measurement in $^{83}$Rb using the plunger and recoil-β tagging technique</td>
<td>B.S. Nara Singh, P. Ruotsalainen</td>
<td>4</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>8</td>
<td>Isospin Symmetry and Shape Coexistence in Mirror Nuclei $^{79}$Kr-$^{83}$Br</td>
<td>A. Boso, D. Jenkins</td>
<td>14</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>9</td>
<td>Search for the isoscalar spin-aligned pairing scheme in self-conjugate $^{109}$Cd</td>
<td>B. Cederwall, B.S. Nara Singh</td>
<td>10</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>10</td>
<td>Isospin-breaking effect in the A=62 isobaric triplet: In-beam recoil-beta tagging study of $^{70}$Ge and $^{70}$Ga employing MARA</td>
<td>P. Ruotsalainen, J. Uusitalo</td>
<td>12</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>11</td>
<td>Mirror energy differences in A=43: a tool to pin down the nature of cross-shell excitations</td>
<td>S.M. Lenzi, A. Boso</td>
<td>7</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>12</td>
<td>Disentangling proton-neutron pairing modes in heavy N-Z nuclei</td>
<td>F. Recchia</td>
<td>16</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>13</td>
<td>Simultaneous lifetime measurements in $^{168}$Fe, $^{168}$Mn and $^{168}$Cr isobaric analogue nuclei using DPUNS and recoil-beta tagging technique to probe isospin symmetry breaking</td>
<td>B.S. Nara Singh, M. Giles</td>
<td>14</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>14</td>
<td>Oblate-deformed proton emitter $^{14}$Lu</td>
<td>K. Auranen, J. Uusitalo</td>
<td>7</td>
<td>15.03.2018</td>
</tr>
<tr>
<td>19</td>
<td>Prompt proton- and gamma-ray spectroscopy of $^{77}$Cu</td>
<td>M. Bentley, U. Forsberg</td>
<td>7</td>
<td>15.09.2018</td>
</tr>
<tr>
<td>20</td>
<td>Nuclear reaction dynamics study at MARA</td>
<td>J. Khuyagbaatar, J. Uusitalo</td>
<td>7</td>
<td>15.09.2018</td>
</tr>
<tr>
<td>22</td>
<td>Towards understanding of isospin-breaking effects in isobaric multiplets: In-beam recoil-β tagging study of $^{84}$Se and $^{84}$As</td>
<td>P. Ruotsalainen, G. Zimba</td>
<td>7</td>
<td>15.03.2019</td>
</tr>
<tr>
<td>23</td>
<td>Octupole correlations in the N=56 neutron-deficient $^{108}$Xe</td>
<td>A. Illana, J.J. Valiente-Dobón</td>
<td>8</td>
<td>15.03.2019</td>
</tr>
<tr>
<td>24</td>
<td>RDQS measurement of lifetimes in $^{107,108}$Te using recoil-decay tagging with JurogamIII and MARA: Probing the emergence of collectivity above $^{108}$Sn</td>
<td>B. Cederwall, T. Grahn</td>
<td>11</td>
<td>15.03.2019</td>
</tr>
</tbody>
</table>

175 days of beam time for JUROGAM 3 + MARA experiments:
- np interaction (30%)
- isospin symmetry, CED
### List of pending proposals as of 6th of June 2019:

<table>
<thead>
<tr>
<th>No.</th>
<th>Title</th>
<th>Spokesperson</th>
<th>Remaining beam time</th>
<th>Submission deadline</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>In-beam study of excited states of $^{105}$Te using recoil-decay tagging with JurogamIII and MARA</td>
<td>B. Cederwall, J. Smith</td>
<td>14</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>2</td>
<td>Identification of excited states in $^{87}$Zr</td>
<td>D. Jenkins</td>
<td>9</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>4</td>
<td>T=0 neutron-proton correlations in $^{115}$Ag</td>
<td>M. Bentley, R. Wadsworth</td>
<td>12</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>5</td>
<td>Isoscalar neutron-proton pairing in N=Z nuclei $^{105}$Mo and $^{109}$Ru</td>
<td>P. Ruotsalainen</td>
<td>16</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>7</td>
<td>Feasibility test of a lifetime measurement in $^{87}$Rb using the plunger and recoil-$\beta$ tagging technique</td>
<td>B.S. Nara Singh, P. Ruotsalainen</td>
<td>4</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>8</td>
<td>Isospin Symmetry and Shape Coexistence in Mirror Nuclei $^{105}$Kr-$^{109}$Br</td>
<td>A. Boso, D. Jenkins</td>
<td>14</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>9</td>
<td>Search for the isoscalar spin-aligned pairing scheme in self-conjugate $^{105}$Cd</td>
<td>B. Cederwall, B.S. Nara Singh</td>
<td>10</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>10</td>
<td>Isospin-breaking effect in the A=62 isobaric triplet: In-beam recoil-$\beta$ tagging study of $^{105}$Ge and $^{109}$Ga employing MARA</td>
<td>P. Ruotsalainen, J. Uusitalo</td>
<td>12</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>11</td>
<td>Mirror energy differences in A=43: a tool to pin down the nature of cross-shell excitations</td>
<td>S.M. Lenz, A. Boso</td>
<td>7</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>12</td>
<td>Disentangling proton-neutron pairing modes in heavy N-Z nuclei</td>
<td>F. Recchia</td>
<td>16</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>13</td>
<td>Simultaneous lifetime measurements in $^{105}$Fe, $^{105}$Mn and $^{109}$Cr isobaric analogue nuclei using DPUNs and recoil-$\beta$ tagging technique to probe isospin symmetry breaking</td>
<td>B.S. Nara Singh, M. Giles</td>
<td>14</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>14</td>
<td>Oblate-deformed proton emitter $^{143}$Lu</td>
<td>K. Auranen, J. Uusitalo</td>
<td>7</td>
<td>15.03.2018</td>
</tr>
<tr>
<td>19</td>
<td>Prompt proton- and gamma-ray spectroscopy of $^{107}$Cu</td>
<td>M. Bentley, U. Forsberg</td>
<td>7</td>
<td>15.09.2018</td>
</tr>
<tr>
<td>20</td>
<td>Nuclear reaction dynamics study at MARA</td>
<td>J. Khuyagbaatar, J. Uusitalo</td>
<td>7</td>
<td>15.09.2018</td>
</tr>
<tr>
<td>26</td>
<td>Towards understanding of isospin-breaking effects in isobaric multiplets: In-beam recoil-$\beta$ tagging study of $^{105}$Se and $^{108}$As</td>
<td>P. Ruotsalainen, G. Zimba</td>
<td>7</td>
<td>15.03.2019</td>
</tr>
<tr>
<td>23</td>
<td>Octupole correlations in the N=56 neutron-deficient $^{108}$Xe</td>
<td>A. Illana, J.J. Valiente-Dobón</td>
<td>8</td>
<td>15.03.2019</td>
</tr>
<tr>
<td>24</td>
<td>RDDS measurement of lifetimes in $^{107,109}$Te using recoil-decay tagging with JurogamIII and MARA: Probing the emergence of collectivity above $^{105}$Sn</td>
<td>B. Cederwall, T. Grahn</td>
<td>11</td>
<td>15.03.2019</td>
</tr>
</tbody>
</table>

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

- *np* interaction (30%)
- isospin symmetry, CED (42%)
JUROGAM 3 scientific program at JYFL

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

<table>
<thead>
<tr>
<th>No.</th>
<th>Title</th>
<th>Spokesperson</th>
<th>Remaining beam time</th>
<th>Submission deadline</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>Prompt and delayed spectroscopy of neutron deficient trans-lead nuclei $^{202,203}_{\text{Ac}}$</td>
<td>K. Auranen</td>
<td>14</td>
<td>15.03.2017</td>
</tr>
<tr>
<td>151</td>
<td>Investigation of the high-spin isomeric states and collective structures in the very neutron-deficient $^{202,204}_{\text{Bi}}$ nuclei</td>
<td>A. Herzan, S. Juutinen</td>
<td>15</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>152</td>
<td>Understanding Proton-, gamma- and alpha-emission within a simultaneous theoretical approach: Lifetime measurements in $^{188}_{\text{Re}}$</td>
<td>M. Giles, T. Grahn</td>
<td>9</td>
<td>15.09.2018</td>
</tr>
<tr>
<td>153</td>
<td>First lifetime measurements of excited states in the triaxial three-dimensional proton emitter $^{152}_{\text{Tm}}$</td>
<td>D. Cullen, L. Barber</td>
<td>9</td>
<td>15.09.2018</td>
</tr>
<tr>
<td>24</td>
<td>In-beam spectroscopy of $^{208}_{\text{Pb}}$ using the SAGE spectrometer at the MARA separator</td>
<td>J. Pakarinen</td>
<td>14</td>
<td>15.09.2017</td>
</tr>
<tr>
<td>25</td>
<td>Probing shape coexistence via E0 transitions in the mass A=70-80 region using the SAGE spectrometer at the MARA separator</td>
<td>M. Sandzelius</td>
<td>7</td>
<td>15.09.2018</td>
</tr>
<tr>
<td>26</td>
<td>Identification and study of parity-doublet bands in $^{235}_{\text{U}}$ using recoil-decay tagging with SAGE and RITU</td>
<td>J. Smith</td>
<td>14</td>
<td>15.03.2019</td>
</tr>
</tbody>
</table>

47 days of beam time for JUROGAM 3 + RITU experiments:

35 days of beam time for SAGE + MARA experiments:

257 days 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.
Experimental and theoretical efforts to find "fingerprints" of \( np \) pairing:

1. Binding energies
2. Low-lying states of odd-odd self-conjugate nuclei
3. Rotational response
4. Gamow-Teller \( \beta \)-decay
5. Pairing vibrations
6. …
**np pairing correlations**

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:

$^{58}\text{Ni} + ^{28}\text{Si} \rightarrow ^{84}\text{Mo} + 2n$:
- Extend level scheme in $^{84}\text{Mo}$ to higher angular momentum.
- Investigate existence of 16$^+$ spin trap isomer.
- Investigate the role of T=0, np pairing.

$^{32}\text{S} + ^{58}\text{Ni} \rightarrow ^{88}\text{Ru} + 2n$:
- Extend level scheme in $^{88}\text{Ru}$ to higher angular momentum.
- Investigate the role of T=0, np pairing.

![Graphs showing np pairing correlations](image)
${}^{84}\text{Mo}$

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

Gamma-ray energy

JUROGAM 3: gamma-ray singles

Counts / 1 keV

Gamma-ray energy [keV]

Gamma-ray energy [keV]

$A=84$

$A=83$
$^{84}\text{Mo}$

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

JUROIGAM 3 gamma-rays

with qp veto

and mass gate

$^{84}\text{Mo}$
 Spin-aligned, T=0 np-coupling scheme in $^{92}$Pd

"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."

B. Cederwall et. al., Nature (2011)
np pairing correlations

JUROGAM 3 + MARA experiments:

$^{58}\text{Ni} + ^{40}\text{Ca} \rightarrow ^{94}\text{Ag} + \text{p3n}$:
- Identify low-lying T=0 and T=1 states in $^{94}\text{Ag}$
- Investigate the effect of the possible T=0 spin-aligned np-pairing schemes.

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

$\delta = -1 \rightarrow \text{interaction off}$

$\delta = 2 \rightarrow \text{twice the strength}$
**np pairing correlations**

**JUROGAM 3 + MARA experiments:**

\(^{58}\text{Ni} + ^{40}\text{Ca} \rightarrow ^{96}\text{Cd} + 2n:
- Identify low-lying excited states in \(^{96}\text{Cd}.
- Investigate the effect of the possible T=0 spin-aligned np-pairing schemes.

![Shell-model prediction for \(^{96}\text{Cd}\)](image)
np pairing correlations

JUROGAM 3 + MARA experiments:

$^{58}\text{Ni} + ^{40}\text{Ca} \rightarrow ^{96}\text{Cd} + 2\text{n}$:
- Identify low-lying excited states in $^{96}\text{Cd}$.
- Investigate the effect of the possible $T=0$ spin-aligned np-pairing schemes.

$^{36}\text{Ar} + ^{58}\text{Ni} \rightarrow ^{91}\text{Pd} + 3\text{n}$:
- Identify states up to $25/2^+$ state.
- Extract MED between $A=91$ mirror pair.
- Investigate the type of nucleons aligning angular momenta.

Experimental MED

"quasi-alignment - measure of the type of nucleons aligning"
Isospin symmetry breaking

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

Isospin symmetry is broken mainly due to the Coulomb interaction.

Degeneracy of energy levels across the isobaric triplets.

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

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

Isospin symmetry is broken mainly due to the Coulomb interaction.

“Coulomb energy differences”
\[ \text{CED}_{J,T} = E_{J, T_z=0} - E_{J, T_z=+1} \]

“Mirror energy differences”
\[ \text{MED}_{J,T} = E_{J, T_z=-1} - E_{J, T_z=+1} \]

“Triplet energy differences”
\[ \text{TED}_{J,T} = E_{J, T_z=-1} + E_{J, T_z=+1} - 2 \times E_{J, T_z=0} \]

\[ N = Z - 2 \quad N = Z \quad N = Z + 2 \]

\[ \begin{align*}
E_3 & \quad 6^+ \\
E_2 & \quad 4^+ \\
E_1 & \quad 2^+ \\
E_0 & \quad 0^+ 
\end{align*} \]  

\[ \begin{align*}
E_3 & \quad 6^+ \\
E_2 & \quad 4^+ \\
E_1 & \quad 2^+ \\
E_0 & \quad 0^+ 
\end{align*} \]  

\[ \begin{align*}
E_3 & \quad 6^+ \\
E_2 & \quad 4^+ \\
E_1 & \quad 2^+ \\
E_0 & \quad 0^+ 
\end{align*} \]

Degeneracy of energy levels across the isobaric triplets.

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

"Triplet energy differences"

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

"Mirror energy differences"

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

- **el.m. spin-orbit potential** (effects both protons and neutrons):
  \[ E_{ls} \simeq (g_s - g_i) \frac{1}{2m_N e^2} \left( -\frac{Ze^2}{R_C^3} \right) \langle \vec{l} \cdot \vec{s} \rangle \]

- **Radial term, nuclear radius changes as a function J.**
  \[ V_{Cr}(J) = -\frac{3}{5} Z(Z - 1)e^2 \frac{\Delta R(J)}{R_C^2} \]

- **Single-particle shift for protons.**
  \[ E_{ll} = -4.5Z_{cs}^{13/12}\frac{[2l(l + 1) - N(N + 3)]}{A^{1/3} \left( N + \frac{3}{2} \right)} \text{ keV} \]
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

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

JUROGAM 3 + MARA experiments:

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

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

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

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

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

\[ ^{36}\text{Ar} + ^{24}\text{Mg} \rightarrow ^{57}\text{Cu} + 2\text{n} \]  
- Identify prompt proton decay in \(^{57}\text{Cu}\).  
- First experiment of the planned in-beam proton-\(\gamma\) coincidence spectroscopy campaign.  
- Study competition between \(\gamma\)- and proton emission in weakly-bound systems.  
- Extract MED for A=57 mirror pair.
Isospin symmetry breaking

**JUROGAM 3 + MARA experiments:**

\[ ^{36}\text{Ar} + ^{40}\text{Ca} \rightarrow ^{74}\text{Rb} + \text{pn} : \]
- DPUNS + RBT proof-of-principle experiment.
- Measure excited state lifetimes in \(^{74}\text{Rb}\).

\[ ^{40}\text{Ca} + ^{12}\text{C} \rightarrow ^{50}\text{Fe} + 2\text{p}, ^{50}\text{Mn} + \text{pn}, ^{50}\text{Cr} + 2\text{n} : \]
- Simultaneous DPUNS (+ RBT) measurement of \(2^+\) state lifetimes in \(^{50}\text{Fe}, ^{50}\text{Mn}\) and \(^{50}\text{Cr}\).
- 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 Advanced Plunger – Particle detector Array (APPA).
JYFL nuclear spectroscopy group

P. Greenlees
J. Uusitalo
R. Julin
M. Leino
S. Juutinen
J. Pakarinen
T. Grahn
P. Rahkila
M. Sandzelius
J. Sarén
P. Ruotsalainen
J. Partanen
M. Luoma
J. Ojala
H. Tann
G. Zimba

Men behind MARA

Juha Uusitalo
Jan Saren
Jari Partanen

Thank you!