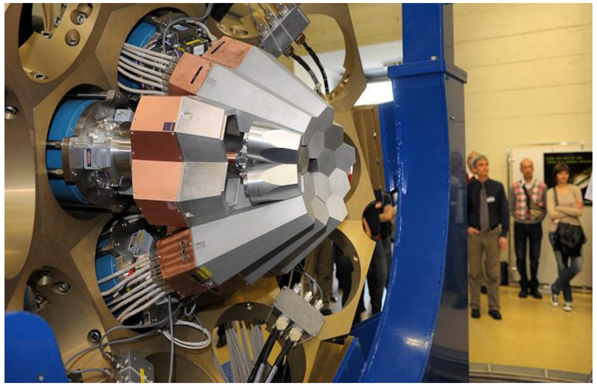
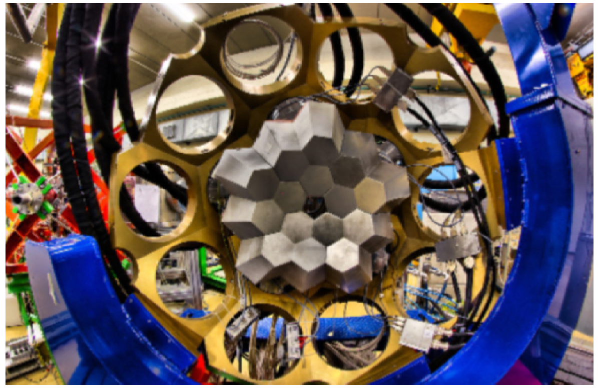




Physics Highlights from the AGATA Campaign at Legnaro National Laboratory

Sean J Freeman The University of Manchester

Development of the Scientific Programme

- A lot of discussions about tracking array physics in the years up to the decision to site AGATA at Legnaro.
- Kick-off science workshop Legnaro Nov 2007:
  23 (48 institutions from 16 countries) LOIs generated for PAC June 2008.
- Physics workshop Istanbul May 2010:
  Further 7 LOIs added.

From LNL-PAC July 2008

AGATA @ LNL

Main Aim:

demonstrate the feasibility of the gamma-ray tracking concept and validate the AGATA Demonstrator

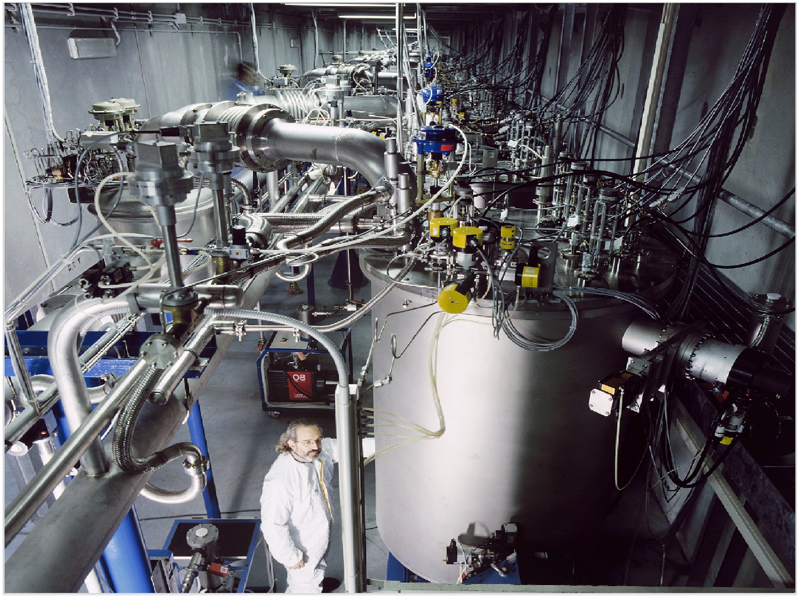
Explore physics opportunities:

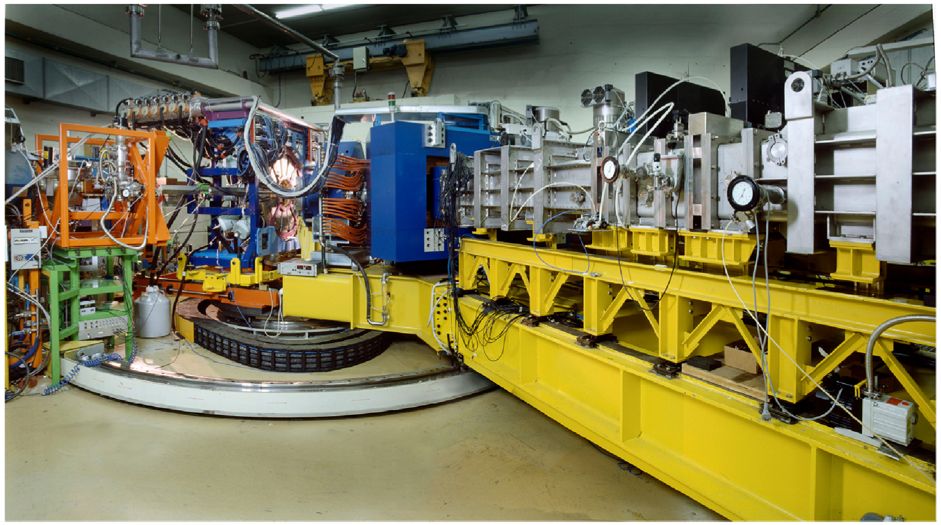
a subsequent experimental campaign at LNL to exploit the unique features of the Demonstrator, particularly the coupling to PRISMA

From LNL-PAC July 2008

LNL Opportunities

- Expertise in multi-nucleon transfer
- Coupling to PRISMA Spectrometer
- Experience with CLARA + PRISMA
- Beam variety with accelerator system: particularly medium and heavy beams at >6 MeV/A

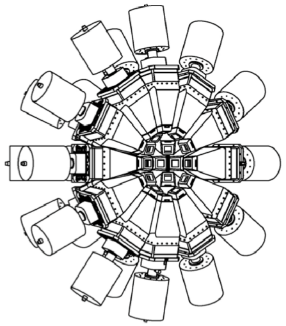




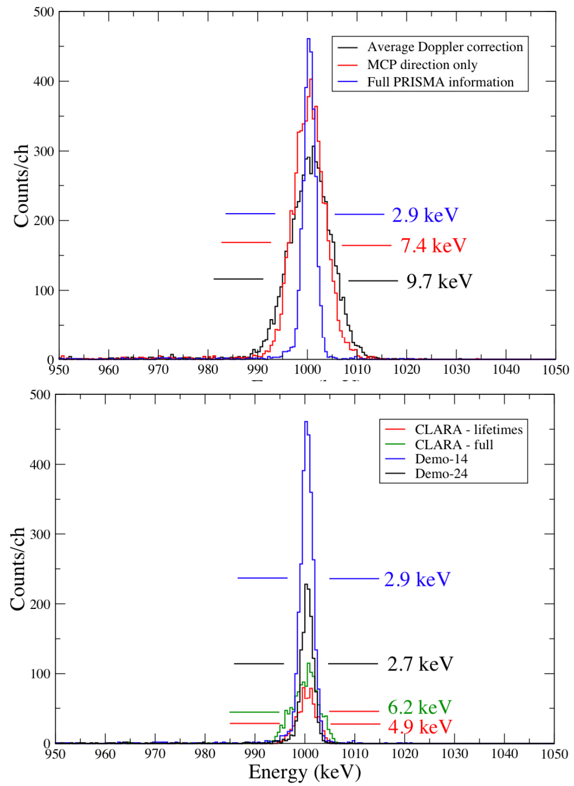
Majority of Letters of Intent use multi-nucleon transfer as the population mechanism taking advantage of PRISMA and beams in 6-7 MeV/A

From LNL-PAC July 2008

AGATA Opportunities

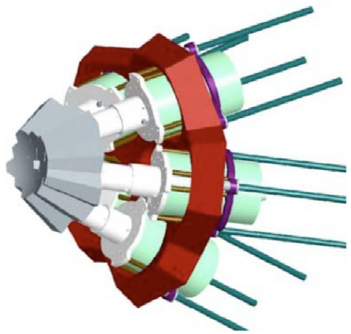


<u>CLARA</u>:
Efficiency at 1MeV: ~2.6%
Peak/Total: ~40%
Angles covered: from 102º to 180º
(½ of the efficiency located at 102º)
FWHM, β~10%, 1MeV: 7 to 10 keV



^{90}Zr@350 MeV average energy, Gaussian dispersion with σ=20%

<u>AGATA DEMONSTRATOR</u>:
Efficiency at 1MeV: ~6% at 14cm
Peak/Total: ~50%
Angles covered: from ~135º to 180º
FWHM, β~10%, 1MeV: <4 keV



All of Letters of Intent benefit from improved spectral quality obtained from localisation of gamma interactions in AGATA and the majority from determination of ion trajectories using PRISMA.

In particular, Doppler-based lifetime techniques benefit greatly from improved resolution and angular definition; many proposals suggest recoil-distance measurements.

PAC Proposals and Campaign Operation

After technical and scientific checks, physics proposals submitted from June 2009:

20 approved with a total of 142 days (about 3500 hours) approved

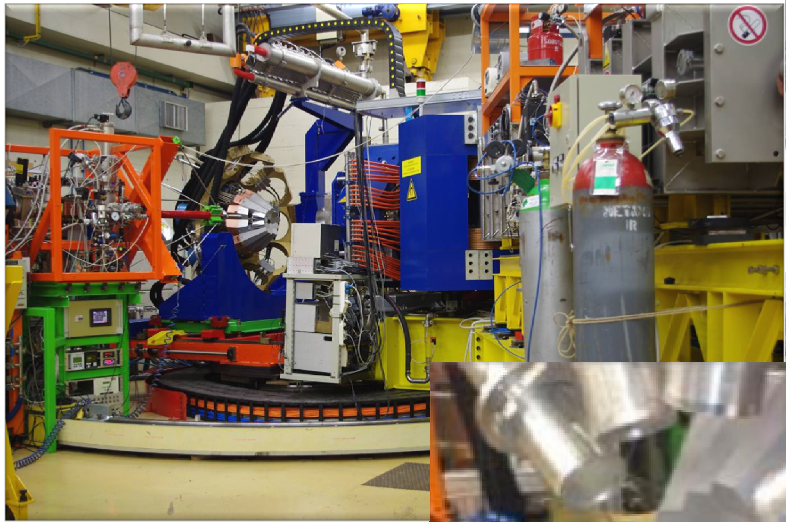
very little overlap in scientific cases (partly through coordination through workshops, partly due to the profusion of ideas).

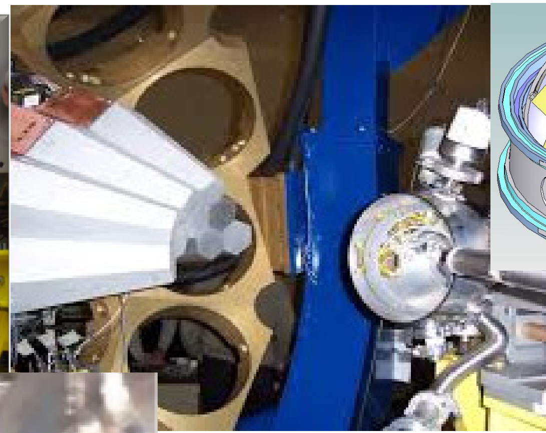
In-beam commissioning and technical validation in 2009.

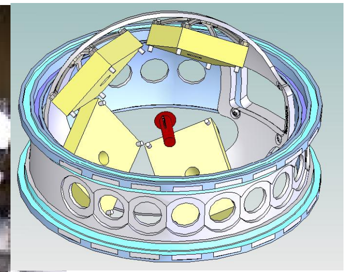
Physics campaign began in February 2010 until December 2011.

Ancillary Devices

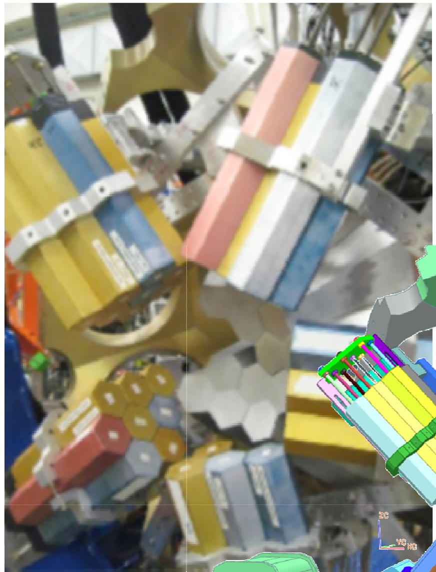
PRISMA: magnetic spectrometer with trajectory reconstruction to identify reaction products

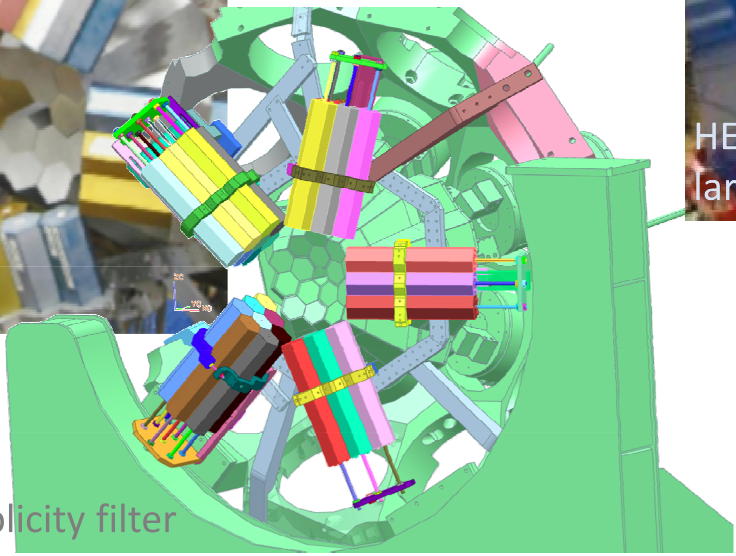


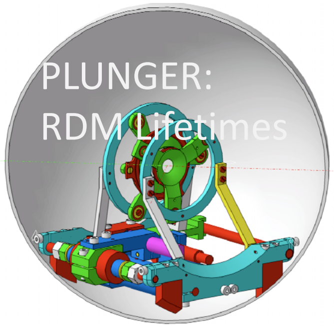


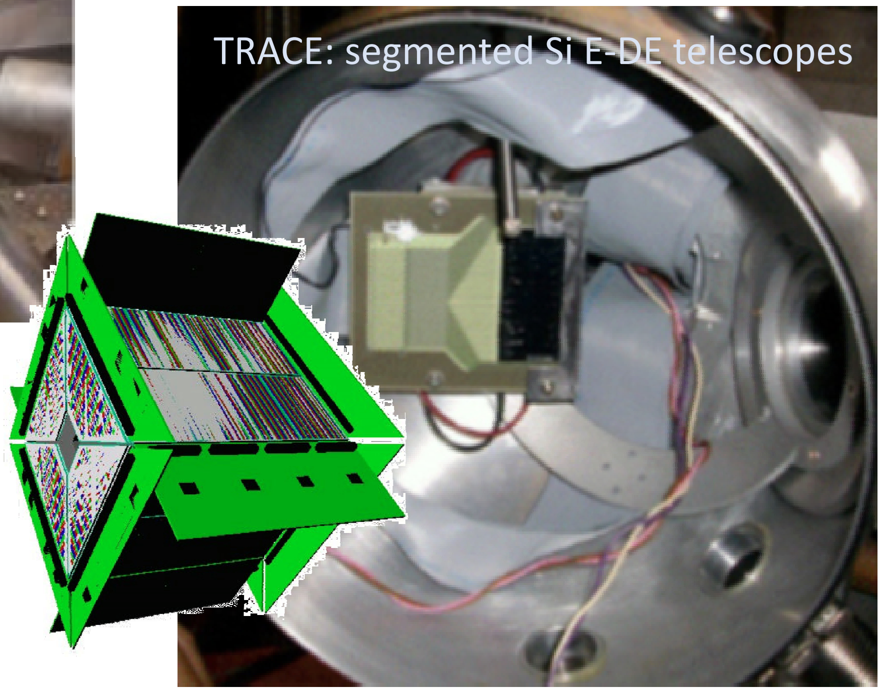


DANTE: MCP target array defines a fraction of product trajectories not in acceptance of PRISMA

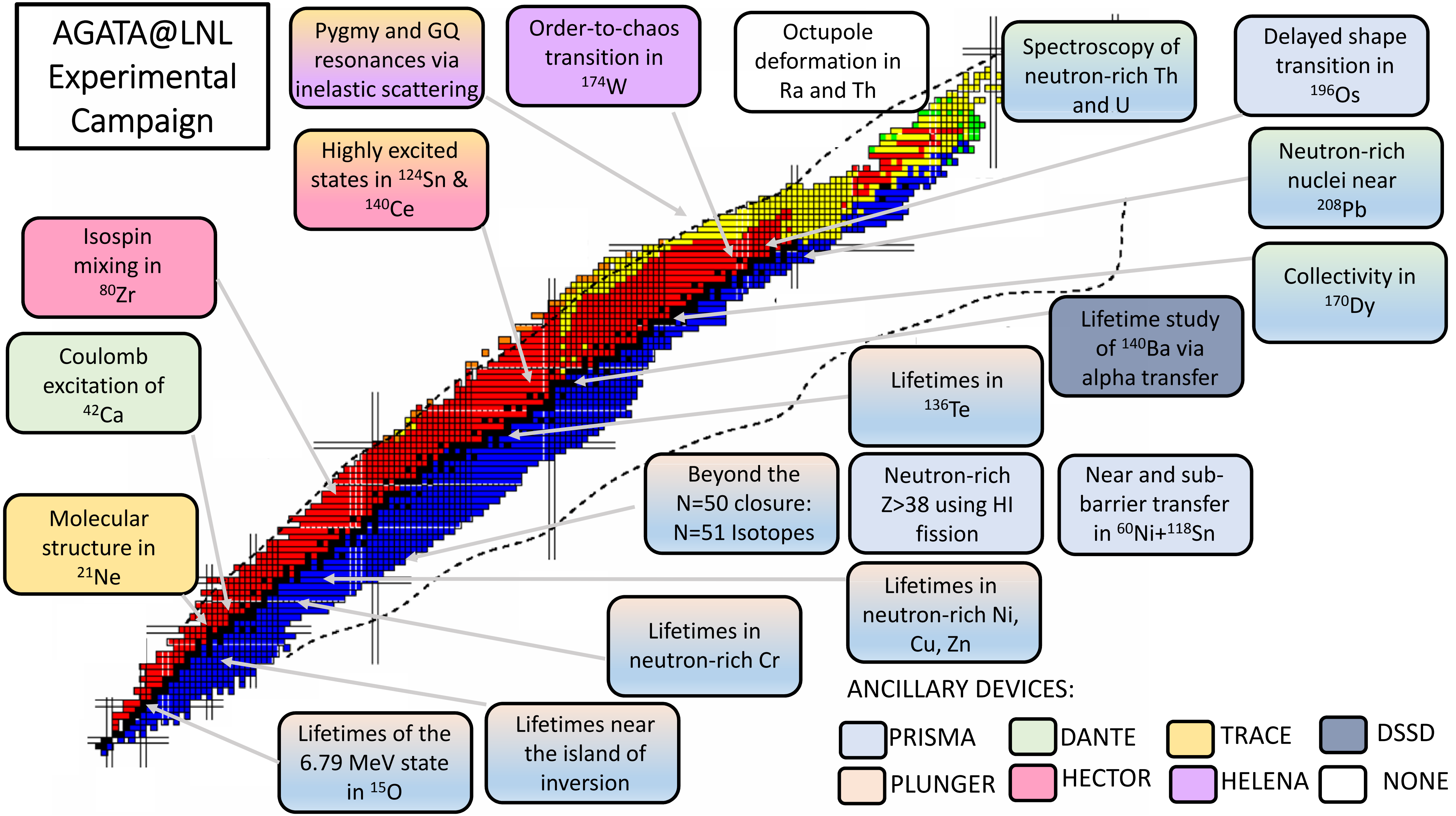








HELENA:
BaF_2 multiplicity filter


AGATA@LNL Experimental Campaign
Pygmy and GQ resonances via inelastic scattering
Order-to-chaos transition in ^{174}W
Octupole deformation in Ra and Th
Spectroscopy of neutron-rich Th and U
Delayed shape transition in ^{196}Os
Highly excited states in ^{124}Sn & ^{140}Ce
Neutron-rich nuclei near ^{208}Pb
Isospin mixing in ^{80}Zr
Collectivity in ^{170}Dy
Lifetime study of ^{140}Ba via alpha transfer
Coulomb excitation of ^{42}Ca
Lifetimes in ^{136}Te
Beyond the N=50 closure: N=51 Isotopes
Neutron-rich Z>38 using HI fission
Near and sub-barrier transfer in ^{60}Ni+^{118}Sn
Molecular structure in ^{21}Ne
Lifetimes in neutron-rich Ni, Cu, Zn
Lifetimes in neutron-rich Cr
ANCILLARY DEVICES:
Lifetimes of the 6.79 MeV state in ^{15}O
Lifetimes near the island of inversion
PRISMA
DANTE
TRACE
DSSD
PLUNGER
HECTOR
HELENA
NONE

Highlights from the Legnaro Campaign

- 20 experiments
- 142 days
- 3500 hours
- 19 papers in PRL, PLB, PRC plus a couple under review
- Many more contributions to workshops and conferences.

- Inelastic scattering
- Coulex
- Multi-nucleon transfer
- Fusion-evaporation
- Fission
- Alpha transfer

Published experiments:

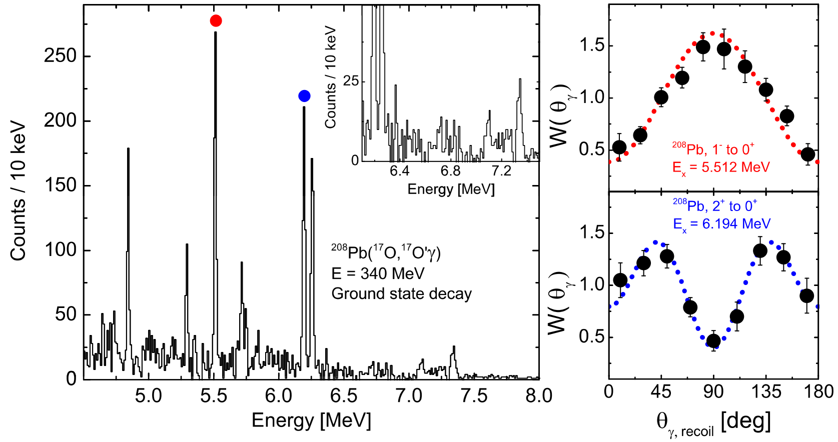
- Mostly 5 triple clusters
- A few with 4
- A couple with 3
- Physics results on ^{40}K from commissioning with only 1

THE REVIEWER'S POSIONED CHALICE:
Much excellent physics - have to select highlights – can't please everyone.
But even those selected – they might not be pleased.
Apologies for the wrong emphasis, simplifying to the extent of trivialising, missed subtle points or mistakes!
Members of the are likely to give better answers to questions....

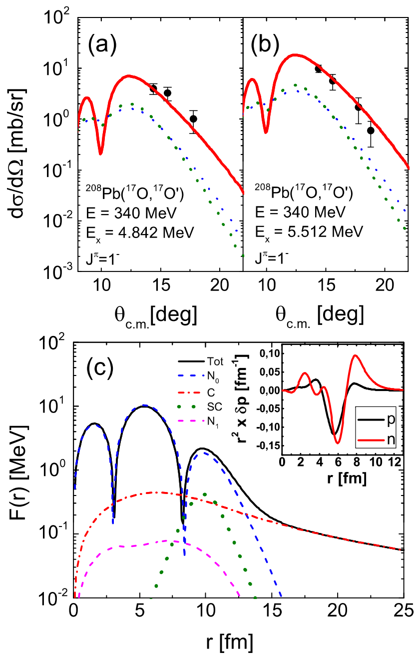
Pygmy Dipole Resonances (PDR) via HI Inelastic Scattering in ^{208}Pb

Crespi et al. PRL 113, 012501 (2014)
AGATA & TRACE: ^{17}O@340 MeV +^{208}Pb

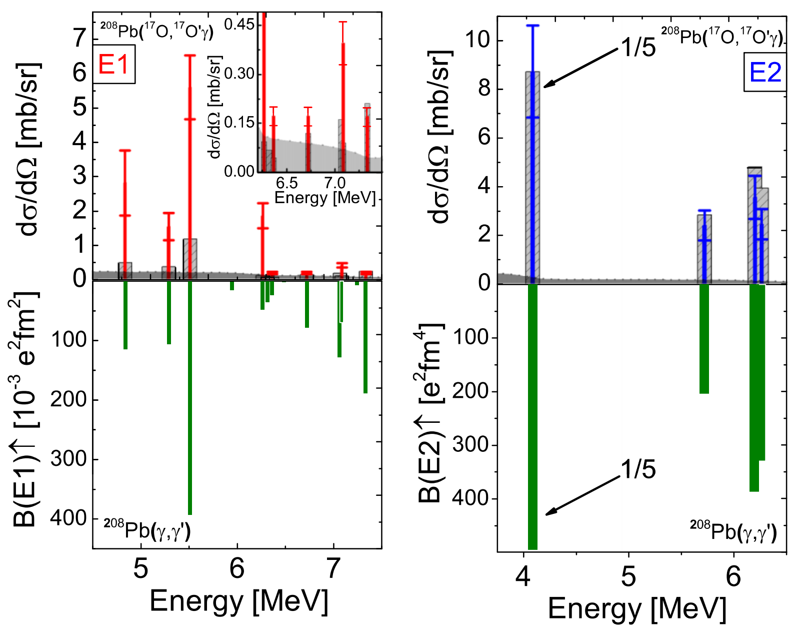
Close to particle threshold, excess of E1 strength corresponding to the oscillation of the neutron skin about the core – strong influence on r-process nuclear synthesis and can probe equation of state.
Transition densities are surface peaked – HI inelastic scattering should be a useful probe.



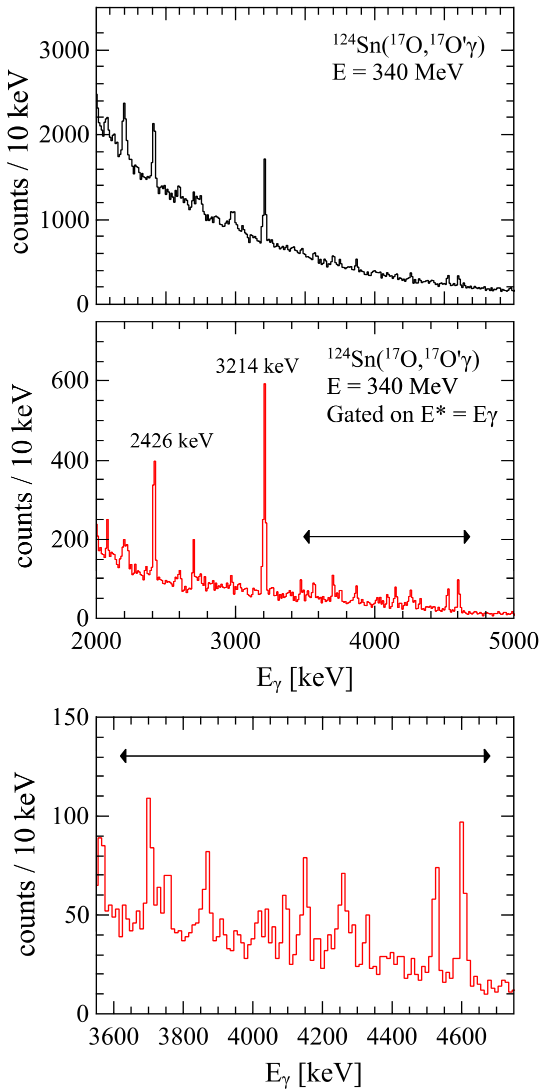
Position definition of particles and γ rays using TRACE and AGATA allow Doppler correction. High segmentation in both allows detail angular distributions.
Cross sections deduced by normalisation to elastics – well described by reaction modeling, as are strong states with known B(E2) and B(E3).



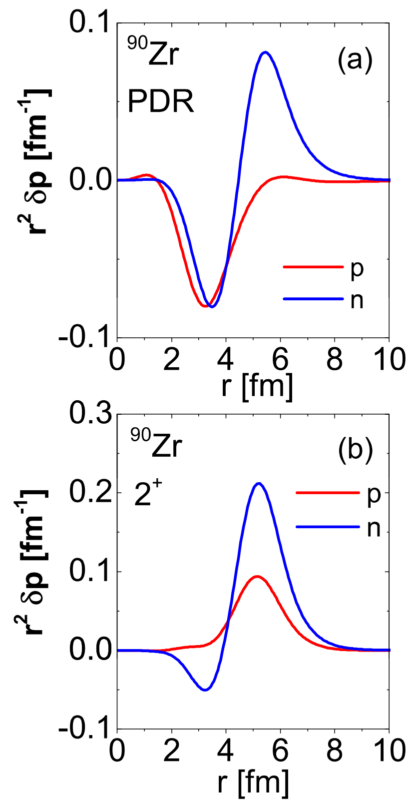
- Good correspondence of 1^- states with (γ,γ′)
- Strong disagreement in measured cross sections with those expected from *B(E1)* and standard form factors (similar to Coulex only). Doesn't reproduce the particle angular distributions, where available.
- Discrepancies due to nuclear contributions.
- New form factor (double folding with M3Y) and transition density (HF+RPA) developed - strong isoscalar PDR characteristics (p&n in phase inside, with strong surface n).
- Good tool for E1 and higher multipoles (high-lying E2 excitations seen). Similar studies with radioactive beams on ^{13}C target possible.

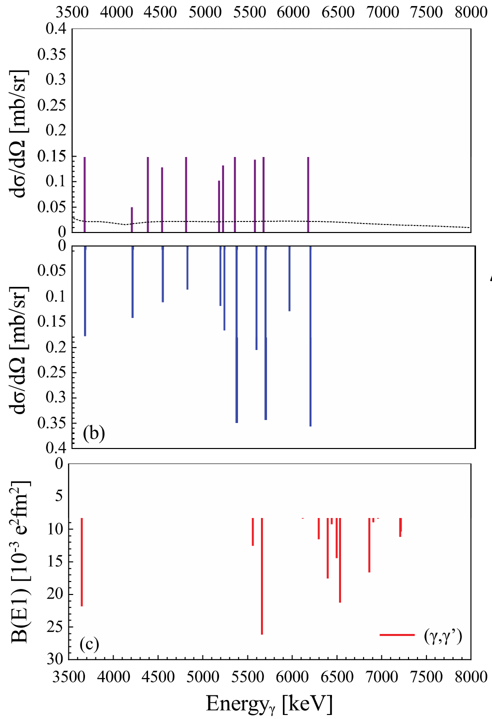


Multipole Responses in ^{90}Zr, ^{140}Ce and ^{124}Sn



Technique extended to studies of E1 and higher multipoles in other systems.



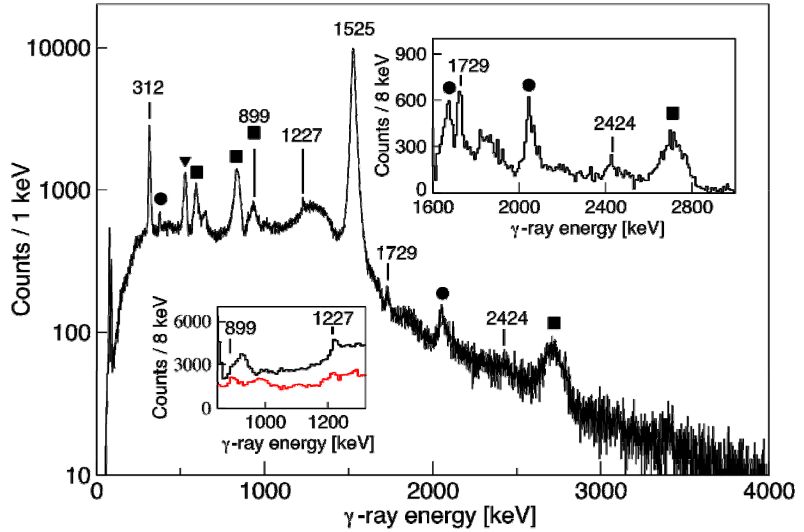


Pellegri et al. PLB 738 (2014) 519-523 and PRC 92, 014330 (2015)
AGATA & TRACE: ^{17}O@340 MeV +^{124}Sn
Krysiek et al. PRC 93, 044330 (2016)
AGATA & TRACE: ^{17}O@340 MeV +^{140}Ce
Crespi et al. PRC 91, 024323 (2015)
AGATA & TRACE: ^{17}O@340 MeV +^{90}Zr

- ^{124}Sn: correlations between HI inelastic scattering against previous (α,α′γ) – similar DWBA analysis verified approach in another system to give comprehensive description.
- ^{124}Sn: E2 population analysed in detail and compared to DWBA predictions with good agreement – evidence for PQR, quadrupole excitations of neutron skin.
- ^{90}Zr and ^{140}Ce: detailed spectroscopic investigations with the new tool.

Super-deformed and triaxial states in ^{42}Ca

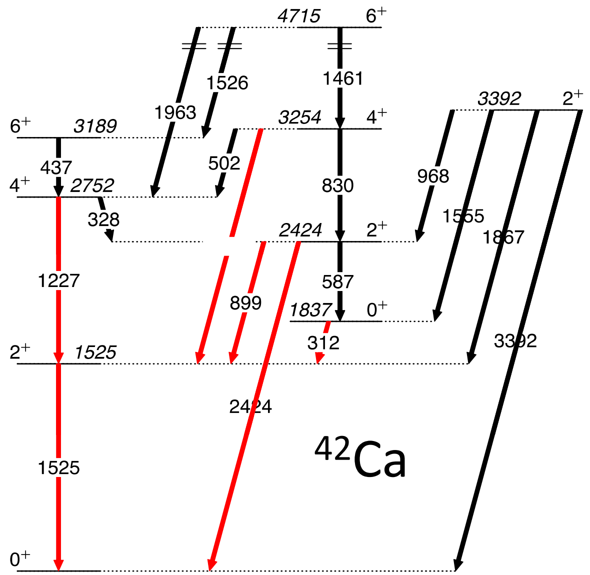
Hadynska-Klek et al. PRL submitted (2016)
AGATA & DANTE: ^{42}Ca@170MeV+^{197}Au/^{208}Pb



Super-deformed configurations in light systems arguably more accessible to theoretical modeled and are connected to low-lying states via visible transitions.

Low-energy Coulex experiment aim to measure E2 matrix elements of transitions populating low-lying states including SD side bands.

Position definition of particles and γ rays using DANTE and AGATA allow Doppler correction.



- First population of SD bands in Coulex.
- Populate 0, 2 and 4$^+$ states of the GSB and SDB.
- Extract quadrupole deformation for the 0 and 2$^+$ states.
- Spherical GS shape.
- *β=0.43(2)* and *β=0.45(2)* for the SD 0 and 2$^+$ states.
- Triaxiality in SD band *γ=13°(6)* – non-axial character of SD bands in *A=40* region for the first time.
- General picture of spherical GSB and slightly triaxial SDB reproduced in calculations using shell-model and beyond-mean-field approaches.

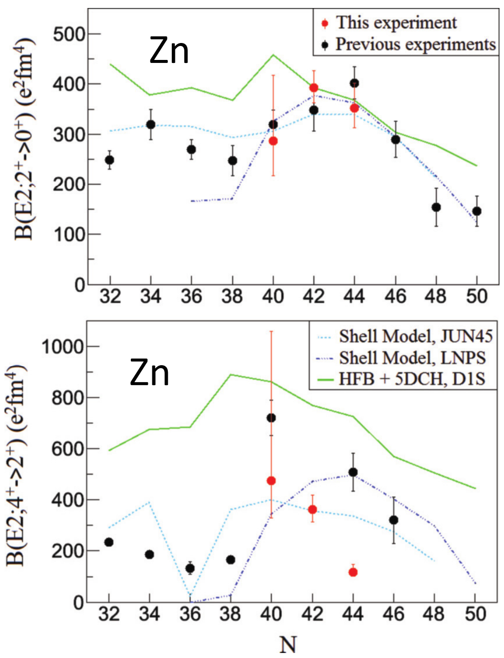
Lifetimes in Neutron-Rich Zn and Cu Isotopes

Louchart et al. PRC 87, 054302 (2013)
Sahin et al. PRC 91, 034302 (2015)
AGATA, PLUNGER & PRISMA: ^{76}Ge @577MeV +^{238}U on ^{181}Ta, with ^{93}Nb degrader

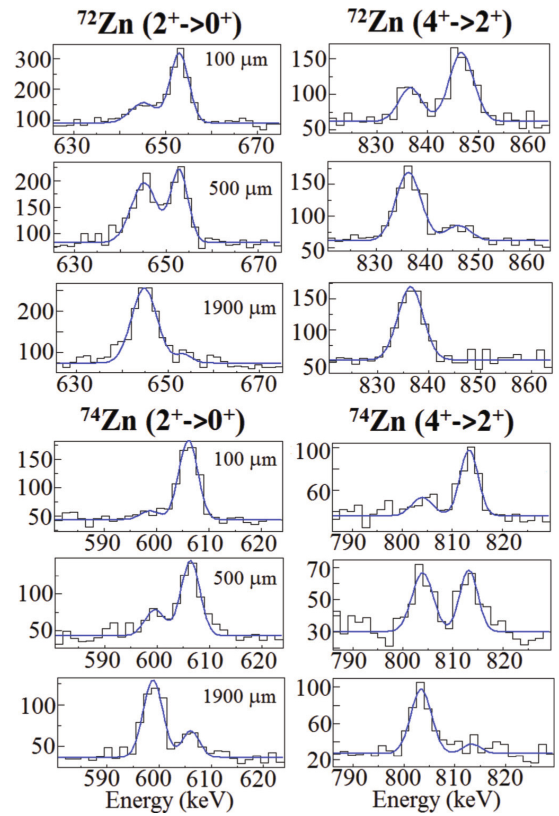
Region above ^{68}Ni: single-particle migration, e.g. "$\pi f_{5/2}$" falls with N crossing "$\pi p_{3/2}$" to assume the gs in ^{75}Cu – assess nature of low-lying states in odd isotopes using lifetimes.

In *fp* shell, increases in collectivity seen on approaching *N=40* reproduced in SM only using $pf_{5/2}g_{9/2}+ d_{5/2}$ space. Probe $d_{5/2}$ occupation and collectivity via *B(E2)*. Done with RNB Coulex – peak at *N=44*, but at *N=42* in Ge and Se.

Good resolution needed in plunger spectra to resolve shifted and unshifted components – aided by the angular definition provided by tracking.



- Yrast 2$^+$ lifetimes in ^{70,72,74}Zn – maximal collectivity at *N=42*, similar to Ge and Se.
- *B(E2: 4=>2)* show significant discrepancies from previous measurements AND theory, especially the unusually large lifetime of the 4$^+$ state in ^{74}Zn. Ratios to *B(E2: 2=>0)* in ^{72,74}Zn less than 1, typical for non-collective states near closed shells.
- Side-feeding issues HAVE been carefully considered: unobserved feeding estimated in errors and sensitivity to Q from PRISMA investigated.
- In odd ^{69,71,73}Cu, lifetimes used to help understand the structure of 7/2$^-$ state, potentially arising from $\pi f_{5/2}$ or $\pi p_{3/2}$ coupled to a 2$^+$ core excitation.

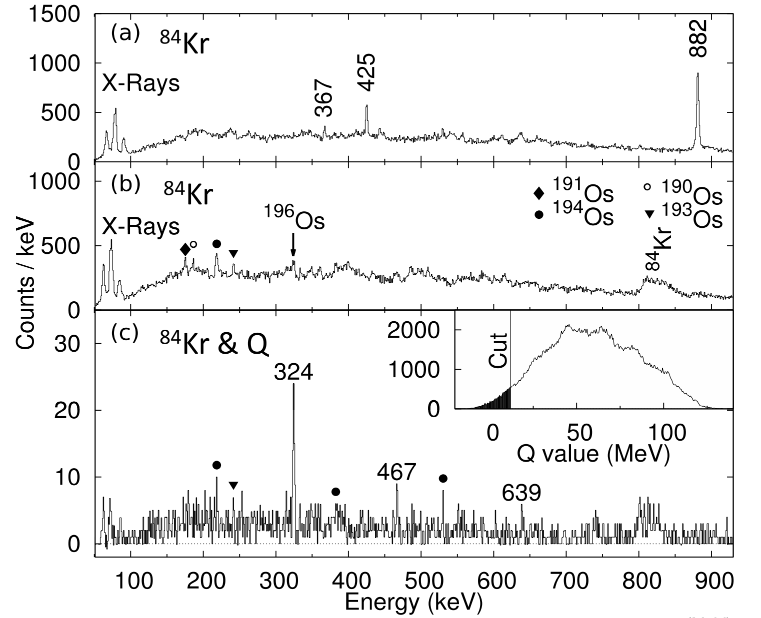


Shape Evolution around *A=200*

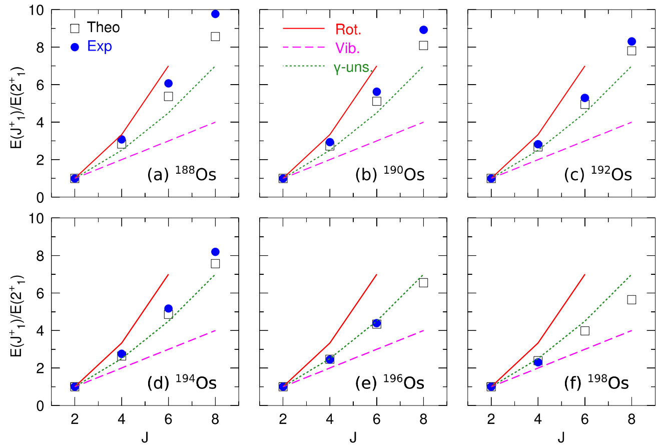
John et al. PRC submitted (2016) and PRC 90, 021301 (R) (2014)

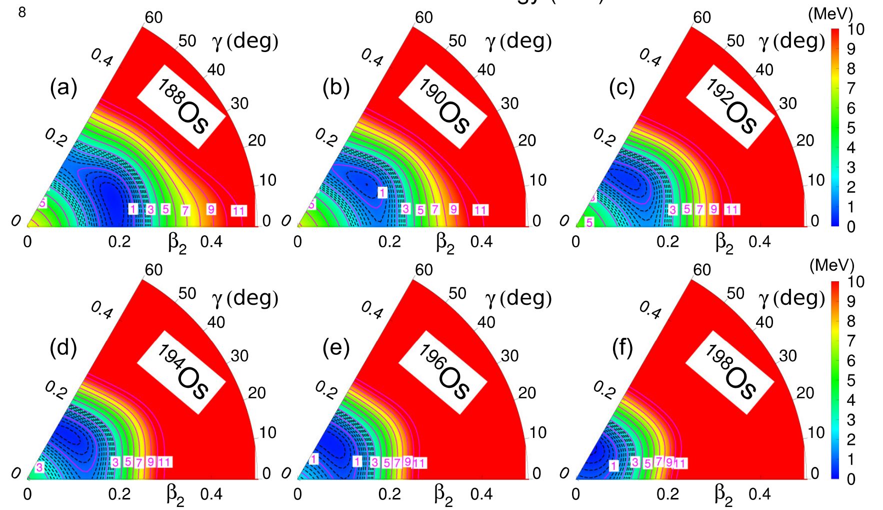
Few-nucleon removal on ^{198}Pt to investigate shape evolution probed by yrast levels in heavy neutron-rich nuclei in the approach to *N=126*. Notoriously difficult to produce:
Eg. osmium: serendipitous isomer in ^{198}Os allowed some delayed spectroscopy; two non–yrast states in ^{196}Os

AGATA & PRISMA: ^{82}Se@426MeV + ^{198}Pt



Beam-like fragments in PRISMA with 1/280 mass resolution.
Condition on beam-like mass is an upper limit on the heavy fragment mass due to evaporation.
Reduced if gate the Q value so energies are less than S_n.
Further confirmation by γ coincidence.





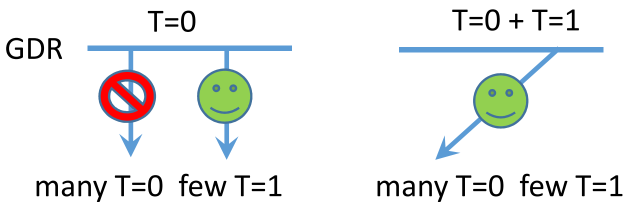
- Yrast sequence in ^{196}Os for the first time; yrast 6 and 8$^+$ in ^{200}Pt.
- Comparisons with beyond mean-field calculations: smooth evolution from prolate (^{188}Os) through transitional triaxial minima ($^{190-192}$Os) to oblate ($^{194-196}$Os), but with significant triaxial degree of freedom.
- ^{196}Os – comparison with geometric limits shows close agreement with γ-unstable rotor.
- ^{200}Pt – closer to *N=126*, additional yrast states reveal a transitional character between lighter γ-unstable systems and heavier nuclei that are predicted to be spherical.

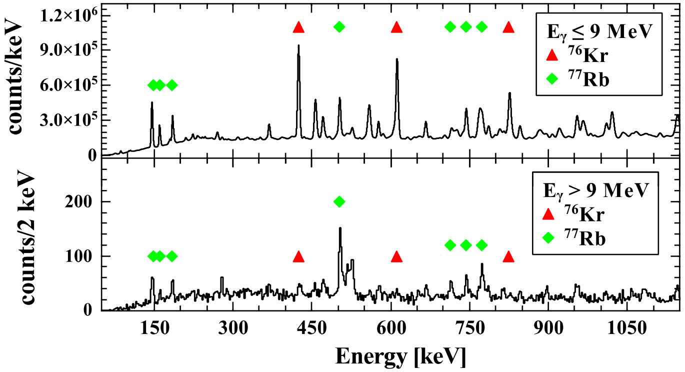
Isospin Mixing in ^{80}Zr: From Finite to Zero Temperature

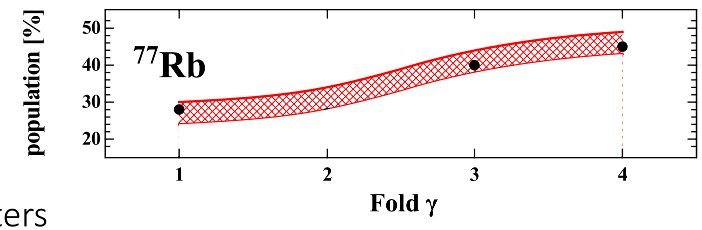
Ceruti et al. PRL 1154, 222502 (2015)

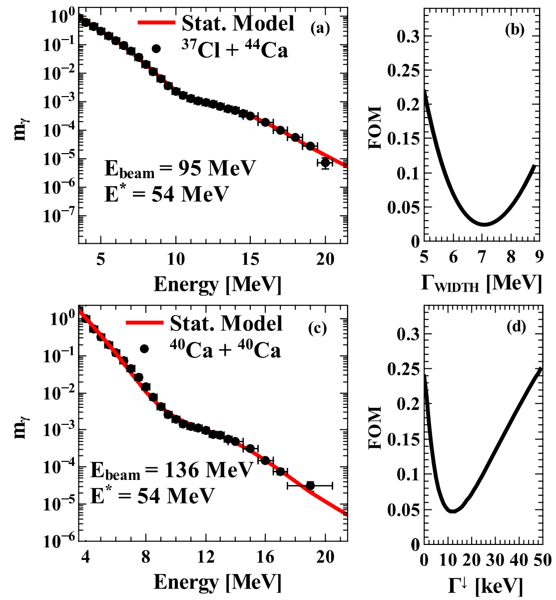
AGATA & HECTOR: ^{40}Ca@136MeV + ^{40}Ca and ^{37}Cl @95MeV + ^{44}Ca

Use the concentration of E1 strength in GDR to investigate isospin mixing via E1 isospin selection rule.
Fusion of self-conjugate nuclei to make a nominally isospin zero system.
First-step E1 decay depends on degree of isospin mixing.



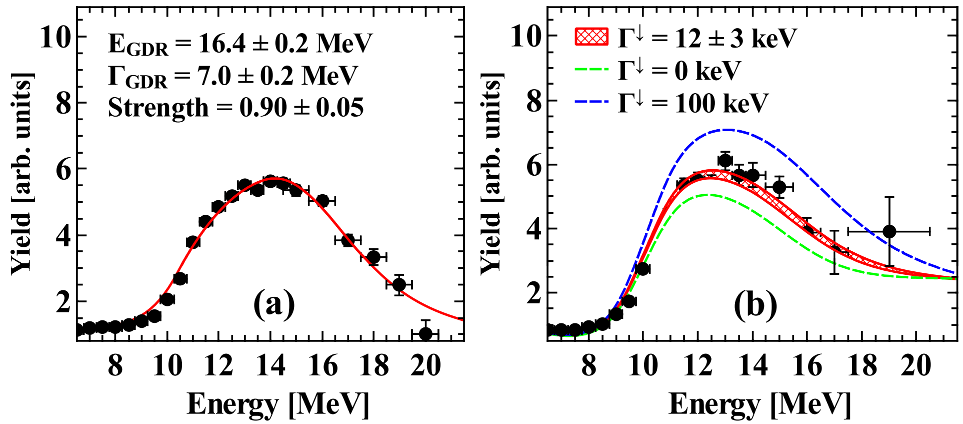






Yields using AGATA => check statistical model.
Spectra from HECTOR on reference reaction => GDR parameters
Only parameter left to fit ^{80}Zr spectrum related to isospin mixing.

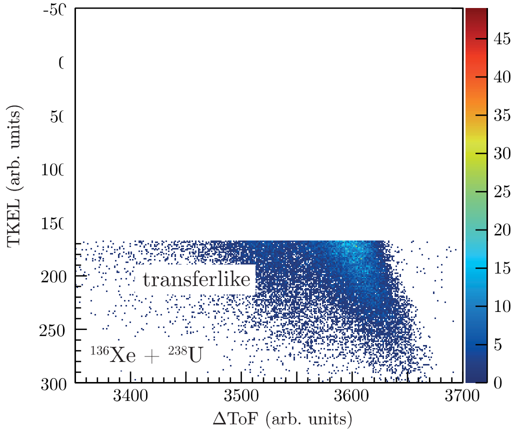
- Coulomb spreading width $\Gamma^{\downarrow}$=12(3) keV @ E^*=54 MeV.
- Deduced isospin mixing larger than some models expect – supports dynamical mechanism related to state lifetime (Wilkinson 1956).
- Combined with previous value at E^*=84 MeV – check the temperature dependence and extract mixing at zero temp.
- Can related that to the isospin mixing correction for *ft* values from super-allowed Fermi β decays.



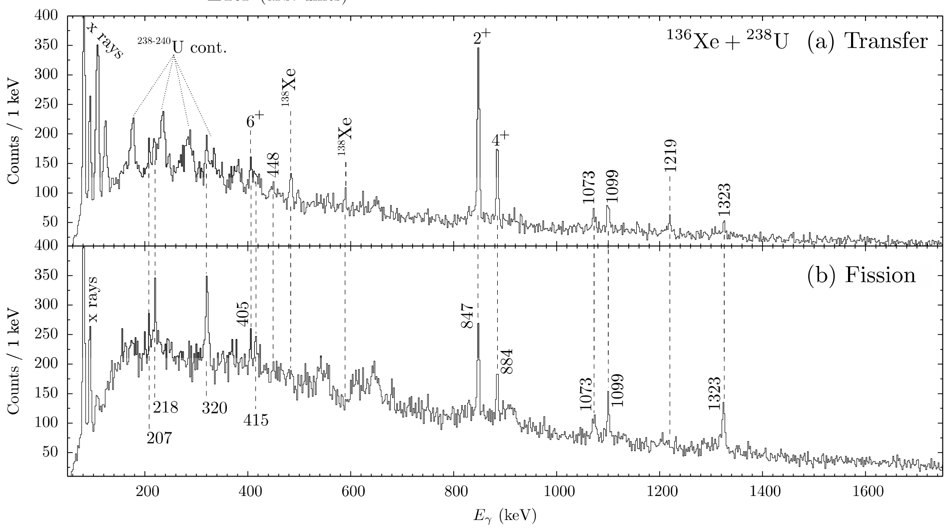
Reactions between Heavy Ions

Vogt et al. PRC 92, 024619 (2015)
^{240}U Birkenbach et al. PRC 92, 044319 (2015)
^{134}Xe Vogt et al. PRC 93, 054325 (2016)
AGATA, DANTE & PRISMA: ^{136}Xe @1GeV+^{238}U

Target-like spectroscopy of actinide systems provide interesting benchmarks for models that provide predictions for the heaviest nuclei.
Projectile-like spectroscopy in the vicinity of *N=82* can be used in the development of shell-model descriptions of neutron-rich systems.



TOF differences between coincident products in PRISMA and DANTE reveal different mechanisms – used to identify transitions from highly-excited fission fragments or cold multi-nucleon transfer products.
Angular intensity ratios enable some spin information from new transitions.
AGATA used to probe the population and survival of actinide products using observations of X rays and γ rays, and neutron-induced events in Ge as signal of neutron evaporation.



- Confirmed the feasibility of in-beam actinide spectroscopy in these reactions for few-neutron transfer and two proton removal.
- Unambiguous identification of new transitions in ^{134}Xe, with conclusions about their excitation energies and spin changes..
- Combined with previous data sets established new levels above two long-lived isomers in ^{134}Xe and compare to SM.
- Extensions to the spectroscopy of ^{240}U, where ground state band extended beyond 20ħ, well-described by CR-HFB.
- Significant extension of the first-excited negative-parity band, which shows properties consistent with a $K^{\pi}=0^{-}$ octupole vibrational band.

Many other interesting publications:

Population of the 2^+ mixed symmetry state of ^{140}Ba with the α-transfer reaction
Stahl et al., PRC 92, 044324 (2015)
High-spin structure in ^{40}K
Söderström et al., PRC 86, 054320 (2012)
Global properties of K hindrance probed by the γ decay of the warm rotating ^{174}W nucleus
Vandone et al., PRC 88, 034312 (2013)
Lifetime measurements in neutron-rich ^{63,65}Co isotopes using the AGATA demonstrator
Modamio et al., PRC 88, 044326 (2013)
Transition probabilities in neutron-rich ^{84,86}Se
Litzinger et al., PRC 92, 064322 (2015)
Pair neutron transfer in ^{60}Ni + ^{116}Sn probed via γ -particle coincidences
Montanari et al., PRC 93, 054623 (2016)

Several publications are currently under review…

…analyses of several experiments are continuing.

WATCH THIS SPACE

Concluding remarks:

- A surprising range of exciting science – perhaps not anticipated before the initial workshops.
- Importance of a range of ancillary detectors – work for the in-house team.
- Productive in publications – but it takes some time on a new device – work for the scientific teams.
- AGATA is a demonstration of γ-ray tracking, but also of European collaboration at it's best.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