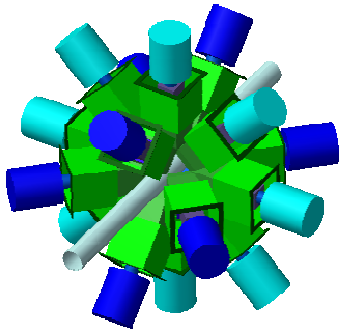
Argonne NATIONAL LABORATORY

CAGRA at Grand Raiden

***C**ompton **A**rray **G**amma-ray spectrometer at **R**CNP/RIBF*
*for **A**dvanced studies*



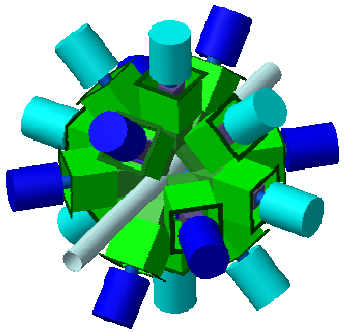
CAGRA

NNR16 Workshop
RCNP
September 30, 2016
M.P. Carpenter

U.S. DEPARTMENT OF ENERGY

Outline of Talk:

- Short history of the CAGRA collaboration
- The components of CAGRA
- RCNP campaigns
  - En Course campaign
  - Grand Raiden campaign
- Summary



CAGRA

CAGRA project

- Create a pool of Compton Suppressed Ge Clover detectors from laboratories in Japan and the U.S. + China which can be assembled at RCNP/RIBF to be utilized in gamma-ray spectroscopy.
- Physics experiments at RCNP using EN, GR, MuSIC
- At RIBF using both energy degraded and stopped beams of exotic nuclei.
- Mechanical Infrastructures to be built
  - Self contained, trigger-less acquisition system using Gretina Digitizers
  - Liquid Nitrogen filling system
  - Support structure
- Original Physics Scope
  - Multi-Step Coulomb excitation
  - Transfer or Deep Inelastic reactions
  - Fusion Evaporation
  - Stopped Beams

DOE Funding

FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT

U.S. Department of Energy

Office of Science
Office of Nuclear Physics

Research Opportunities at Rare Isotope Beam Facilities

Funding Opportunity Number: DE-PS02-08ER08-10

Project funded through FOA at ~$720,000

CAGRA: DOE Funded items

- Mechanical Infrastructure (Deliverables)
  - Self contained, trigger-less acquisition system using Gretina Digitizers
  - Liquid Nitrogen fill system
  - Support structure
  - High Voltage supply system (ISEG)
- Shipping costs between USA and Japan
- Travel and per diem for USA researchers to setup and operate device in Japan

CAGRA: Brief History

- Dec. 2008, workshop at ANL to discuss physics opportunities at RIBF using Clover Array.
- Dec. 2008, proposal submitted to DOE to fund infrastructure of Array.
- Apr. 2010, notified that proposal is accepted and will receive funding.
- Nov. 2010, DOE funding begins.
- Dec. 2012, workshop to discuss physics opportunities at RCNP and RIBF held at RCNP - recommendation was to explore siting CAGRA at RCNP first.
- December 2013, workshop to discuss physics opportunities at RCNP & RIBF with CAGRA with the emphasis on RCNP
  - EN beam line - in flight RIB production capability
  - Grand Raiden beam line to couple CAGRA with the large spectrometer.
- April 2014 - proposal submitted to RCNP P-PAC and received recommendation to run a campaign of CAGRA experiments in 2015 and 2016.
- Mar – May 2015, campaign of 6 experiments run at EN Beam Line.
- Oct – Dec 2016, campaign at Grand Raiden Beam line.

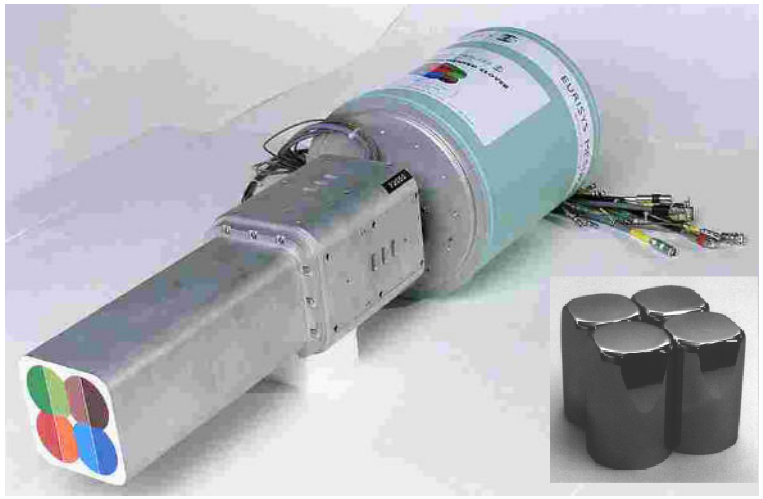
CAGRA Board

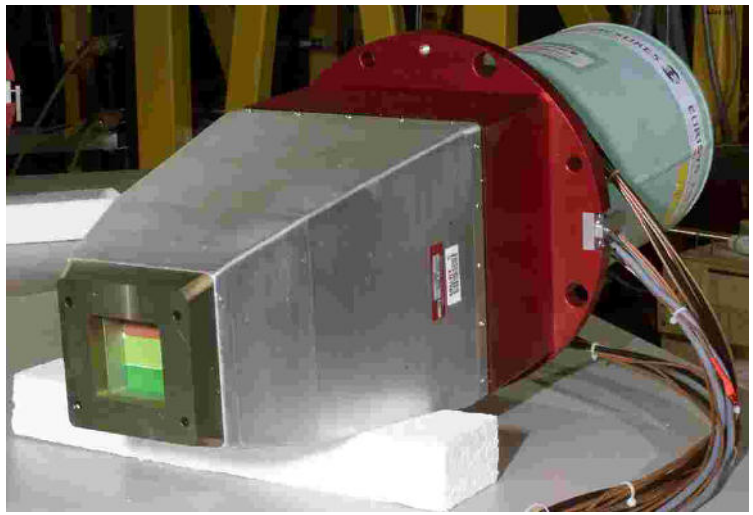
Due to the expansion in scope of the Physics program that resulted from the 2013 workshop, it was decided to appoint a board to examine issues when needed.

CAGRA board members

- CARPENTER Michael (Chair, ANL)
- IDEGUCHI Eiji (vice chair, RCNP)
- KOIKE Takeshi (Tohoku University)
- FALLON Paul (LBNL)
- WERNER Volker (TU Darmstadt)
- AOI Nori (RCNP)
- BRACCO Angela (Milano)
- GARG Umesh (University of Notre Dame)
- von NEUMANN-COSEL Peter (TU Darmstadt)
- SAKURAI Hiroyoshi (RIKEN/Tokyo)
- SHIMOURA Susumu (CNS)
- TAMII Atsushi (RCNP)
- ZEGERS Remco G. T. (NSCL)

CAGRA Status: Detector Availiability





6 Clovers + Compton Suppression Shields from Tohuku University. Inventory from Hyper-Nuclei program at JPARC (T. Koike)

10 Clovers + Compton Suppression Shields come from CloverShare in USA.
(M.P. Carpenter, P. Fallon)

2 Clover Detectors from Army Research Laboratory USA - can be used in Compton Suppression Shields (Jeff Carroll)

3 Clover Detectors from IMP China – larger and do not have Compton Shields.

Other collaborators with Clover detectors are welcome!

U.S. Clover Share Collaboration

Steering Committee:
J. Burke (LLNL), M. P. Carpenter (ANL), P. Fallon (LBNL), S. Liddick (MSU, chair)

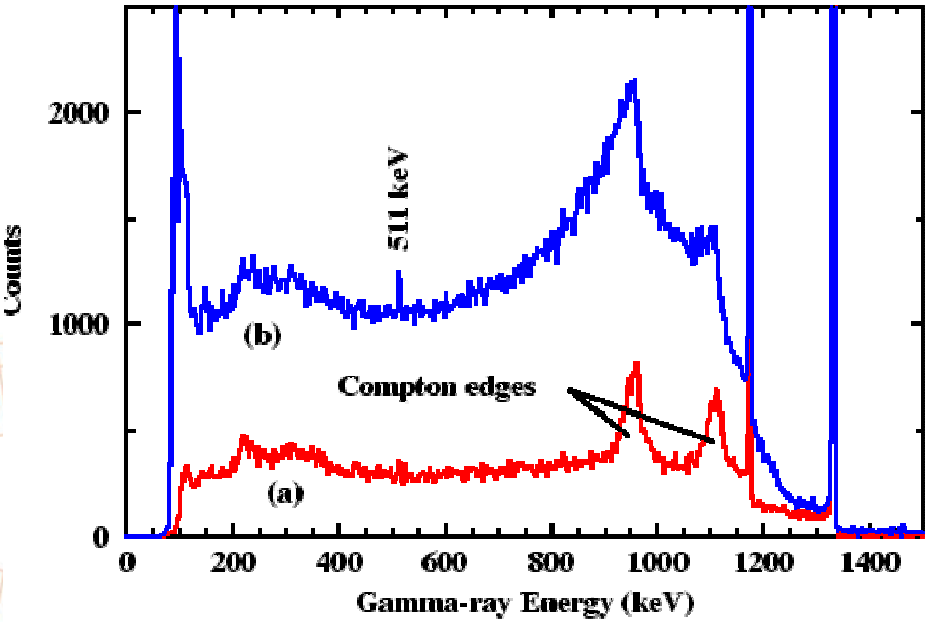
Steering committee is responsible for prioritizing requests for the Yale Compton-Suprressed Clover detectors based on scientific merit and institutional scheduling constraints.

Experimental Campaigns:

- NSCL: Mar–May 2014 (Beta Decay Studies) – 9 Clovers
- RCNP: Feb-May 2015 (In-Beam) – 10 Clovers + Shields
- Texas A&M: Aug-Oct 2015 (In-Beam) – 7 Clovers + Shields.
- Notre Dame: Mar. 2016 – Jun 2016 (In-Beam) - 7 Clovers + Shields
- RCNP: Oct-Dec. 2016 – Coupled to Grand Raiden Spectrometer.

Compton Suppression

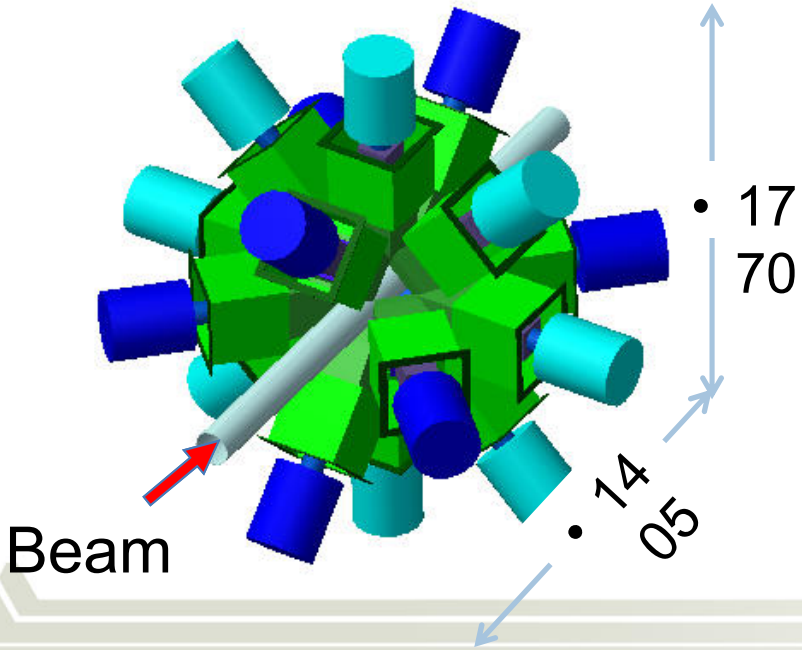
Suppressed and Unsuppressed ^{60}Co spectrum

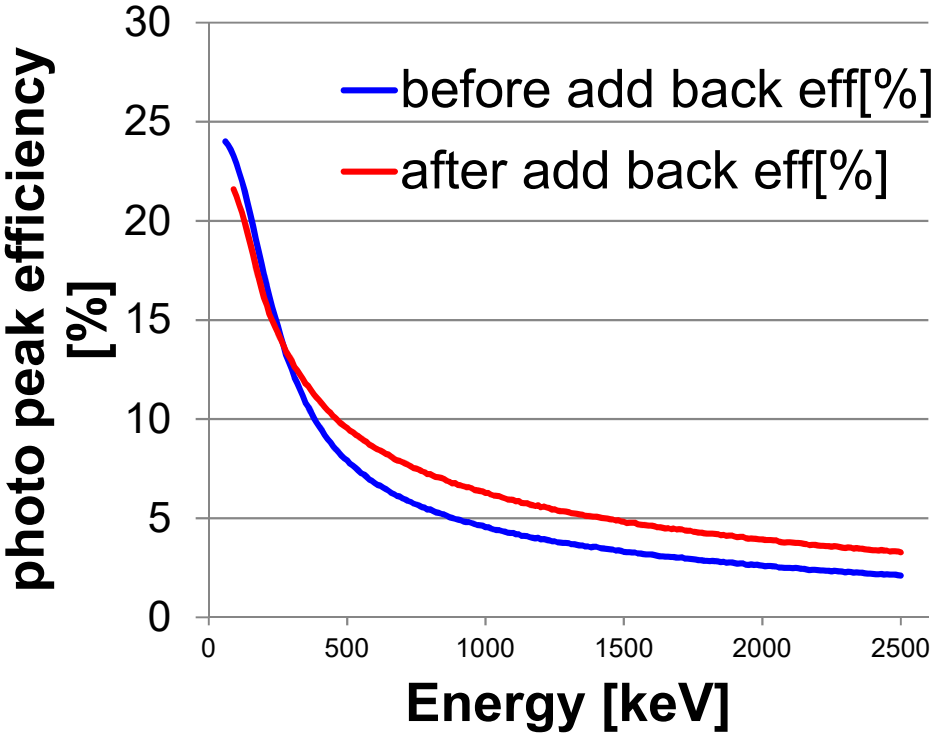


Vastly improved peak to background

Simulation of Efficiency

- 16 Compton suppressed Clover Ge detectors
  - 4 detectors at 45°
  - 8 detectors at 90°
  - 4 detectors at 135°
- **Target—Ge：16cm**
- ε_{ph}(1MeV)～6%

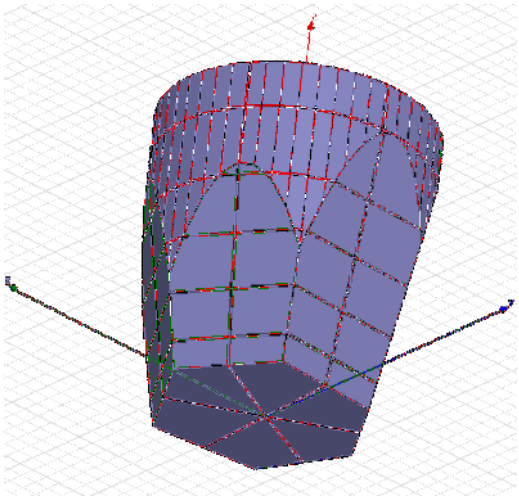




Future Possibilities: Ge Tracking Detector

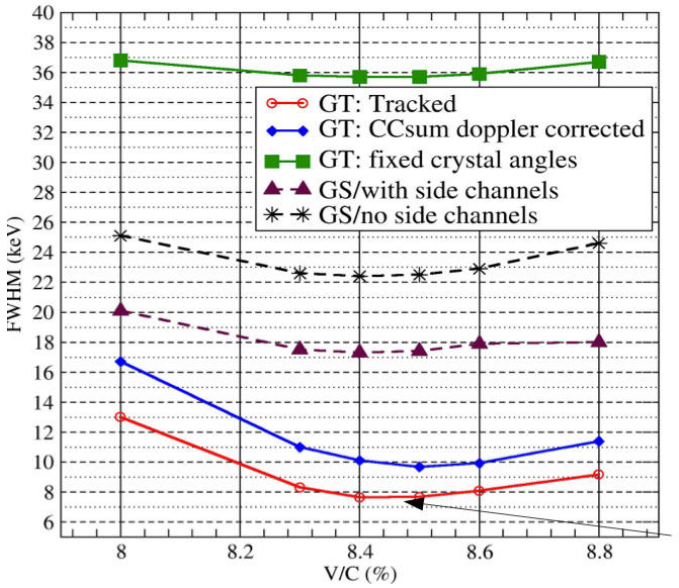
Gretina Detector

1π Ge tracking array



- 36 segments/crystal
- 1 central contact
- 4 crystals/module
- Gretina has 10 modules
- RCNP – 1 Gretina module (N. Aoi, E. Ideguchi)

- By measuring pulse shapes on all pads, γ-ray interactions can be isolated to ~ 2mm.
- Compton-suppression can be obtained by applying Compton formula.
- Provides superior Doppler reconstruction.



E_γ = 2 MeV, v/c = 8.4%

CAGRA Status: Hardware Components

Digitizer Module (LBNL)

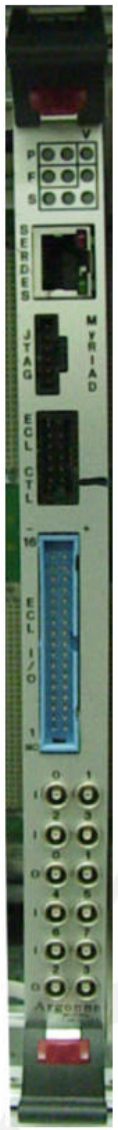
- 10 Channel
- 14 Bit, 100 MHz
- Energy
- Leading Edge Timing
- Constant Fraction Timing
- Pulse Shape

Trigger Timing and Control Module (ANL)

- 1 Master, 1 Router/8 Digitizers
- Sync All Clocks
- Fast Multiplicty Triggers ~ 500ns
- Slow triggers ~ 2⌈ sec
  - Multiplicty
  - Energy

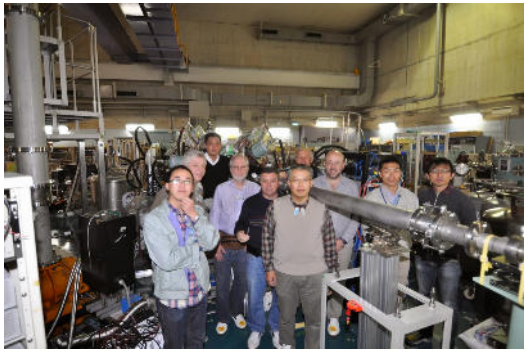
Firmware developed at ANL and will be implemented in Majorana Demonstrator both of which utilize the same hardware developed for GRETINA.

Interfacing CAGRA with Grand Raiden



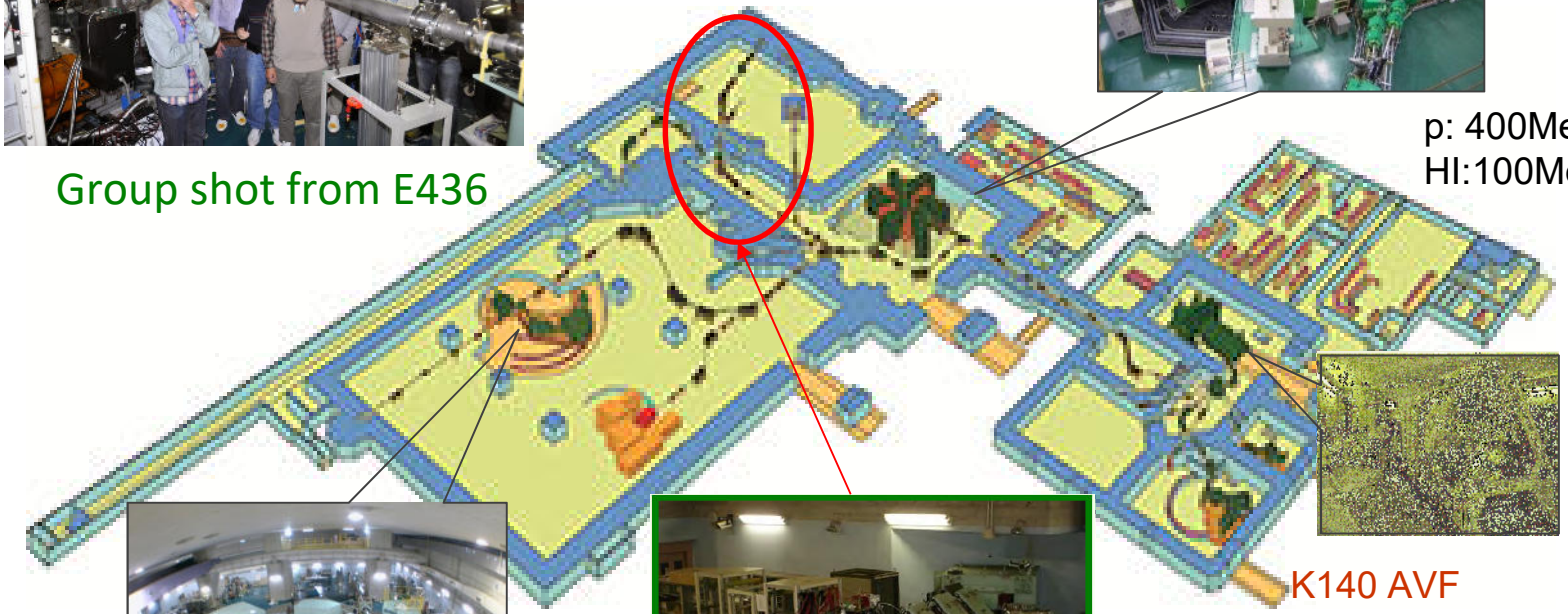
- Generic interface to auxiliary detectors for both Gammasphere and GRETINA (MyRIAD)
  - A generic interface between the SERDES link, VME and ECL/NIM
  - Large number of ECL I/O
  - Good number of NIM I/O with fast receivers
  - Works in any VME crate (standard or VME64)
  - Sufficient FPGA for general gating logic
  - Large FIFO allowing buffering of auxiliary detector data
  - Capable of acting as FERA data receiver if needed
  - Current Implementations - Chico 2, Phoswich wall, RCNP VME DAQ, Goddess – ORNL VME DAQ.
  - Future Implementations – LaBr detector array, Microball Hybrid.

CAGRA: RCNP Campaigns



Group shot from E436

p: 400MeV
HI:100MeV/u



K140 AVF cyclotron

p ~ Xe
Pol. p & d

Double arm spectrometer
(Grand Raiden & LAS)

EN beam line for RI beam

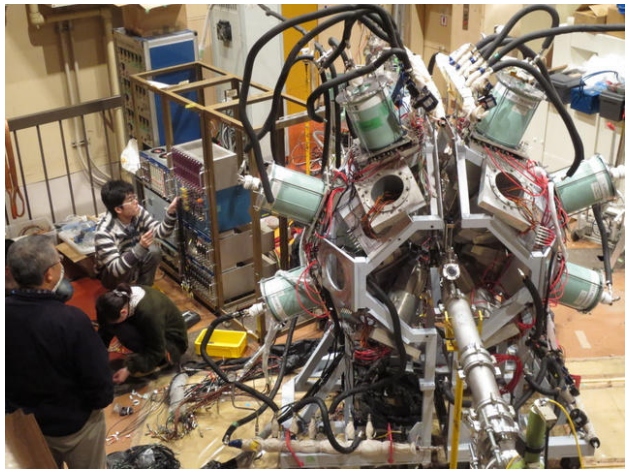
CAGRA: First Tests at Tohuka University

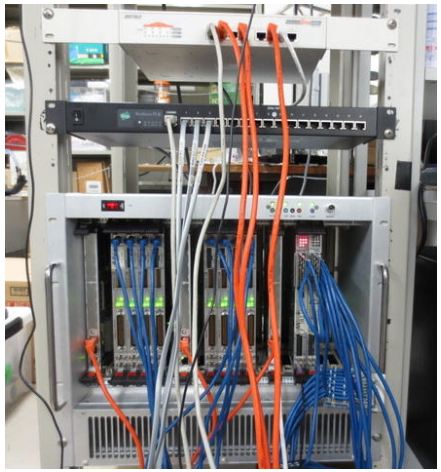
Purpose:

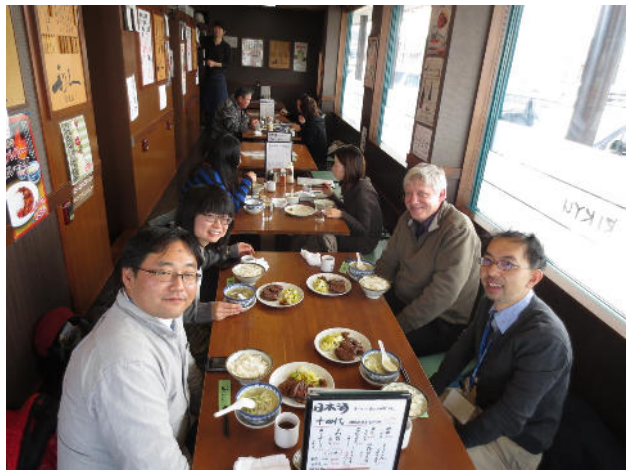
- Testing of digital electronic with Tohoku clovers in coincidence mode
- Reproduce level scheme of ^{136}Nd

Experimental Setup:

- 6 Clovers and BGO ACSs in the Hyperball-2 frame
- ^{20}Ne beam at 87 MeV, 3pnA
- 1mg/cm^2 ^{120}Sn target with Au backing (or ^{206}Pb)
- Pb collimator on BGO ACS
- 3 shifts approved at CYRIC Accelerator Facility Feb, 2014.
- Data taken with digital DAQ.

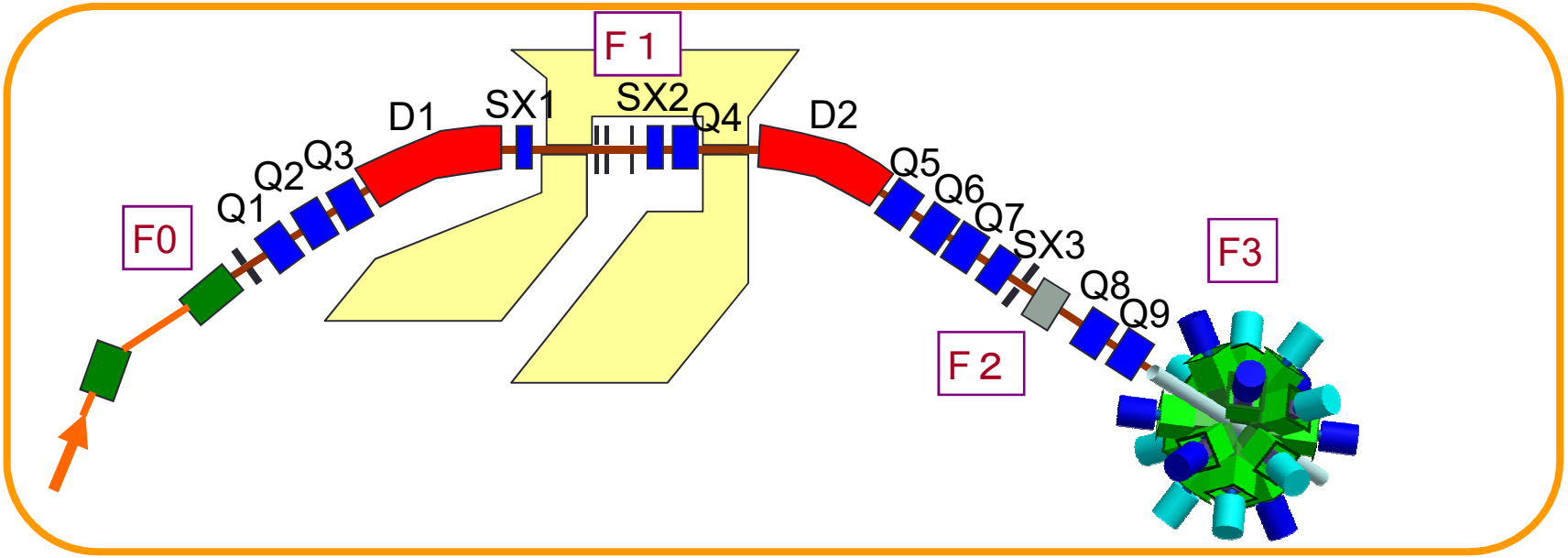






EN Beam Line

RCNP secondary beam line using Heavy Ion Beams



T. Shimoda et al., NIM B70 (1992) 320.
S. Mitsuoka et al., NIM A372 (1996) 489.

RI beam with beam energy
from low (~ MeV/u)
to high (~several tens MeV/u)
can be delivered.

Maximum rigidity 3.2 Tm
Energy acceptance $\otimes E/E$ = 16 %
Angular acceptance $\otimes\alpha$ = 40 mrad
$\otimes\beta$ = 28 mrad
Path length 16.8 m

- CAGRA Array

- High-rate capability using
- fast digital DAQ system
- stands for 10 times stronger
- beam intensity: 2pnA → 20pnA

Experiments of First CAGRA Campaign

Experiments using stable beam

1. Study of superdeformed structure in ^{44}Ti, ^{45}Sc (E. Ideguchi, RCNP-Osaka)
2. Structure of excited states above the long-lived ($T_{1/2}\sim1.5\times10^{5}$y), $K^{\pi} = 8^{+}$ isomer in ^{186}Re (F.G. Kondev, ANL)

Experiments using unstable beam

1. Probing High-Spin States in ^{61,62}Fe Using the ^{48}Ca(^{17}N,pxn) Reaction (M.P. Carpenter, ANL)
2. Study of High-Spin States by RI Beam Induced Fusion Reaction (A. Odahara, Osaka)
3. Study of shell evolution at N=20 in neutron-rich region through nucleon transfer reaction (T. Yamamoto, RCNP-Osaka)
4. Spectroscopy of ^{15}B: A search for unexpected bound states (C.R. Hoffman, ANL)

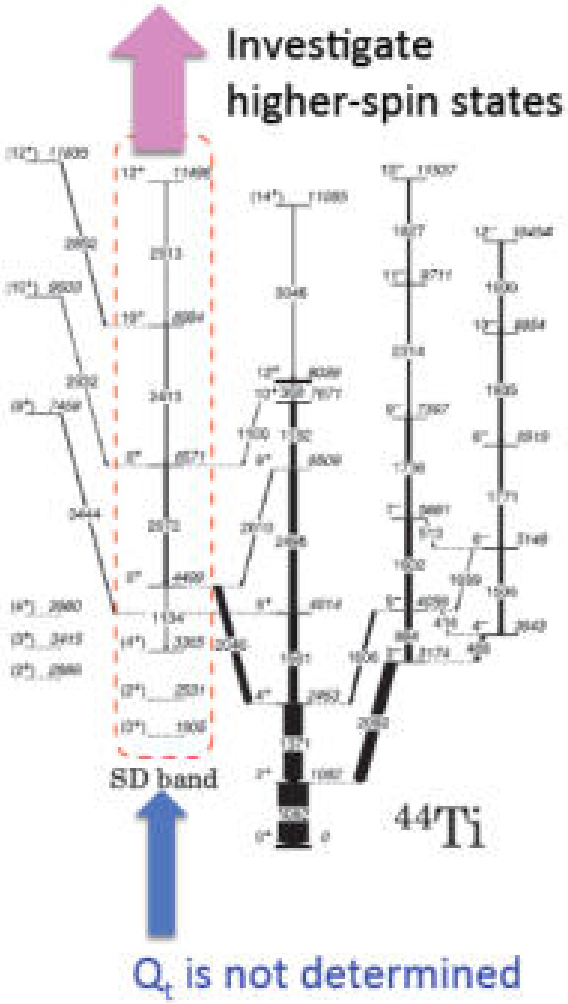
E438 Experiment E - E. Ideguchi

E438, E. Ideguchi

- Study of superdeformed structure in ^{44}Ti, ^{45}Sc
  - Investigate higher spin states of SD band in ^{44}Ti
  - Life time measurement of ^{44}Ti SD band
  - Search for SD band in ^{45}Sc
  - Search for octupole collectivity built on the SD band of ^{44}Ti

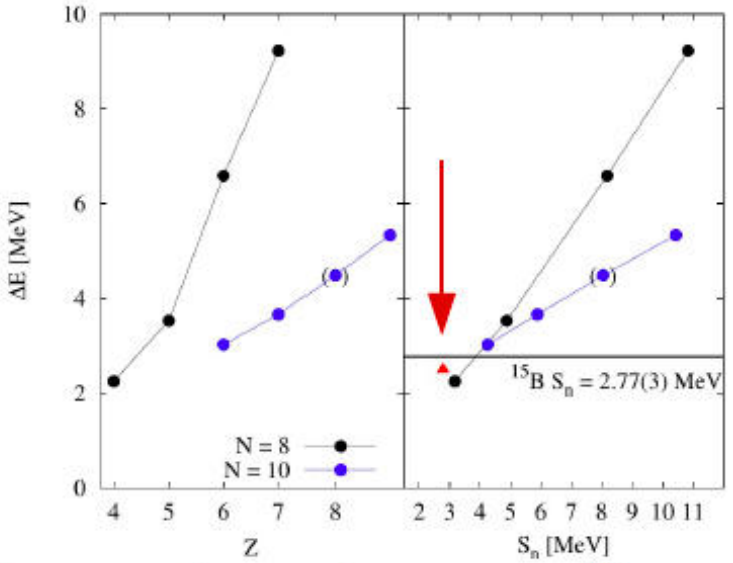
Octupole excitation :

- [200]1/2 → [321]5/2
- [321]3/2 → [202]3/2



Q_t is not determined

Spectroscopy of ^{15}B: A search for unexpected bound states – E437 (Hoffman)



- Physics motivation
  - Determine if smooth trend of lowest-lying 2-particle excitation as a function of binding energy is robust for weakly bound N=10 isotones, e.g., ^{15}B
- Measurement
  - Proton removal from ^{16}C to search for new bound states in ^{15}B
- Experimental details
  - ^{16}C beam produced at >10^5 pps and 60 MeV/u
  - Recoils were identified in Si array telescope
  - γ-ray coincidences measured between CAGRA and ^{15}B recoils in the Si array telescope and the incoming ^{16}C beam by was tracked by PPACs

CAGRA-Grand Raiden Campaign at RCNP

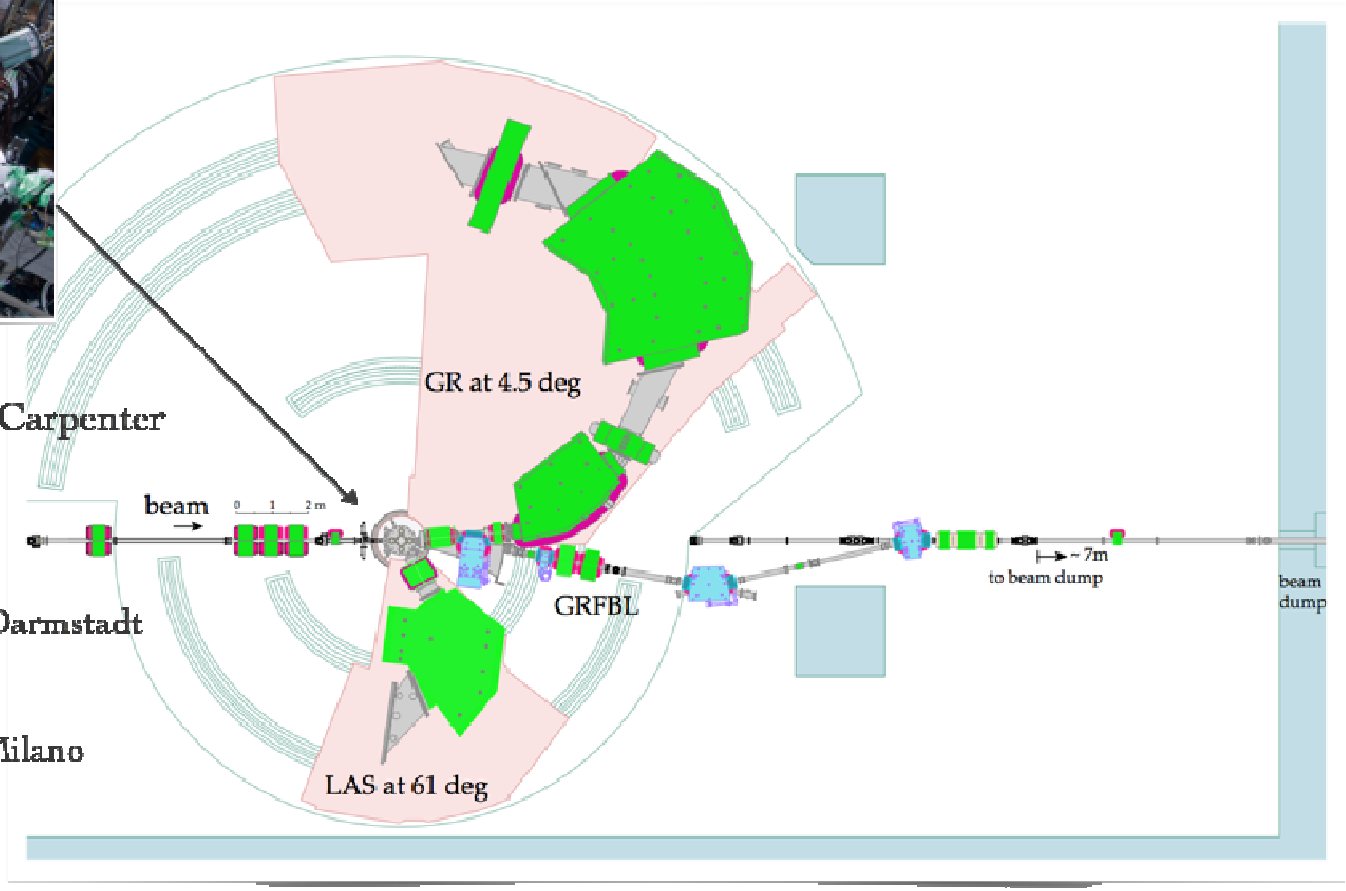
Purpose: To perform high-resolution coincident measurements between reacting light-ions (Grand Raiden) and de-excitation γ-rays (CAGRA).

CAGRA

E. Ideguchi and M. Carpenter

TU-Darmstadt

Milano

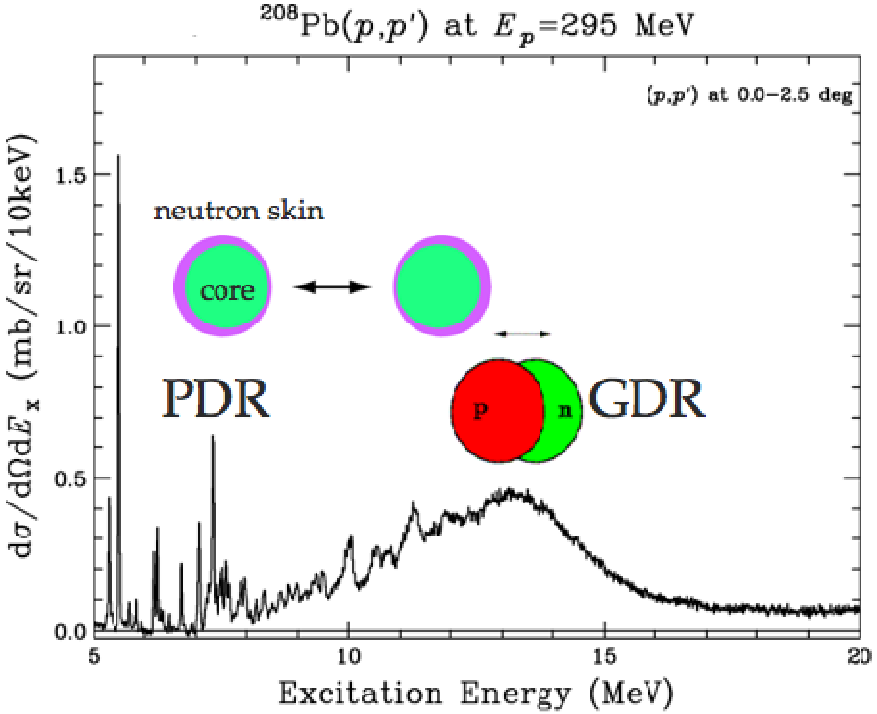


RCNP, Tohoku, ANL, LBNL, Milano, TU-Darmstadt, GSI, Köln, KVI, IFJ-PAN, IMP, York, ARL, …

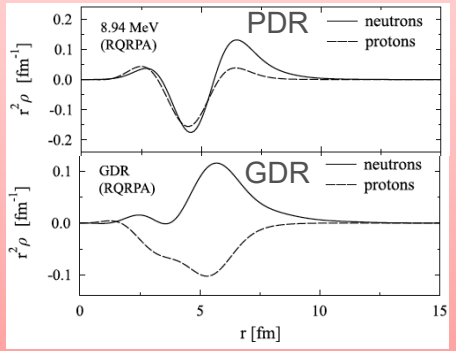
Study of PDR by (*p*, *p*'γ) and (⟨ ,⟨ 'γ)

(p,p'γ) and (α,α'γ) for PDR in
^{64}Ni, ^{90,94}Zr, ^{120,124}Sn, ^{206,208}Pb

Total of 36 days for all measurements



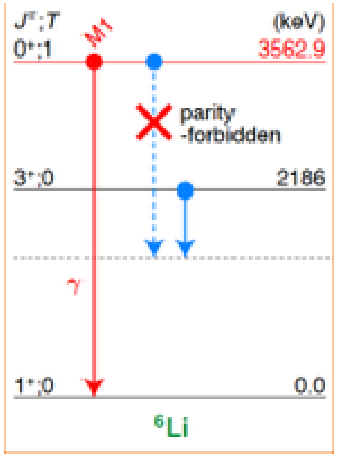
PDR structure
transition density,
isospin-structure,
angular dependence



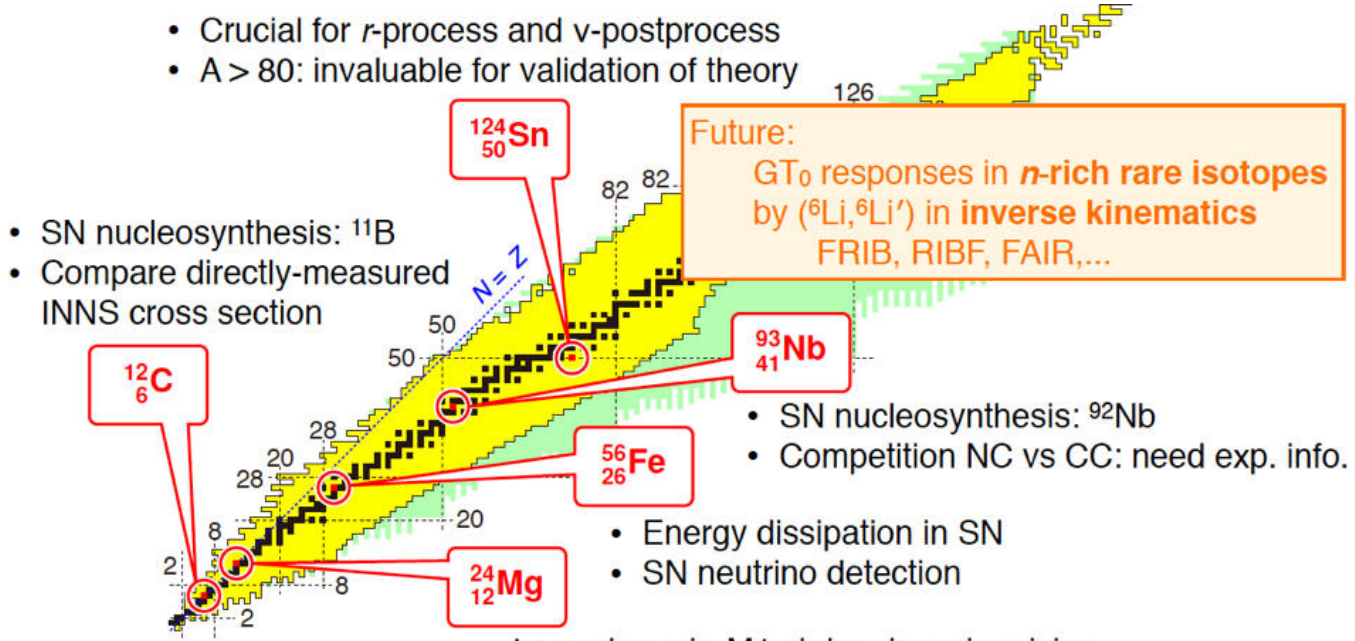
A. Bracco, F. Crespi, V. Derya, M.N. Harakeh, T. Hashimoto, C. Iwamoto, A. Maj, P. von Neumann-Cosel, N. Pietralla, D. Savran, A. Tamii, V. Werner, and A. Zilges *et al*.

(^{6}Li, ^{6}Li'+γ): a new probe of IV Spin-Flip Excitations

- **A direct probe for GT_0**
  - Final 3.56 MeV state has $J^\pi = 0^+$, $T = 1$
    - Selectivity $\Delta S = 1$, $\Delta T = 1$, $\Delta T_z = 0$ guaranteed.
    - cf. (p,p'): $1/2^+;1/2 \rightarrow 1/2^+;1/2$
  - γ decay directly to the ground state.
    → Reaction channel is identified by coincidence with 3.56 MeV γ ray



- Crucial for *r*-process and ν-postprocess
- A > 80: invaluable for validation of theory



Future:
GT_0 responses in ***n*-rich rare isotopes** by (^{6}Li,^{6}Li') in **inverse kinematics**
FRIB, RIBF, FAIR,...

- SN nucleosynthesis: ^{11}B
- Compare directly-measured INNS cross section

- SN nucleosynthesis: ^{92}Nb
- Competition NC vs CC: need exp. info.

- Energy dissipation in SN
- SN neutrino detection

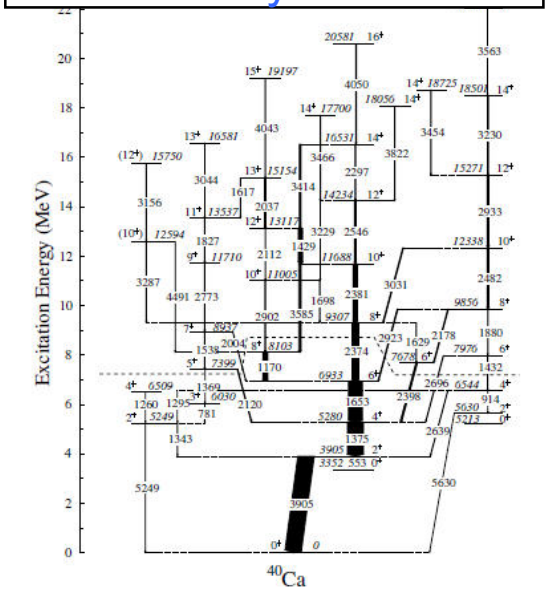
- Isoscaler spin-M1 states, isospin mixing
- Basic study of the nature of the probe

S. Noji, R.G.T. Zegers, C. Sullivan *et al.*,

Excitation of High-Spin States by Nuclear Interaction of light particles

E. Ideguchi, A. Tamii *et al.*

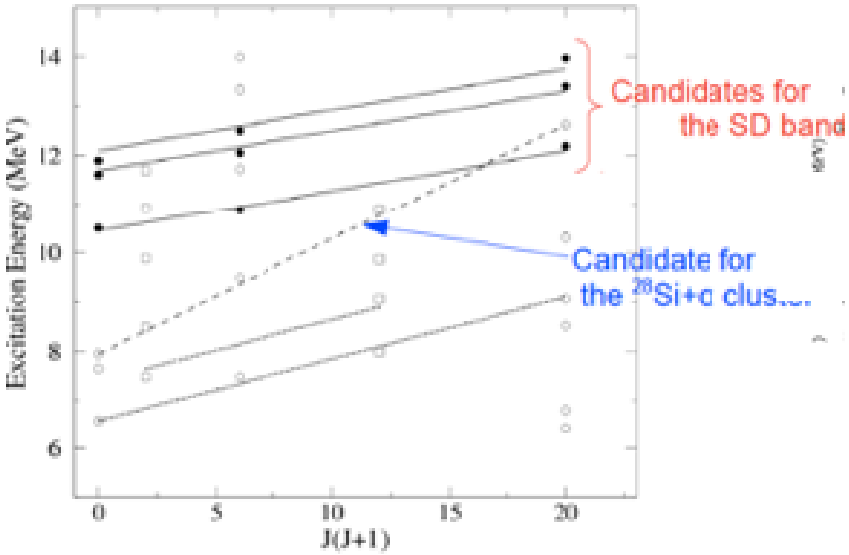
From heavy-ion fusion



- With ^{40}Ca(^{6}Li,d)^{44}Ti measure excitation energy with GR and study γ de-excitation with CAGRA.
- Does this give us access to non-yrast states at high-spin, and thus provide a method to study states which are inaccessible using other types of reactions?

Search for superdeformed states in ^{28}Si

D. Jenkins *et al.*



M.Itoh, S.Kishi, H.Sakaguchi *et al*, to be published.

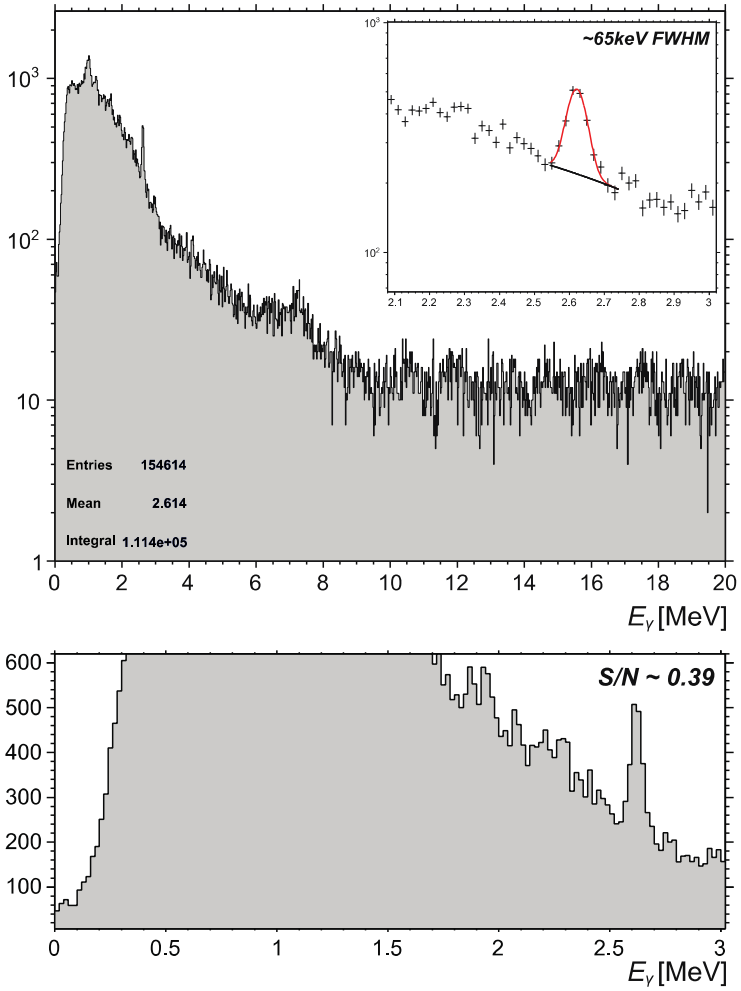
Populate states with ^{28}Si(α,α') and study γ-decay by selecting excitation energy from GR.

Test Run - June 2016

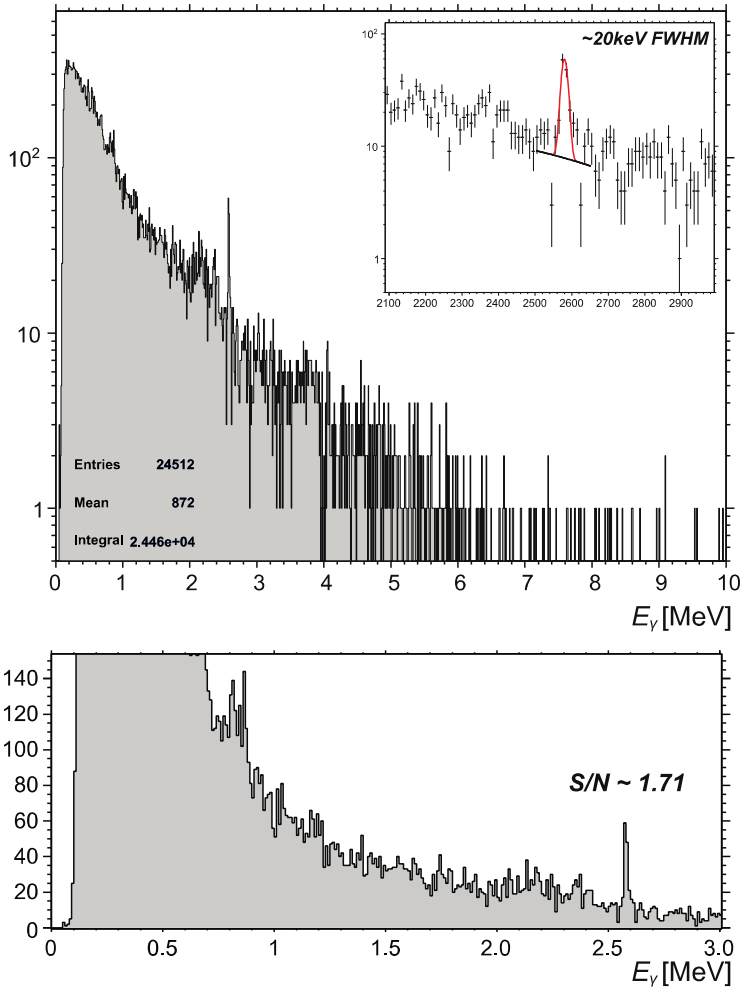
Target: ^{208}Pb Beam: ^{4}He [10nA @ 130MeV] - *Run2010*

Chris Sullivan I NSCL

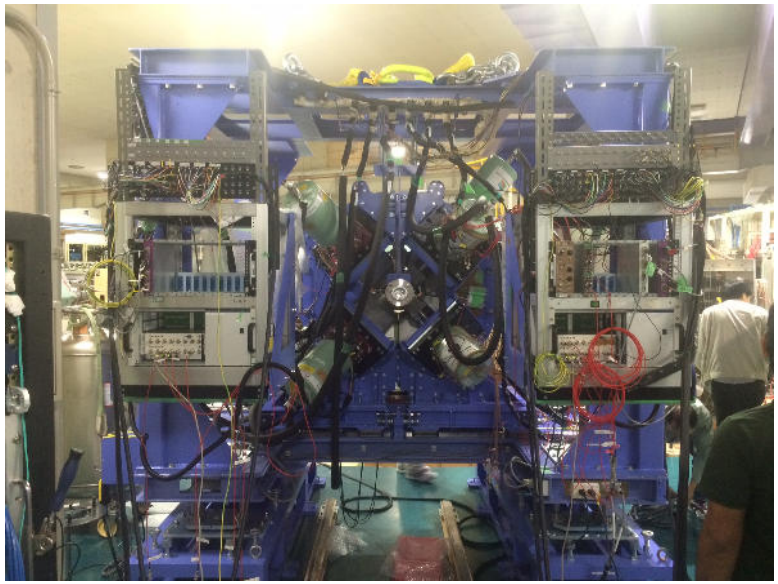
LaBr @ 45 degrees - Prompt



Ge detector @ 45 degrees - Prompt



CAGRA at Grand Raiden



- Due to harsh conditions at target position during beam tuning, Ge detectors must not be present.
- This is accomplished by moving entire frame.
- First move to target position with Ge's installed – yesterday!

Upcoming Beam Schedule for CAGRA-GR

Oct-3: 9 am (the beam energy might be changed to α130)

CAGRA	α140	2.0 days AVF	commissioning		
E450	α140	0.9 days AVF	tuning/calibrations		… 2.9 days
E450 Bracco et al.	α140	1.5 days AVF	prio-1 ^{90}Zr	4.5-deg	
E450 Bracco et al.	α140	1.5 days AVF	prio-1 ^{94}Zr	4.5-deg	
E454 Savran et al.,	α140	1.5 days AVF	^{64}Ni	4.5-deg	
E450 Zilges et al.	α140	1.8 days AVF	prio-2 ^{120}Sn	4.5-deg	
E450 Zilges et al.	α140	1.8 days AVF	prio-2 ^{124}Sn	4.5-deg	
E450 Savran et al.	α140	3.0 days AVF	prio-3 ^{206}Pb	4.5-deg	
E450 Savran et al.	α140	3.0 days AVF	prio-3 ^{208}Pb	4.5-deg	
E470 Jenkins	α140	6.0 days AVF	^{28}Si	10 deg	... 20.1 days

Oct-26: 9 am— break

Nov 3: 9 am

E450	p80	1.6 days AVF	tuning/calibrations		… 1.6 days
E450 Iwamoto et al.	p80	5.0 days AVF	prio-1 ^{208}Pb	4.5, 6.8, 9.1, 11.4 deg	
E450 Bracco et al.	p80	1.0 days AVF	prio-1 ^{90}Zr	4.5-deg	
E450 Bracco et al.	p80	1.0 days AVF	prio-1 ^{94}Zr	4.5-deg	
E450 Zilges et al.	p80	1.2 days AVF	prio-2 ^{120}Sn	4.5-deg	
E450 Zilges et al.	p80	1.2 days AVF	prio-2 ^{124}Sn	4.5-deg	
E450 Savran et al.	p80	2.0 days AVF	prio-3 ^{206}Pb	4.5-deg	... 11.4 days

Nov 16: 9 am —- break (annealing/maintenance) 0-dg setup

Dec 3: 9 am

E454 Savran et al.,	p300	4.5 days RING	^{64}Ni	0-deg	... 4.5 days

Dec 7: 9 pm—- break

Dec 13: 9 am

E441 Noji et al.	^{6}Li600	5.0 days RING	^{56}Fe, ^{12}C, ^{93}Nb, ^{124}Sn, ^{24}Mg	0-deg	... 5.0 days
Beam line modification for GRAF					… 0.5 days
E471 Ideguchi et al.,	^{6}Li600	3.0 days RING	^{40}Ca or ^{100}Mo	11 deg	… 3.0 days

Dec 21: 9 pm

Summary

- CAGRA is a project partially funded by DOE through FOA DE-PS02-08ER08-10 for experimental campaigns in Japan.
- First experiments are at RCNP Osaka: Campaign I was at the EN Course where 6 experiments were performed Feb-May 2015.
- The Grand-Raiden campaign will begin next week and run through Dec. 2016.
- Topics to be explored
  - Characterization of the PDR as a function of *Z* and *N* with both *p* and α probes.
  - Measure of the GT response function using the (^{6}Li,^{6}Li'+γ) reaction.
  - Search for rare decays and shapes in ^{28}Si and ^{40}Ca using light-ion scattering.
- Thank you to A. Tamii and E. Ideguchi for supply material for a number of the slides in this talk.