Goal:
Search and Measurement of E1 strength around threshold in 70Ni

Why?:
The Distribution of E1 strength function is an important nuclear structure information, directly correlated to neutron skin and EOS.

In nuclear astrophysics E1 strength around threshold influences significantly the r-process.

It is better known (also with a lot of open problems) in stable nuclei but practically not in neutron rich nuclei.
PDR states in nuclei

**What We know**
- Pygmy Dipole States are strongly correlated with the size of the neutron skin (or proton skin)
- Pygmy Dipole Resonance (PDR) is a «collective» excitation of the least bound neutrons (or protons)
- PDR is mostly of Electric Dipole (E1) character
- PDR is relevant for astrophysical r-process

**What we want to know:**
- Level of collectivity?
- How (collective) properties change with neutron number?
- How isospin changes mean field?
- In exotic nuclei: does PDR strength exist also below neutron threshold and to which extend?
- No High resolution/statistics measurements available
- Present in all nuclei and mass regions?
- Effect of deformation?
- Proton Pygmy, still to proof?
- "Picture" of PDR, toroidal mode
- From pygmy strength deduce dipole polarizability over more nuclei
- Isovector and Isoscalar mode
PDR is measured in **stable** nuclei
With different probes (in different Labs):
- **real photons**
  (scattering $\gamma, \gamma$, dissociation $\gamma, \gamma, \gamma, n, \gamma, p$
  - $p, \alpha, ^{17}O, \ldots$

**LNL, OSAKA, KVI...**

ISOSCALAR part of Pygmy
(n & p behave similar)

(p, p'); ($\alpha$, $\alpha'$); ($^{17}O$, $^{17}O'$) ... 
(p, p', \gamma); ($\alpha$, $\alpha', \gamma$); ($^{17}O$, $^{17}O'$, $\gamma$) ... 

But in unstable nuclei relevant for the r-process?
Experimental Method @ RIBF:
Relativistic Virtual Photon Scattering under coulomb excitation conditions

Using a fast (260AMeV) $^{70}$Ni beam on thick 2g/cm$^2$ Au target, we strongly excites E1 IV states, E2 and other states are much less excited, nuclear contributions are strongly suppressed.

Theoretical Predictions in exotic nuclei ..... In $^{70}$Ni

Alternatives for exotic nuclei (in part):
- C. break-up/missing mass (R3B, Samurai)
  Talk of K. Boretzky
- Oslo/MSU beta method
Relativistic **Virtual photon scattering** for PDR search in n-rich nuclei

**high selectivity for dipole E1 excitation**

Virtual photon excitation

and decay of GDR + PYGMY + E1 states

\[
\frac{d\sigma_C}{dE^*} = \sum_{\pi\lambda} \frac{1}{E^*} N_{\pi\lambda}^{(E^*)} \cdot \sigma_{\pi\lambda}^{\gamma}(E^*)
\]

To excite Dipole states one needs:
- High beam energy
- Large cross sections
- Large $\sigma_{GDR}/\sigma_{GQR}$ ratio

To Select projectile PDR one needs:
- High beam energy
- Large Doppler effects 
  \( \rightarrow \) Background REDUCTION
- Good $Z_{proj}/Z_{target}$ ratio
VPS-Coulex experiments

Euroball+BaF$_2$
- 400 MeV/u $^{68}$Ni + $^{197}$Au (May 2004)
- 600 MeV/u $^{68}$Ni + $^{197}$Au (April 2005)

AGATA*+LaBr$_3$:Ce
- 400 MeV/u $^{64}$Fe + $^{208}$Pb (October 2012)
- 430 MeV/u $^{62,64}$Fe + $^{197}$Au (April 2014)

DALI2+LaBr$_3$:Ce
- 280 MeV/u $^{70}$Ni + $^{197}$Au (October 2014)
- 280 MeV/u $^{72}$Ni + $^{197}$Au (future)

Talk of R. Avigo
* With half of HPGe material as EB and 5 times less intense beam

This presentation

VPS-Coulex experiments give important (complementary) informations on existence, position, shape and strenght of PDR
HECTOR⁺ & DALI2 @ RIKEN (Tokyo)
CAMPAIGN of 3* experiments in 2014

- Inelastic alpha scattering on $^{128/132}$Sn (T. Aumann,...)
- Inelastic alpha scattering + coulomb excitation on $^{20/22/24}$O (H. Baba, N. Nakatsuka,...)
- Coulomb excitation on $^{70}$Ni (O. Wieland,...)
RIBF setup in Riken laboratory allows to produce radioactive beams at relativistic energies and **select in flight (fragmentation)** the isotopes of interest (BigRips).

DALI2 coupled with LaBr3:Ce scintillators provide a very large angular coverage and also efficiency at high energies.

Zero degree Spectrometer allows to select reaction products outcoming from secondary target.

**Experiment at RIKEN-RIBF**

**BIGGER Parameters:**
- **238U Primary Beam -> 70Ni secondary Beam at 260AMeV**
  - @F3 48 kcps SECONDARY BEAM PRODUCED
  - @F7 30 kcps SECONDARY BEAM SELECTED with 40% PURITY 70Ni
  - @F11 27 kcps AFTER TARGET AND REGISTERED IN ZERODEGREE SPECTROMETER

→ 1.3*10^9 «good 70Ni» events recorded in 34 hours measurement
Experiment at Riken laboratory to measure PDR in $^{70}\text{Ni}$ with NaI (DALI) and LaBr$_3$:Ce detectors

Primary Beam $^{238}\text{U}$ with 82 GeV total kinetic energy

Gamma ray efficiency $\rightarrow$ select HE gamma ray GS decay
Energy Calibration for High Energy Gammas

- Cover up to 25MeV in C.M. = 40MeV in Lab. @30 deg

Neutron capture gamma
- Ni = 8.9MeV
- Al = 7.7 MeV

15.1MeV from 12C(p,p') test experiment @ RCNP

& A.Giaz NIM A729(2013)910
linearity efficiency up to 22MeV (p,γ)
Background for LaBr$_3$:Ce / DALI2

H. Baba, N. Nakatsuka

- Internal activity of LaBr3 detector
- \( \gamma \)-ray from beam @ forward plastic scintillator
- \( \gamma \)-ray from beam @ target position
- \( \gamma \)-ray from beam @ target position
- \( \sigma = 0.4 \text{ns}!! \) will be even better
- Particles background from the target
Setup/Experiment

**BIGRIPS**

$^{70}\text{Ni}$

260 AMeV

**ZDS**

$^{70}\text{Ni}^*$

**DALI2**

$\gamma$-ray Yield cms

Backward angles $\rightarrow$ target emission

Center angles

Target + Projectile

Forward angles

Projectile emission

LaBr$_3$:Ce

2$^+$

Gate on 2$^+$ State of $^{70}\text{Ni}$

Preliminary

November 2014

Ground State

2$^+$ 1260 keV

**Gate on 2$^+$ State of $^{70}\text{Ni}$**

Preliminary

6$^+ \rightarrow$ 4$^+$

4$^+ \rightarrow$ 2$^+$

**Known Benchmark**

To DETERMINE E1 strengths

Gold Target Background

E[keV]

E[keV]
High Energy gamma ray spectra

70Ni

Unresolved E1 strength below threshold

To Do:
- fix (low energy) tail of GDR, target contribution and background
- then unfold with response function

Preliminary
Summary and Status

- We have measured the E1 strength in $^{70}\text{Ni}$ neutron-rich nuclei around threshold
  - We have used DALI2+ large volume LaBr$_3$:Ce on thick gold target with $^{70}\text{Ni}$ beam @ 260AMeV
- Analysis is ongoing
  - Analysis meeting Milano 2015 Sep.21-25
  - Analysis meeting Darmstadt 2015 Okt.
  - Analysis meeting at Tokyo 2016
- Next nucleus $^{72}\text{Ni}$ (DALI2+Hector+),
Thank you and
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et al. ...