DREB Studies at RIKEN RI Beam Factory

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* radioactive isotope

- a next new-generation exotic beam facility
<= projectile fragmentation / in-flight U-fission
fast beams, stopped RI

May 2007
Fast RI beams - RIPS

SHE (Z=110, 111, 112, 113) - GARIS

135 MeV/nucleon for light nuclei (1986-)

RI beams (<5 AMeV) - CRIB

~5 MeV/nucleon

pol. d beams

350 MeV/nucleon up to U

RI beams with U-fission NOW!

1st beam in Dec. 2006
U beam in Mar. 2006

RIBF: Accelerator Complex in RIKEN Nishina Center
$K = 2,500 \text{ MeV}$

Self Magnetic Shield
Self Radiation Shield
3.8T (240 MJ)
18-38 MHz
8,300 tons
Two mechanisms of RI beam production

Projectile Fragmentation

Large acceptance of the separator (Big RIPS):

- <= large-aperture superconducting quadrupoles
- => accepting RI beams by in-flight fission of U

In-flight fission

Separator (Big RIPS)
Atomic nuclei (isotopes)

- stable: ~300
- known: ~2,700
- total: ~10,000?
use of beams -- DREB

fast RI beams very far from stability

| fast (200-300 MeV/nucleon): Zero Deg., SHARQ, SAMURAI |
| nuclear reactions with no mass transfer <= matching:
  elastic, inelastic, charge exchange, knockout, projectile fragmentation, multi fragmentation, (reaction cross section, isotope search) ….. |
| trap by an isochronous ring (Rare RI Ring) |
| stopped:
  in solid: $\beta$ decay, $\mu$, $Q$ by $\beta$-NMR, isomers, …(IRC beam) |
| in gas: mass (trap), (charge) radius, …..
  SLOWRI, (SCRIT) |
| degraded (< 50 MeV/nucleon):
  reactions with mass transfer:
    fusion (spectroscopy), transfers, … |

# some topics: possible by BigRIPS alone (+ small setups)
Intensity of Ni isotopes (350 AMeV, 1µA)

Ni Yield@BigRIPS

Currently:

E(2+): up to $^{76}$Ni
B(E2): up to $^{68}$Ni

$\beta_2(pp')$ for $^{74}$Ni

Intensity of Ni isotopes (350 AMeV, 1pµA)
Zero-degree spectrometer

particle ID / momentum analysis

e.g. Doppler shifted $\gamma$-ray measurements with identification of products

$^{132}\text{Sn}$

$^{133}\text{Sn}$

$^{131}\text{Sn}$

GRAPe (Ge)

From BigRIPS

DALI2 (NaI)

GRETA?
What are necessary? (RIBF)
- spectroscopy / nuclear astrophysics with DREB reaction calculations with poor experimental information
  sophisticated (microscopic) theoretical treatments
  more theoretical control for parameters
    e.g. optical pot. (imaginary part)
  good “parametrization” for nuclear structure <=> unknown
    ANC instead of $S$?
  deformation, $M_n M_p$, ...

Theories suitable for 200-300 AMeV
  Glauber, eikonal (CDCC), relativisititc impulse,…
  Schoroedinger + relativistic kinematics, …

New methods
New equipment

May 2007
DREB
use of IRC beams (moments, applications) new injector

135 MeV/nucleon for light nuclei
350 MeV/nucleon up to U

zero degree (spectrometer)

RIBF (2007 -)
PAC for RIBF
1st: 9, 10 Feb. 2007

19 (5) proposals for BigRIPS (+ ZeroDegree)

<DR(EB) experiments approved / differed>

Measurements of reaction cross sections T. Ohtsubo
Proton elastic scattering H. Sakaguchi
(p,2p) Knockout Reactions T. Kobayashi
Production of spin-aligned RI beams H. Ueno
3N force via dp elastic scattering K. Sekiguchi
2+ states of heavy tin and tellurium nuclei -(p,p') Zs. Dombrádi
Pionic Atoms in (d,^3He) K. Itahashi
Magicity in ^42Si and ^54Ca - coulex S. Takeuchi
^78Ni and its vicinity - 2n removal / inelastic K. Yoneda
Beyond ^132Sn - 2n removal / coulex N. Aoi
"Island of Inversion" - 2p removal / (p,p') / coulex H. Scheit

(5 LOI)
2nd: Sept.

Facility information:
Big RIPS - RI beam separator
exotic nuclear structure
shell closure
behaviors of p & n - correlated / decoupled

astrophysics
solar fusion
explosive burning

16C: “egg” structure? decoupled n-motion

32Mg: large deformation

28O: particle unstable
new magic #, N=16

neutron skin

molecular structure

heavy hydrogens

solar neutrino production

explosive hydrogen burning
世界初の超伝導リングサイクロトロン (SRC)

K = 2,500 MeV
Self Magnetic Shield
Self Radiation Shield
3.8T (240 MJ)
18-38 MHz
8,300 tons
with fRC (SRC)

350 MeV/nucleon
U (8Tm)

1 pμA (goal)
(5x10^{12} pps)

100 kW
1st RI beams with U in-flight fission

Mar. 27, 2007

May 2007
RI beams at RIKEN

Ring Cyclotron (1987) + RIPS (~1990) <= LBL, GANIL (LISE)
fast “RI-beam” or “RNB” by fragmentation (< 100 AMeV)
the most intense beams for some light nuclei

stop  $\mu$- and $Q$-moments for neutron-rich nuclei
fast new lifetime measurements ($^{16}$C, …)
fast Coulomb dissociation
  for structure of light drip-line nuclei ($^{11}$Li, $^{11}$Be, …)
  for astrophysics ($^{14}$O, $^8$B .)
fast fast Coulomb excitation, inelastic scattering ($^{32}$Mg, ..)
fast $\gamma$ spectroscopy w. secondary fragmentation ($^{34}$Mg, ..)
fast charge exchange, (p,p$'$), …
deg. low energy reactions w. degraded beams (fusion, astro.)
fast new isotopes ($^{31}$F, …)

RI Beam Factory (RIBF)
RI beams: fragmentation / in-flight fission
Large solid-angle spectrometer

particle correlation
unbound states
(p,2p)
astrophy. (p,γ)
ucl. matter
Rare RI ring

Isochronous ring with individual injection

mass measurement for short-lived rarely-produced nuclei

~100% injection < 100 s⁻¹

Mass $\frac{\Delta m}{m} \sim 10^{-6}$

Beta decay, …
Self Confining RI Target

electron–RI scattering

RIs trapped by the electron beam

10^5 pps injection
-> \( L \sim 10^{26} \text{ cm}^2/\text{s} \)

Ion source

electron injector

storage ring

Scattered electron
Injector system dedicated for RIBF

Independent operations of RILAC–GARIS (SHE, ..) and RIBF

New injector
DALI2*

High efficiency
Doppler-shift correction

160 NaI(Tl) crystals
4x8x16 cm³
ΔE~9% (FWHM) @ 662 keV
Δθ~9 deg.
For 1 MeV γ (β=0.3, Δβ/β=10%)
ΔE=8.7%
ε=20%

* Detector Array for Low Intensity radiation
Coulomb excitation of $^{32}$Mg ($N=20$)

**Target** ($^{208}$Pb)
- 300 s$^{-1}$
- ~50 A MeV
- 350 mg/cm$^2$

**RI beam** ($^{32}$Mg)

**Charged particles** (**Si stack - $\Delta E-E$**)
- particle ID for ejectiles ($^{32}$Mg)

**$\gamma$-rays** (**DALI - NaI(Tl) array**)
- $\gamma$-ray energy => state ID
- emission angle
  => Doppler correction

**Doppler-shift corrected spectrum**

May 2007

DREB
$^{16}$C + $^{208}$Pb

Inelastic scattering

“egg-like” structure?

strong p-n interaction

2+ excitation: almost only by neutrons.

$\Leftrightarrow$ lifetime, (p,p')

Coulomb-nuclear Interference in angular distribution

Japan-Hungary (ATOMKI) collaboration

$^{208}$Pb($^{16}$C, $^{16}$C*(2+))$^{208}$Pb

$E_{lab} = 52.7$ AMeV

\[ \frac{\delta_n}{\delta_C} = 3.1 \]

May 2007
ongoing collaboration programs (examples)

**RIKEN-GSI**

workshop (theory > experiment)
“Expert Meeting (FRS related technical issues)” w. MSU, …
for experiments / developments with common interests => regular meeting

**Japan-Italy Symposium**

(RIKEN-IN2P3)

Co-hosting: Beijing Summer school / EXON Symposium

new collaboration programs

Japan US Theory Institute for Physics with Exotic Nuclei (about to start)

International collaboration program (UT in collaboration w. RIKEN)

“Associated International Laboratory”
GANIL-RIKEN with institutions of both countries
common experiments / developments
nuclear structure (low energy nuclear physics)
Toward an “Asian regional center”

"Council for China-Japan Research Collaboration on Nuclear Physics"

Pekin U., CIAE Beijing, IMP Lanzhou, SIANP Shangai
RIKEN, ..... 

Pre-meeting: @RIKEN on 6-7th Feb. => regular meeting for Asian collaboration (future)
toward exotic nuclei farther from the stability
new-generation facilities -- RIBF, RIA, GSI-FAIR, Spiral2…
more new methods, probes
  *e.g.* e-RI scattering
  mass measurement of rarely produced RIs
  two nucleon correlation in nucleus
  asymmetric nuclear matter
efficient stopping / degrading fast beams
  => variety of methods, reactions …

impacts to:
  understanding
  many-body dynamics
  nucleosynthesis - origin of matter (*e.g.* r-process)
  evolution of the universe
applications to
  biology, medicine, chemistry, ….
Disappearance sd-pf shell gap $N=20$ in $^{32}\text{Mg}$ and $^{30}\text{Ne}$

In-beam $\gamma$ spectroscopy with Coulex / (p,p')

Motobayashi et al., PLB 346 (95) 9
Yanagisawa et al., PLB 566 (03) 84
Fate of magic numbers

$N=(8, )\ 20$

Coulomb excitation

$(p,p')$

Secondary fragmentation
$E(2^+)/E(2^+)_\text{sd}$

$B(E2)/B(E2)_\text{sd}$ (coullex)

May 2007
$^{16}\text{C}$

- decoupling of p/n motion (shape)

Coulomb-nuclear interference
Lifetime
$(p,p')$
$(Q$ moment of neighbors)
Decoupling of n- and p-distributions in $^{16}$C?

In-beam $\gamma$ measurements with fast $^{16}$C RI beams

$\gamma$-decay lifetime measurement - new recoil-shadow method
$\tau \sim 75 \pm 23$ ps, $B(E2: 2^+ \rightarrow 0^+) \sim 0.3$ W.U.
- the slowest $\gamma$ E2 transition

$I_{\text{Imai et al.}}$ (2003)
nuclear interference

$^{16}$C+$^{208}$Pb inelastic

$M_n/M_p = 7.6 \pm 1.0$
$I_{\text{Elekes et al.}}$ (2003)

$^{16}$C+$^1$H inelastic

neutron-sensitive

$a$ large $\beta$

$M_n >> M_p \sim B(E2)$ for $0^+ \rightarrow 2^+$

$c.f. \ 15^B: Q, \ 12^C$ inel., (p,p$'$)

May 2007

DREB
NN cross section

Data from Particle Data Group
http://pdg.lbl.gov/

(p,p'): sensitive to neutron > proton

Coulomb excitation = proton
NN effective interaction

Transparent
nucl. Interior
single scattering
p-elastic => density

large $V_{\sigma\tau}/V_0$
spin-isospin modes
GT, spin dipole …
\[ \frac{d\sigma}{dE_\gamma} \bigg|_{\text{C.D.}} = \frac{n}{E_\gamma} \sigma_{(\gamma,p)} \]

\[ C.D. \; \Rightarrow - \]

\[ \sigma_{(\gamma,p)} \]

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