Giant Resonances in Tin-region nuclei

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6th International Conference on
Collective Motion in Nuclei under Extreme Conditions

Cape Town, South Africa

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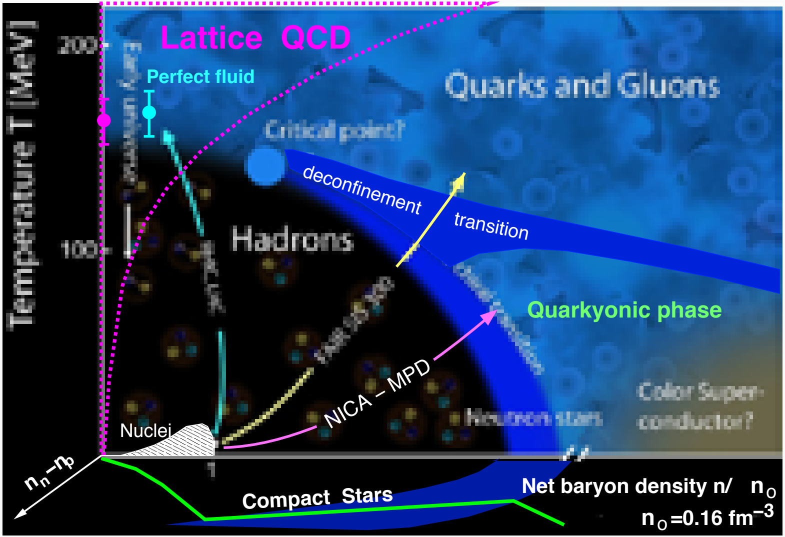
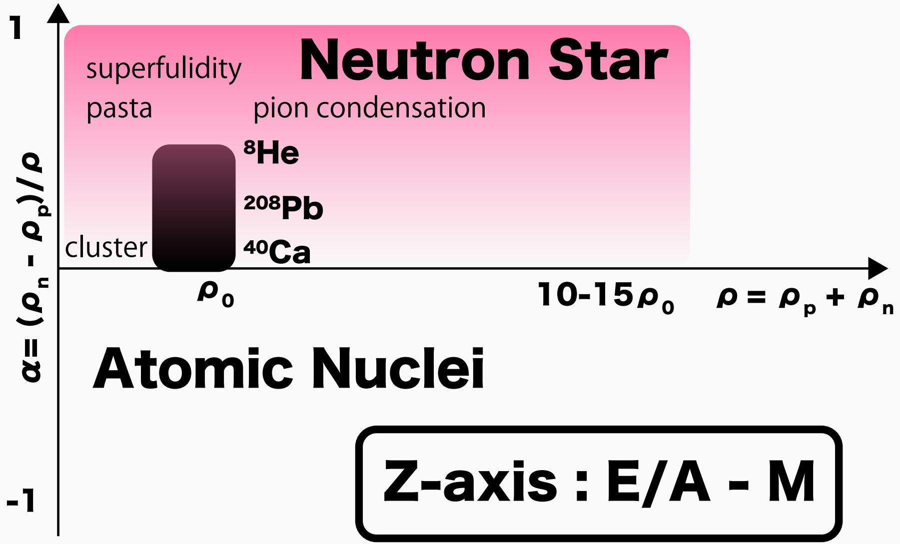
2. Measurement of ISGMR in unstable nucleus and K_τ

Nuclear matter equation of state and its isospin dependence

1.1 Strongly Interacting (QCD) Matter



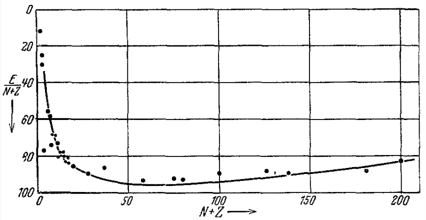

1
-1
α= (ρn - ρp)/ρ
Neutron Star
superfulidity
pasta
pion condensation
8He
208Pb
40Ca
cluster
ρ0
10-15ρ0
ρ = ρp + ρn
Atomic Nuclei
Z-axis : E/A - M

1.3 Role of Nuclear matter equation of state

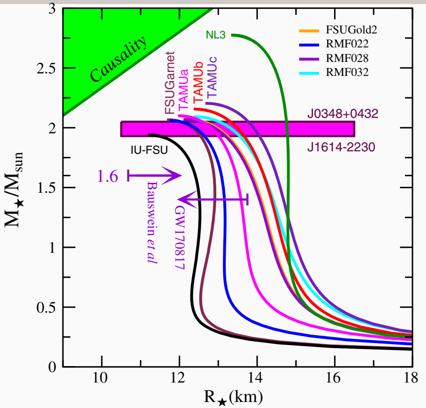
$$E/A - M \equiv \begin{cases} B.E./A(N,Z) & \text{mass formula: } \rho = \rho_0,\ A \lesssim 300? \\ \mathcal{E}(\rho,\alpha) & \text{EoS: any } \rho,\ \alpha, \text{ large } A \end{cases}$$

$\rho_{(0)}$ is (saturation) number density

α is proton-neutron asymmetry



B.E. vs A from Weisäcker1935 ZTK96



M-R relation from Fattoyev+2018 PRL120

Nuclear matter equation of state

connects the worlds of nuclei and astronomical objects

over the discrepancy of 18 magnitude in size and 55 magnitude in nucleon number

1.4 Energy density functional as EoS

Nuclear matter equation of state

$$\mathcal{E}(\rho,\alpha) = \mathcal{E}_{SNM}(\rho) + \alpha^2 \mathcal{S}(\rho) + \mathcal{O}(\alpha^4)$$

$$\mathcal{E}_{SNM}(\rho) = \varepsilon_0 + \frac{1}{2}K_0 x^2 + \frac{1}{6}Q_0 x^3 + \cdots$$

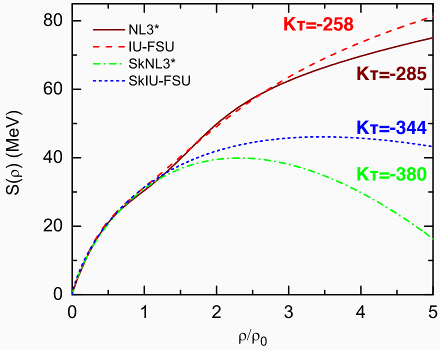
$$\mathcal{S}(\rho) = J + Lx + \frac{1}{2}K_{\rm sym}x^2 + \frac{1}{6}Q_{\rm sim}x^3 + \cdots$$

$\alpha = (N-Z)/A,\ x = (\rho-\rho_0)/3\rho.$

Incompressibility

$$K_0(\alpha) = K_0 + \underbrace{K_\tau}_{\text{isospin dep.}} \alpha^2 + \mathcal{O}(\alpha^4)$$

$$K_\tau = K_{\rm sym} - 6L + \frac{Q_0}{K_0}L$$



Fattoyev+2013

A mission of nuclear study

Determine or restrict coefficients of EoS to construct "realistic" interaction

1.5 Nuclear matter incompressibility

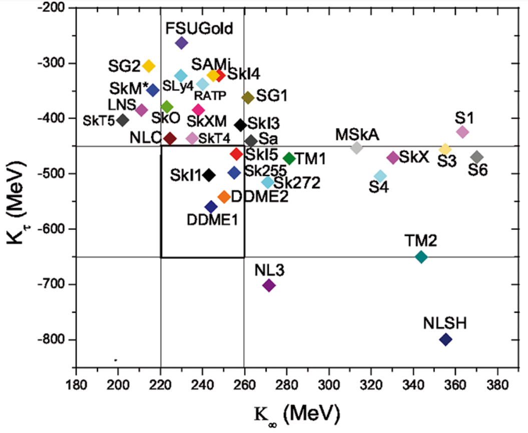
Incompressibility at a new saturation density $\bar{x}$

$$\mathcal{E}(\rho,\alpha) = \varepsilon_0(\alpha) + K_0(\alpha)\bar{x}^2 + \cdots$$

$$K_0(\alpha) = K_0 + K_\tau^\infty \alpha^2 + \mathcal{O}(\alpha^4)$$

$$K_\tau^\infty = K_{\mathrm{sym}} - 6L - \frac{Q_0}{K_0}L$$

K_τ^∞ is isospin dependence of infinite nuclear incompressibility and consists of a arithmetic combination of expansion coefficients at the normal density.

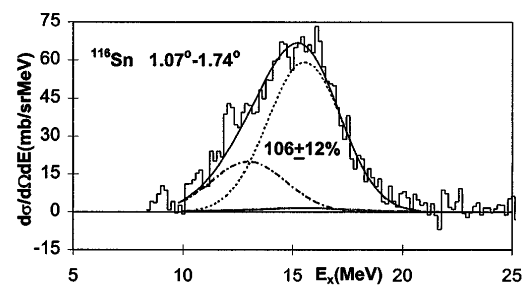


Colo+2014 EPJA50

1.6 Isospin dependence of nuclear incompressibility and ISGMR

$$E_{\mathrm{ISGMR}} = \sqrt{\frac{\hbar^2 K_A}{m < r^2 >}}$$

ISGMR is a direct measure of incompressibility. Incompressibility of symmetric nuclear matter and its isospin dependence can be obtained directly by experiments.



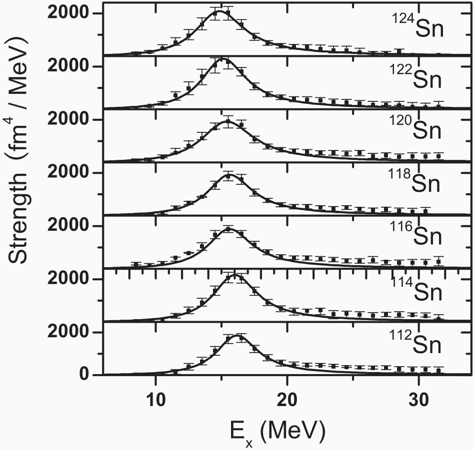
Youngblood+1999PRL82, ^{116}Sn(α,α') at 240 MeV

Nuclear incompressibility and isospin dependence K_τ

$$K_A \sim K_0(1 + cA^{-1/3}) + K_\tau[(N-Z)/A]^2 + K_{\mathrm{Coul}} Z^2 A^{-4/3}$$

Measure the nuclear incompressibility by changing $(N-Z)/A$, *i.e.* along isotopic chain

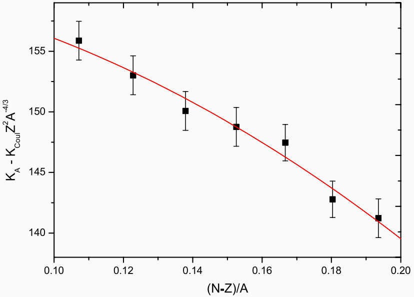
1.7 Previous works at RCNP



$^{112-124}$Sn (α,α') at RCNP, $E_\alpha = 400$ MeV

Multipole decomposition ($L_{\max} = 7$)

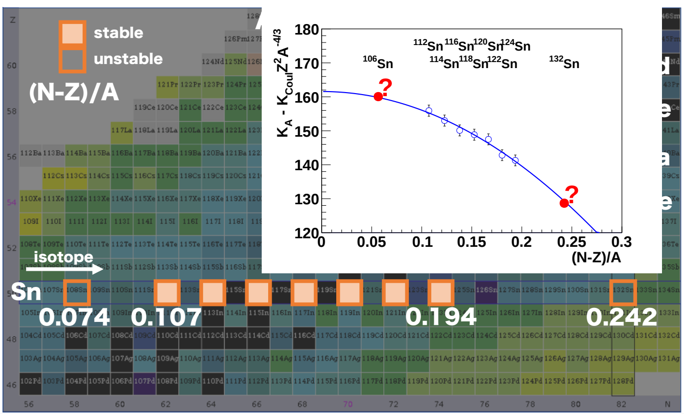
Li+2008 PRL99, Li+2010 PRC81



$$K_\tau = -550 \pm 100 \text{ MeV}$$

1.8 K_τ project: ISGMR in nuclei far from stability

$$\underbrace{K_A}_{\text{to be measured}} \sim K_0(1+cA^{-1/3}) + K_\tau \underbrace{[(N-Z)/A]^2}_{\text{to be varied}} + K_{\mathrm{Coul}} Z^2 A^{-4/3}$$



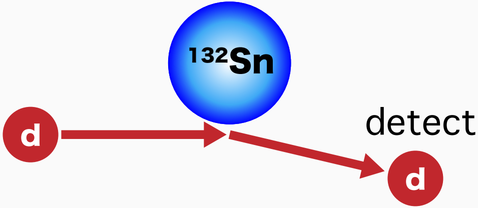
Measurement of ISGMR in unstable nucleus and K_τ

2.1 From Normal to Inverse kinematics

Missing mass spectroscopy

$$M^2 = \|\mathbb{P}_{\mathrm{beam}} + \mathbb{P}_{\mathrm{target}} - \mathbb{P}_{\mathrm{detected}}\|^2$$

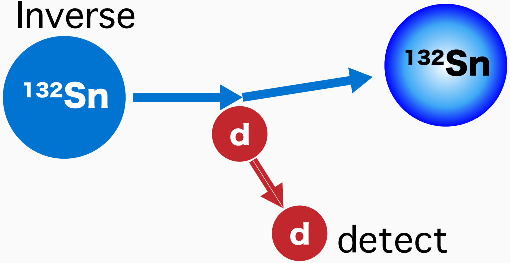
Normal



$$\|\mathbb{P}_{\mathrm{beam}}\| = \|\mathbb{P}_{\mathrm{detect}}\|$$

$$\frac{\partial M}{\partial P_{\mathrm{beam}}} \sim \frac{\partial M}{\partial P_{\mathrm{detect}}}$$

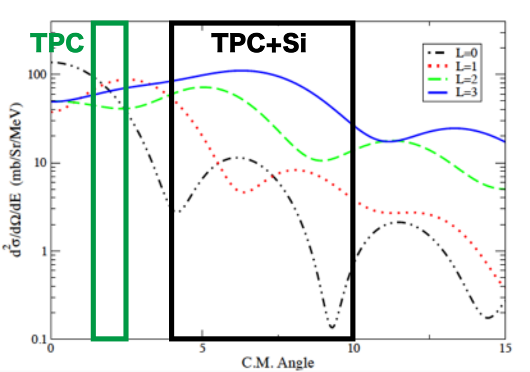
Inverse

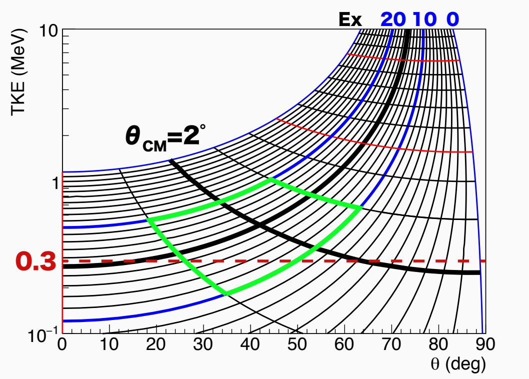


$$\|\mathbb{P}_{\mathrm{beam}}\| \sim M \gg \|\mathbb{P}_{\mathrm{detect}}\|$$

$$\frac{\partial M}{\partial P_{\mathrm{beam}}} \ll \frac{\partial M}{\partial P_{\mathrm{detect}}}$$

2.2 Kinematics of recoil in region of interest





Recoil particle around 2 degrees at Ex = 15 MeV

TKE ~ 0.3 MeV ⇔ range ~ 0.19 mg/cm2 in D_2

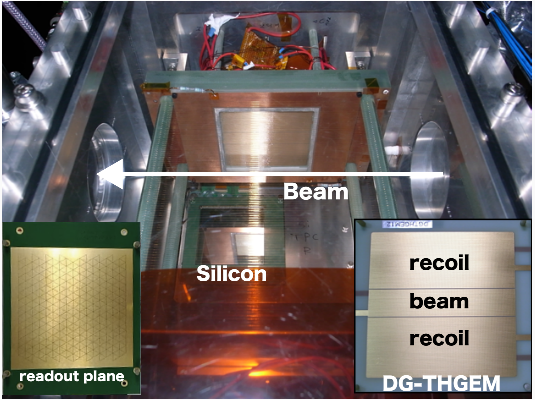
⇒ Needs "gas target + tracking detector" = **ACTIVE TARGET TPC**

2.3 Active target CAT-S

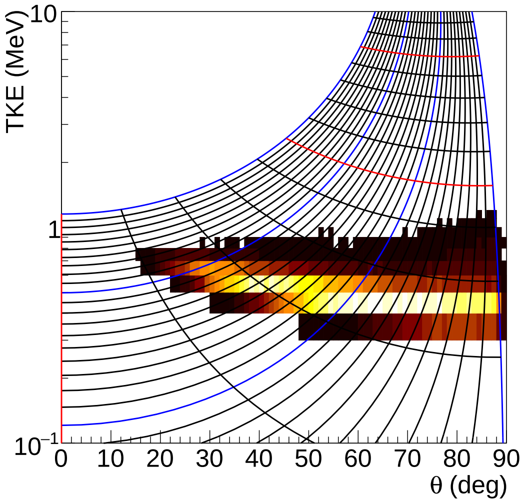
CAT-S

for scattering experiments with high-intensity heavy radioactive beams

- **Beams up to 1 Mcps, upto $A \geq 130$ (space charge), 100-300 MeV/u (delta rays)**
- $10 \times 10 \times 25\text{–cm}^3$ active area
- Pure D_2, H_2, (He) at $0.2 - 1$ atm
- Dual gain thick GEM
- 7-mm side $\triangle$ pad (400 in total)
- Trajectory by fitting Bragg curve
- Two silicon detectors beside TPC
- $\delta Ex \leq 1$ MeV, $\delta\theta_{\mathrm{CM}} \leq 1$ deg

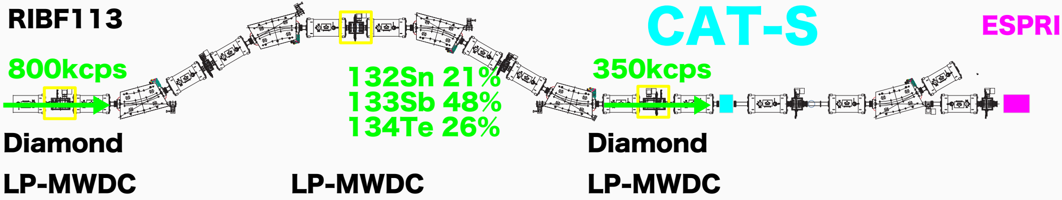


2.4 Acceptance of CAT-S TPC

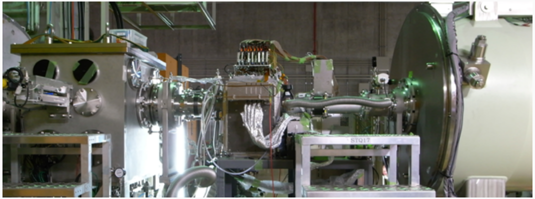


- Covers Ex 15 MeV at $\theta_{\rm CM} \sim 2$deg. with an efficiency of about 20%.
- Ex : 0 - 20 MeV
- $\theta_{\rm CM}$: 1.5 - 2 (dep. on Ex)
- Typically $\delta TKE/TKE \sim 0.1$ and $\delta\theta_{\rm lab} \sim 1$deg $\Rightarrow$ $\delta Ex \sim 1$ MeV and $\delta\theta_{\rm CM} < 1$deg

RIBF113 (S. Ota, U. Garg et. al) : Measurement of ISGMR in ^{132}Sn



- ^{132}Sn(d,d') at 114 MeV/u
- CAT-S with 0.4-atm deuterium
- Beam PID by TOF$-B\rho_{35} - B\rho_{37}$
- Recoil PID by comparing two χ^2's of fitting assuming proton and deuteron Bragg curves



2.6 Energy spectra of deuteron inelastic scattering

Preliminary uncorrected energy spectra for ^{132}Sn, ^{133}Sb, and ^{134}Te.

Particle identifications of beam and recoil particles have been done.

(In presentation, preliminary spectra for for ^{132}Sn, ^{133}Sb, and ^{134}Te are shown)

2.7 Deduction of ISGMR and ISGQR in ^{133}Sb

Assumptions

- only two GRs in 10-20-MeV region (weakness of LE-ISGDR)
- relative position of ISGMR and ISGQR
- fixed widths of ISGMR and ISGMR

Method

Least square method with binned functions of two Lorentzian, one Gaussian and flat distributions, corresponding to ISGMR, ISGQR, unknown strength and quasi-free background, respectively.

(In presentation, preliminary result for ^{133}Sb is shown)

2.8 Deduction of ISGMR and ISGQR in ^{132}Sn and ^{134}Te

(In presentation, preliminary result for ^{132}Sn is shown)

(In presentation, preliminary result for ^{134}Te is shown)

2.9 Comparison with theory

(In presentation, here is comparison with theoretical calculation)

Case of ^{132}Sn

Calculations : Sagawa+ Private Communication

2.10 Isospin dependence of nuclear incompressibility

With assumptions mentioned previously.

- only two GRs in 10-20-MeV region
- relative position of ISGMR and ISGQR
- widths of ISGMR and ISGMR

(In presentation, preliminary Ktau with systematic trend is shown.)

2.11 Outlook: Towards the precise determination of K_τ

$$K_A \sim K_0 + K_{\rm surf} A^{-1/3} + \underbrace{(K_{\tau V} + K_{\tau S} A^{-1/3})}_{K_\tau}[(N-Z)/A]^2 + K_{\rm Coul} Z^2 A^{-4/3}$$

- Analysis of backward angle data in $^{132}\mathrm{Sn}(d,d')$ and try MDA
- How to deal with effect of surface term?
  - Theoretically deduce K_τ in the same manner of experimental one, namely, quadratic fit of calculated ISGMR energy, OR directly compare ISGMR energies
  - Experimentally deduce the surface or higher order terms.
    Isobar chain (fix A and vary $(N-Z)/A$) and several A
    or N=Z chain (vary A and fix $(N-Z)/A$)
    or ISGMR energy nuclear chart like mass one.

Next step

We can measure ISGMR in heavy unstable nuclei now.

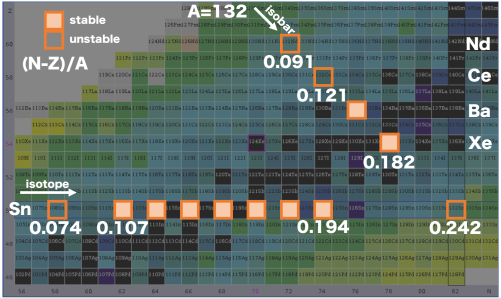
More measurements of ISGMR in unstable nuclei $\Rightarrow$ effective setup

2.11 Outlook: Towards the precise determination of K_τ

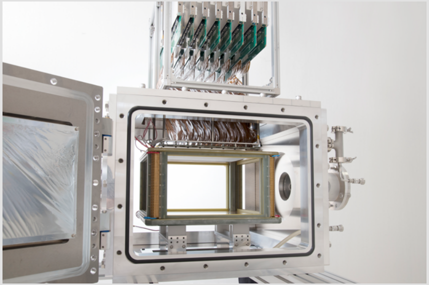
$$K_A \sim K_0 + K_{\mathrm{surf}} A^{-1/3}) + (K_\tau + K_{\tau S} A^{-1/3})[(N-Z)/A]^2 + K_{\mathrm{Coul}} Z^2 A^{-4/3}$$

K_τ project

ISGMR in isomer, isobar, N=Z



CAT-M (32 x 28 x 20 cm^3)



Commissioned in 2017

10 times statistics for same run time

Application for other reactions

2.12 Summary

- The first measurement of ISGMR in ^{132}Sn was performed at RIBF and successfully observed the strength of GRs around 10-20 MeV.
- Active targets CAT-S and CAT-M are ready for experiments
- ISGMRs in larger area of nuclear chart will be performed toward the precise determination of K_τ
- Another programs with CAT-M
  - GDR, PDR and other GRs via (p,p'), (d,d'), and (α,α')
  - Electron capture rate in Iron-group nuclei
  - Transfer reactions at OEDO/SHARAQ (pair condensation, GPV)
  - ... open for collaborations