Weakly Bound Neutron-rich Nuclei and Cosmic Phenomena

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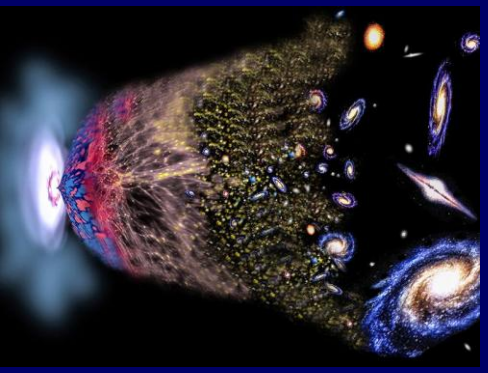
Introduction: Challenges and questions
Unusual properties of exotic nuclei
Method of investigation
Experiments and exciting new Results
Exotic nuclei and its impact on cosmology
Summary and Future

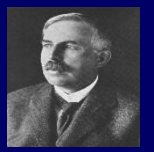
Thirteenth Conference on the Intersections of Particle and Nuclear Physics, Palm Springs, California, 1st June , 2018

Challenges and questions

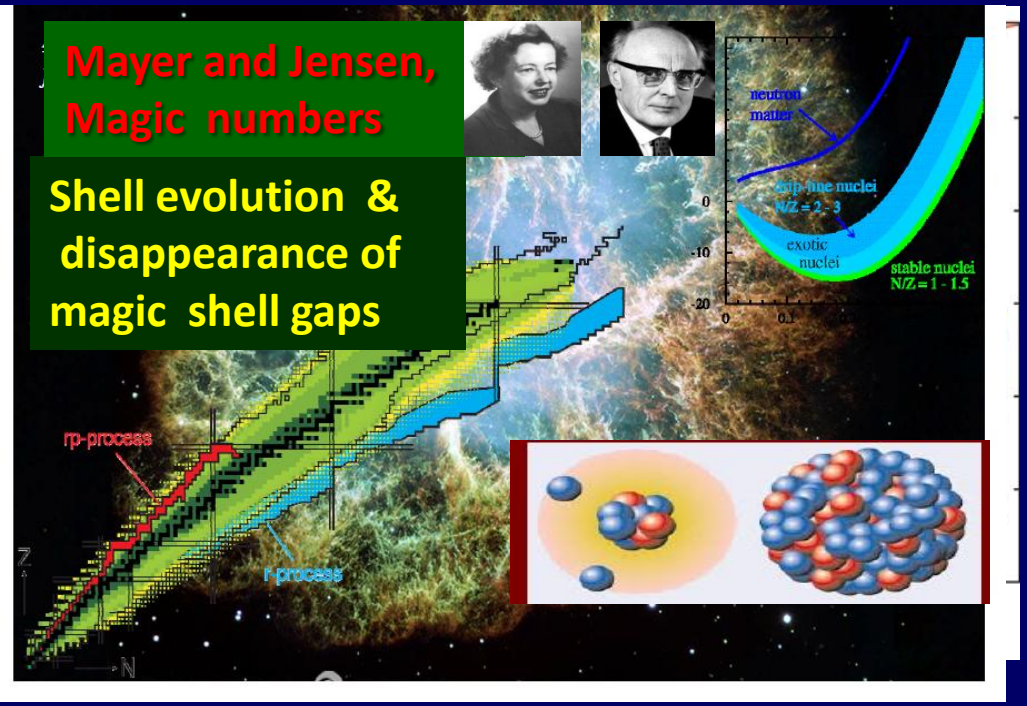


15 billion years ago , 1 sec after big bang, nuclei was formed

10 8 years after discovery of nucleus



What are the limits of existence of the nuclei???



N-N interaction ??????

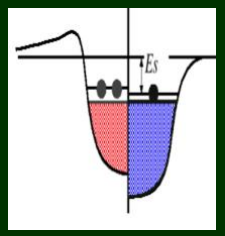
density dependence sym. energy

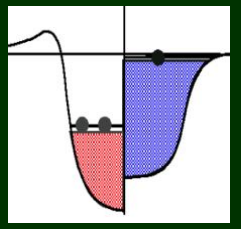
A comprehensive understanding of nuclei

EQS, Neutron Star

How synthesis of elements , r-process nuclei

Why weakly bound nuclei are different??





Nucleus---many body system

averaging

Mean field

Single particle levels

Residual interaction

Two body interaction, SO, pairing

Reduction of spin-orbit inter.

Spin-isospin dep. central part

Tensor part of interaction

Coupling to continuum

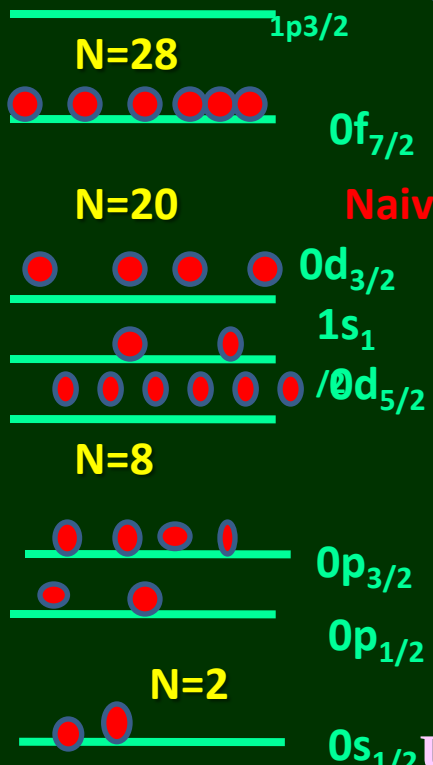
Three body force

……

T.Otsuka , PRL,2001,
PRL, 2005
PRL, 2010

Individual particle

- Decoupling of proton, neutron
- Neutron skin, Diffuse surface



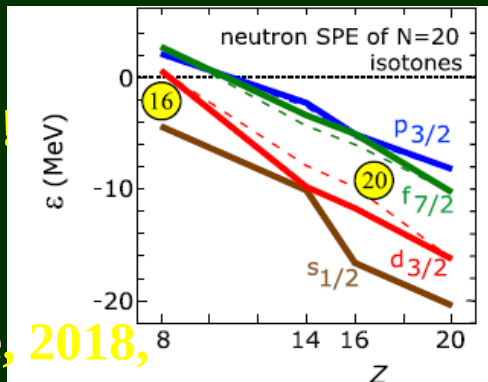
Mixing of the states

Final single particle structure

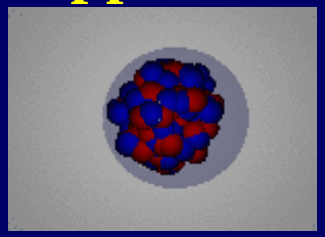
Occup. Prob. of particular state
Spectroscopic factor

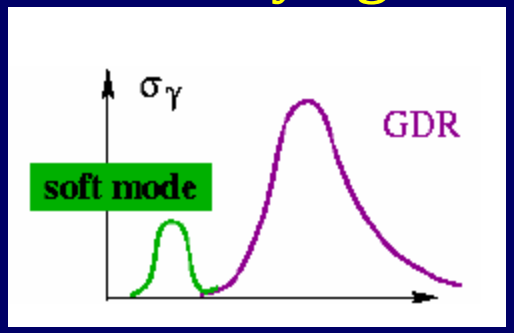
Shell evaluation !!!!!!

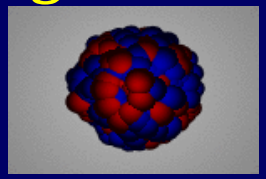
New magic number!!!!

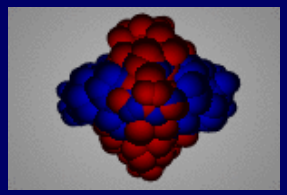


Appearance of low-lying strength in neutron-rich nuclei





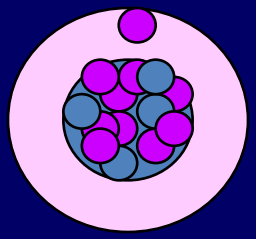


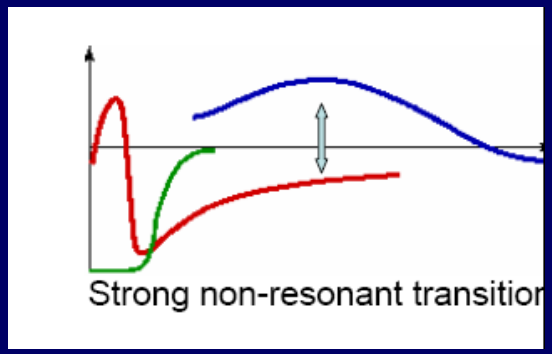


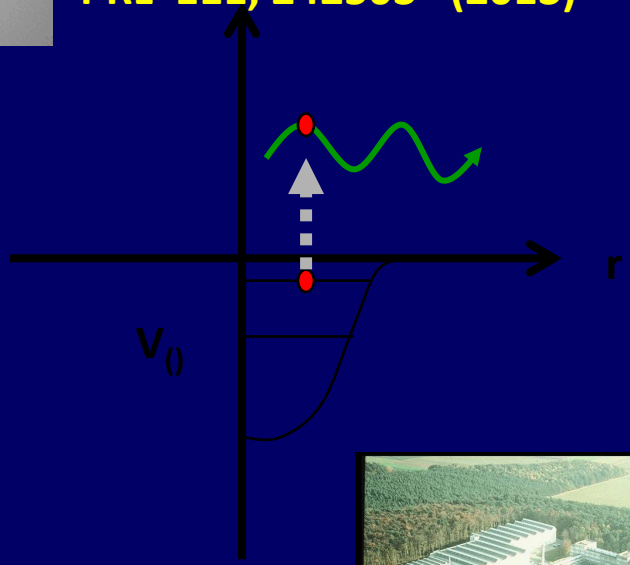
Density dependent symmetry Energy , constraining nn interaction

Phys. Rev. Lett.86 5542, (2001)
Phys. Rev. Lett. 95, 132501, (2005)
Phy. Rev. C76, 051603 (Rap.) (2007)
PRL 111, 242503 (2013)

Threshold strength:

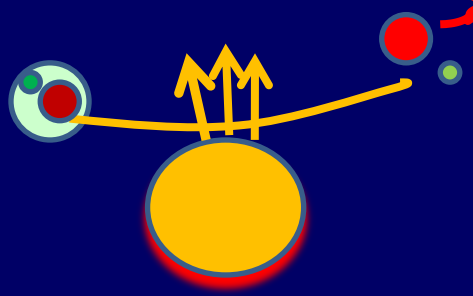




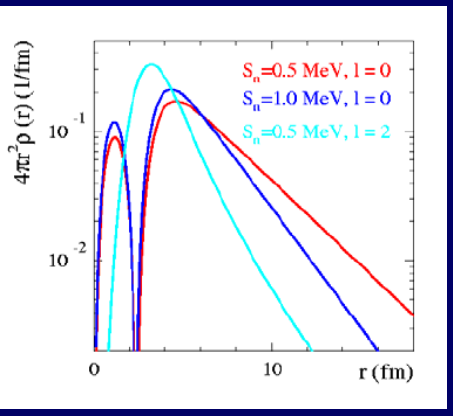


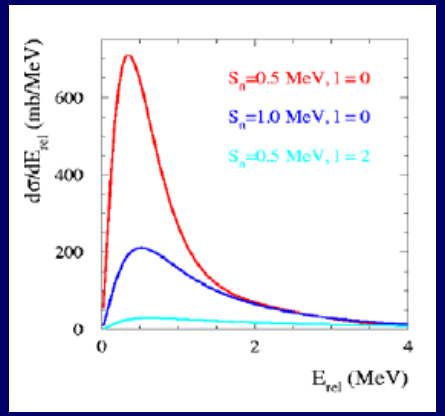
Phys. Lett. B551, 63, (2003)
Phys. Lett. B , (2005)
PPNP 59, (2007)
PRC 94, 034305, (2016)
J.Phys. G 44, (2017)
PRC 96, 034301 (2017)

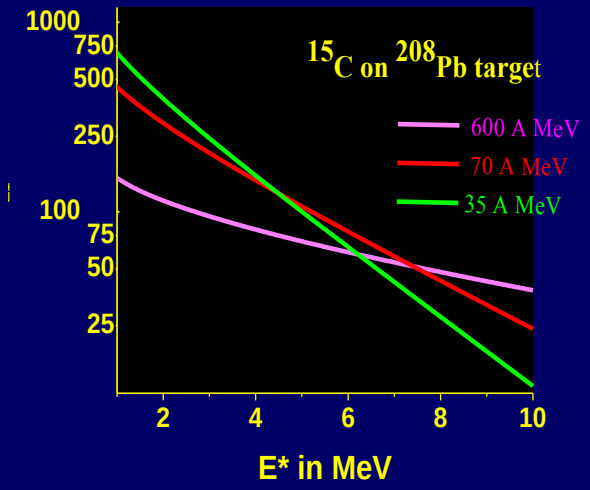
Method of Investigation: Coulomb breakup



Fermi, 1924
Baur, .Bertulani, NPA458, 188





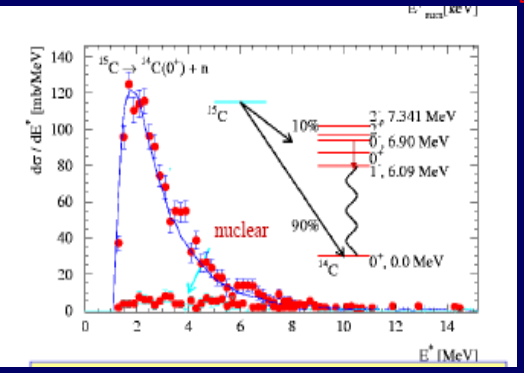


Shape of differential cross section
⇒ angular momentum *l*

Cross section ⇒ spec. factor C^2S

$d\sigma/dE = (16\pi^3/9\hbar c)\, N_{E1}(E*)\, dB(E1)/dE *$ (T. Nakamura et al., PRL83, 1999

$dB(E1)/dE_{rel}\}(I_c) = \sum_{nlj} S(I_c,nlj) \sum_m |\langle q| (Ze/A)\, r\, Y_m^1 |\Psi_{nlj}\rangle|^2$



γ-ray coincidence ⇒
identification of core state I_c

U.Datta Pramanik et al., PLB551, 63 (2003)

Why nuclei around ISLAND OF INVERSION ???

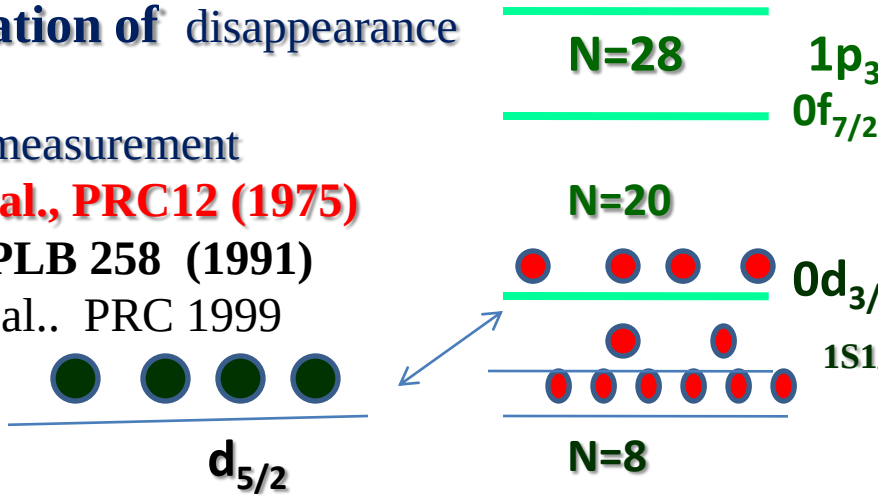
First observation of disappearance of shell gap

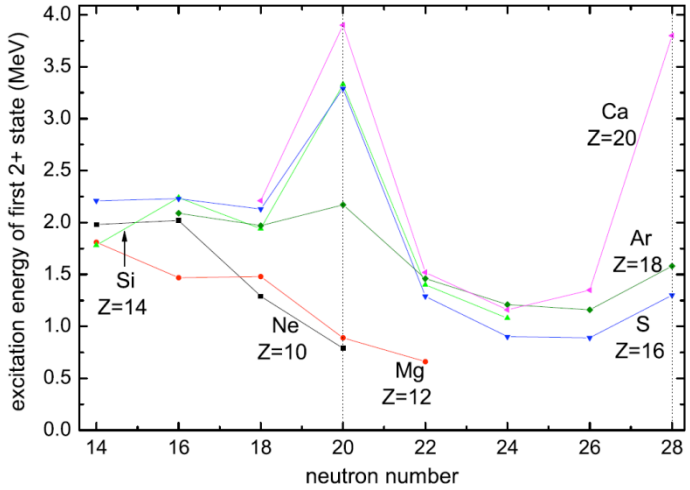
^{31,32}Na mass measurement

C.Thibault et al., PRC12 (1975)

N.Orr et al, PLB 258 (1991)

E.K.Brown et al.. PRC 1999

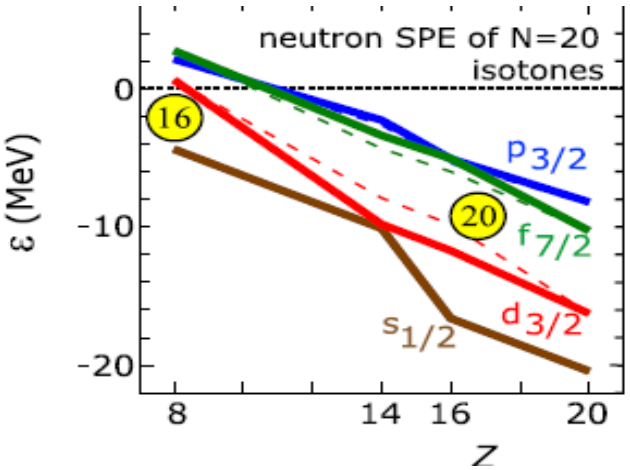




^{32}Mg large deformation

T. Motobayashi et al., PLB 346

^{32}Mg H. T. Fortune, PRC85, (2011)

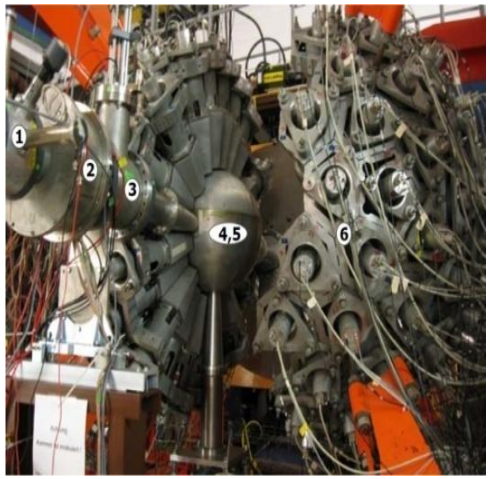


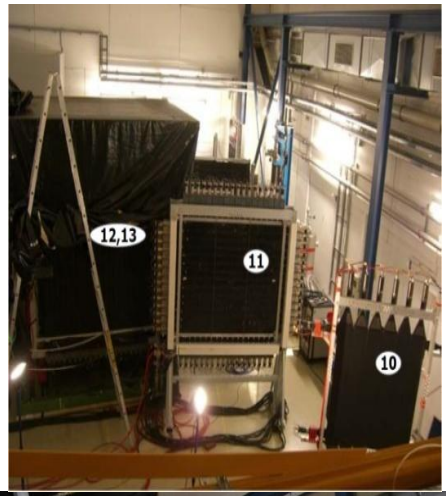
Shell gap disappearance~ N~20 (sd---pf)

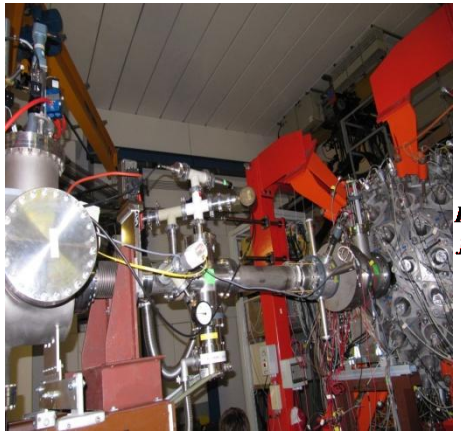
Tensor interaction Otsuka et al

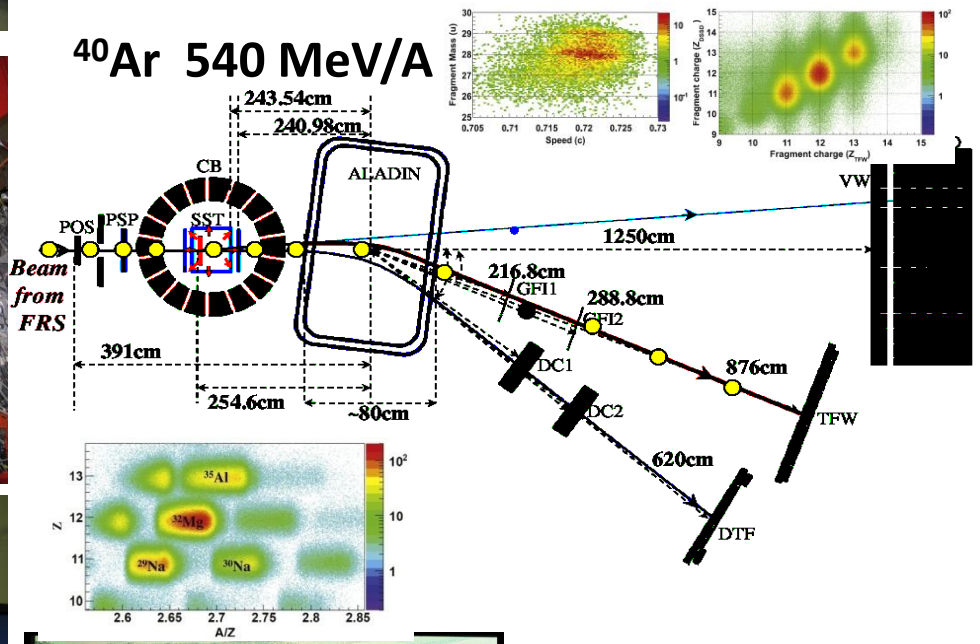
Coulomb Breakup of 'Island of Inversion Nuclei' !!!!!!!!!!!!!!!!!!

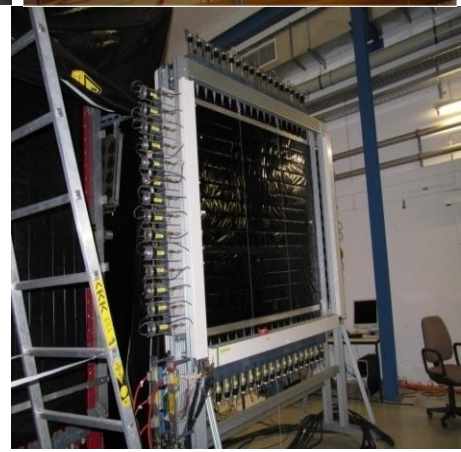
Expt. S306, GSI, Investigation of shell inversion $d_{5/2}$, $f_{7/2}$, $p_{3/2}$……

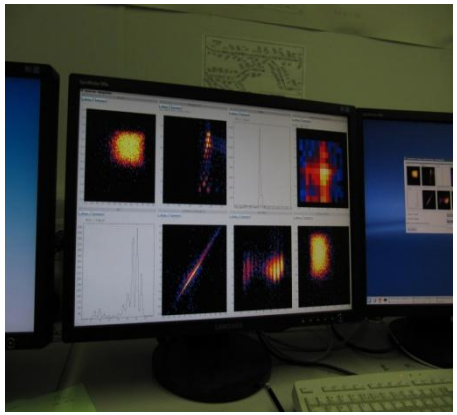


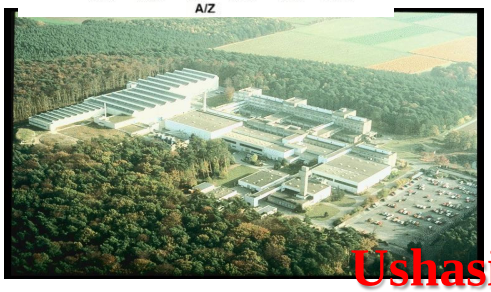






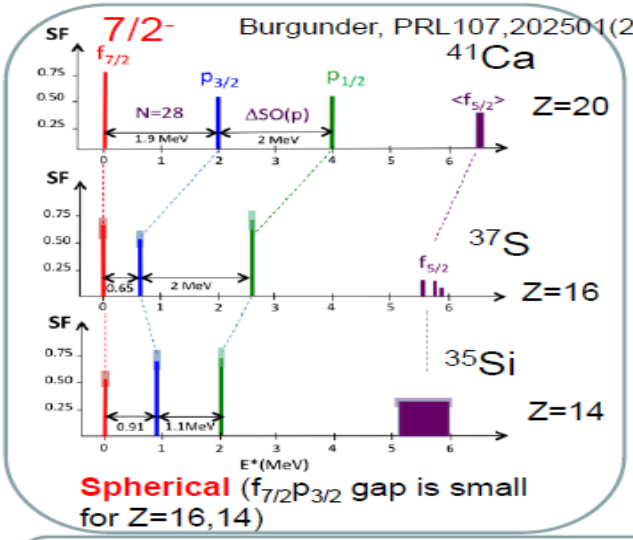


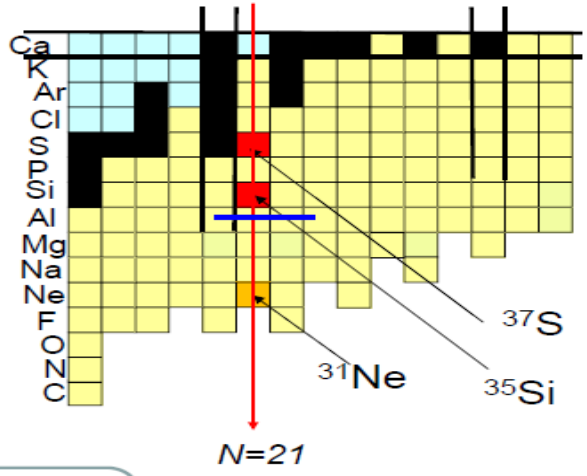




Expt. S306
GSI, Darmstadt+
LAND FRS setup

Shell Evolution towards Drip Line in N=21 isotones





^{33}Mg gs: (3/2$^-$) Z=12
^{31}Ne gs: 3/2$^-$ Z=10
Deformed (gs: 2hω : sd→pf): Island of inversion

Mass measurement and shell model **Ground state of ^{33}Mg**

N.Orr, et al, PLB PLB258 (1991)

Decay ^{33}Na, ^{33}Al, at MSU, ISOLDE,

3/2$^+$ Positive parity , as large gr. state to gr. State

Tripathi et al. PRL101 (2008) , proposed 3/2$^+$

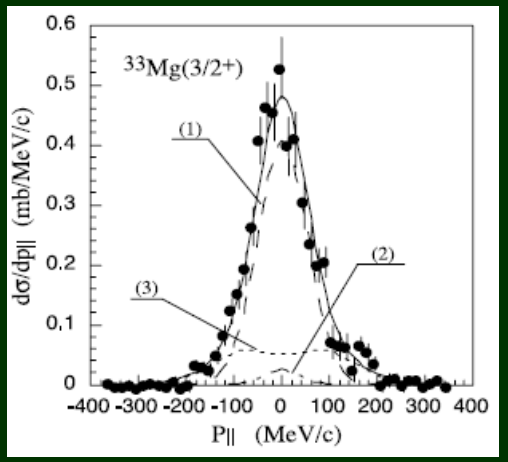
g-factor, ISOLDE, CERN , **3/2- , neutron in p3/2**

Yordanov et al., PRL 99 (2007)

Rodr´ıguez-Tajes et al., PRC 82(2010)

Momn. Dist. from knockout, GSI …Not conclusive

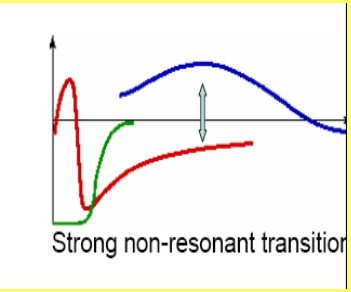
R. Kanungo et al., PLB,(2010) ,

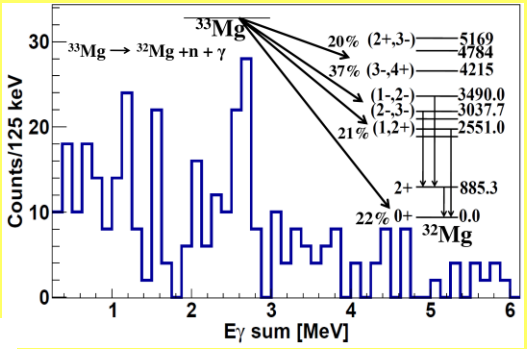


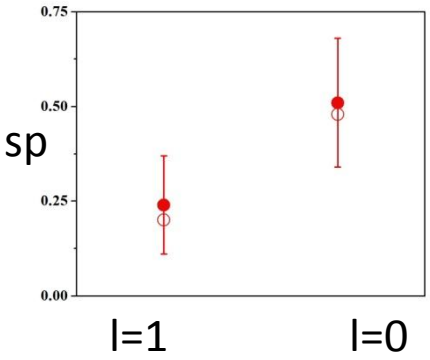
First Direct evidence of multi particle-hole ground state of ^{33}Mg

Threshold strength---direct breakup-----quantum numbers with spectroscopic factor

^{41}Ca (7/2-) ^{33}mg(3/2-)



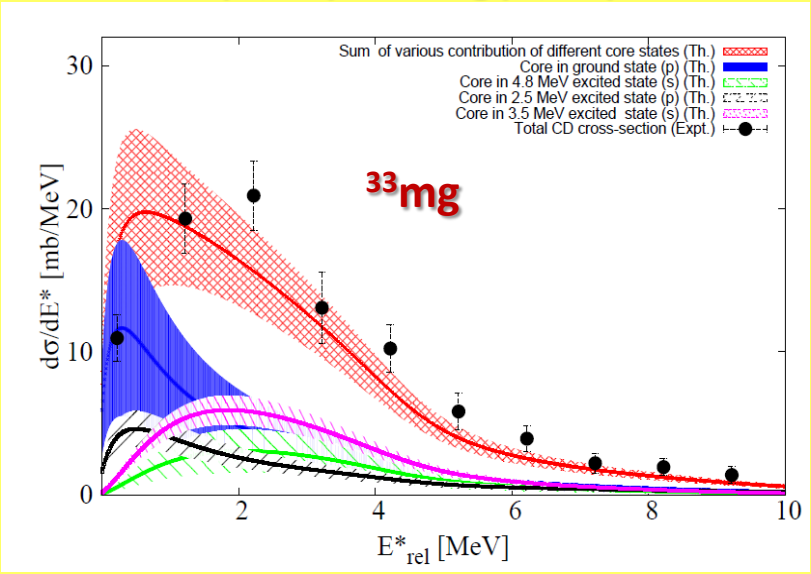




Expt.

Sdpf-M

Y.Utsuno et al,



U.Datta et al, PRC 94, 034304 (2016),

^{32}Mg(0, gr) ⊗ν p3/2

^{32}Mg(3.5, 1-) ⊗ν s1/2

^{32}Mg(2.5, 2 +) ⊗ν p3/2

½[200] ~ 60-70% j1/2

Yordanov et al., PRL 104(2010)

magnetic moment~- 0.86 μn, expt.- 0.745 μn

Larry et al, PLB23(1966) explained

similar observation by deformed core

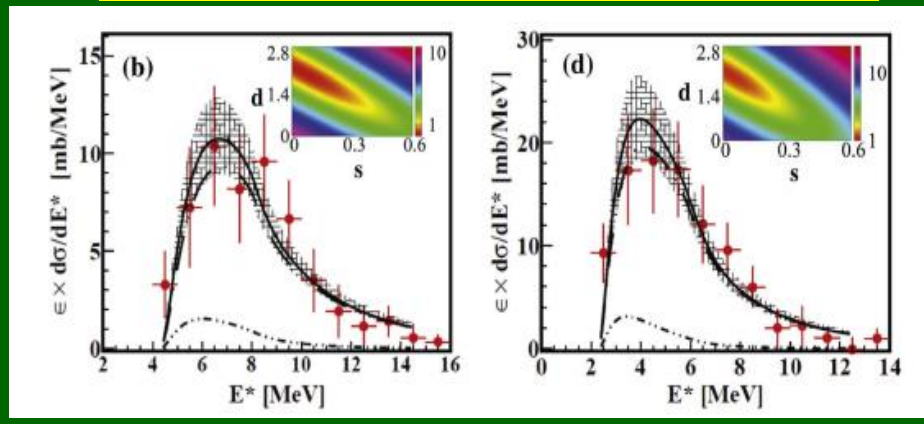
Re-defining boundary of ISLAND of inversion

g-factor: $3/2^+$ gr state,Huber PRC18(1978)

~40% pf cont. A.M. Hurst et al., PLB674, 2009

V.Tripathi et al, PRL94 2005

$^{29,30}Na(3/2^+) \rightarrow {}^{28,29}Na(1^+) \otimes \nu_{s,d}$



A. Rahaman, EPJ web 66, 2014

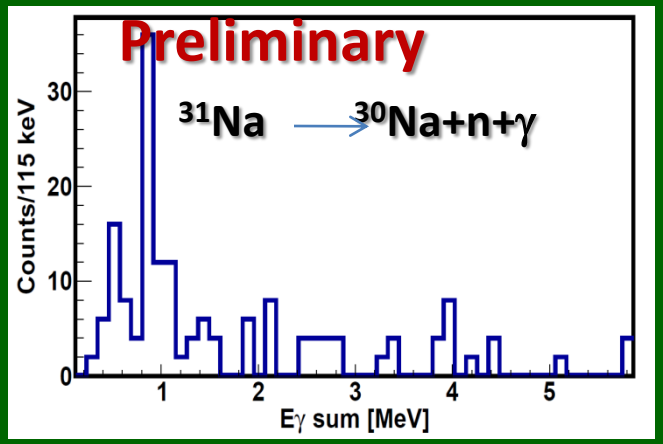
A.Rahaman, J.Phys.G 44, 045101 (2017)

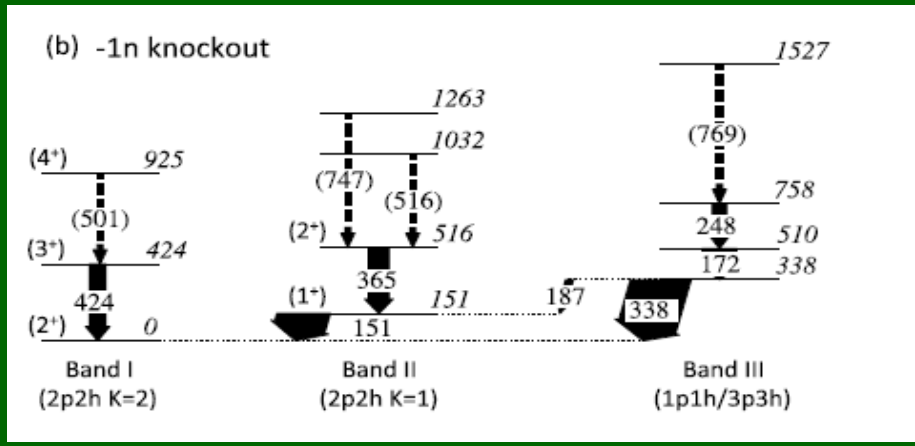
Valence neutron occupies mainly $d_{3/2}$

Sp(d3/2)= 2.09∓0.3 is lower than

USDB cal, (b.A.Brown , MSU) 2.97

Wildenthal et al, PRC22(1980)

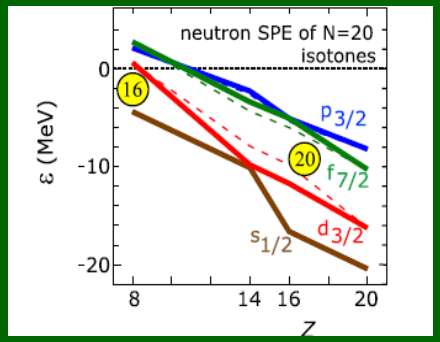


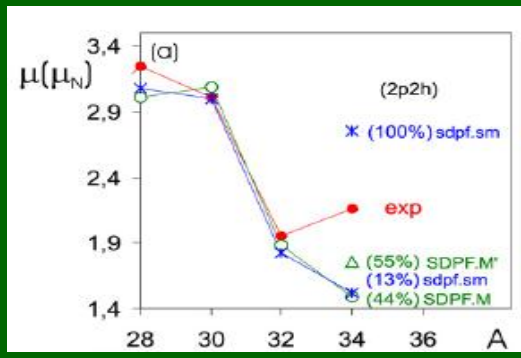


M.Petri et al. PLB748, 143

CD of ^{31}Na (N=20) more than 60% populated multi-particle hole configuration

Disappearance of magic shell gap





P.Himpe et al, PLB658 (2008)

Ground state spin experimentally not known

Rodr´ıguez-Tajes et al., PRC **82'10**

knockout reaction at GSI

Nociforo , et al, PRC 85 2012

Long, moment. dist. 168±64MeV,

CD cross-section of

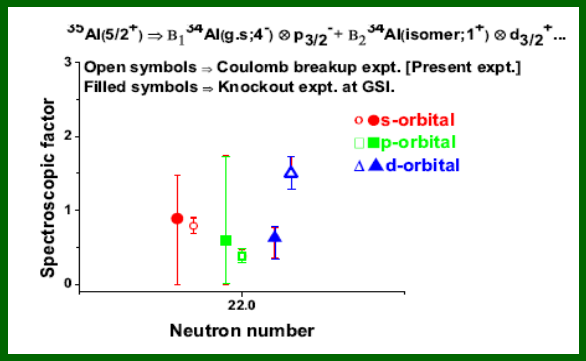
^{35}Al $\rightarrow$ ^{34}Al (gr) + n

~ 59 mb

Cross-section does not support the valence neutron in $f^{7./2}$

S.Chakraborty et al EPJ 66 (2014)

Chakraborty et al., PRC 96, 034301 **(2017)**



^{35}Al $\rightarrow$ ^{34}Al $\otimes \nu_{p,d}$

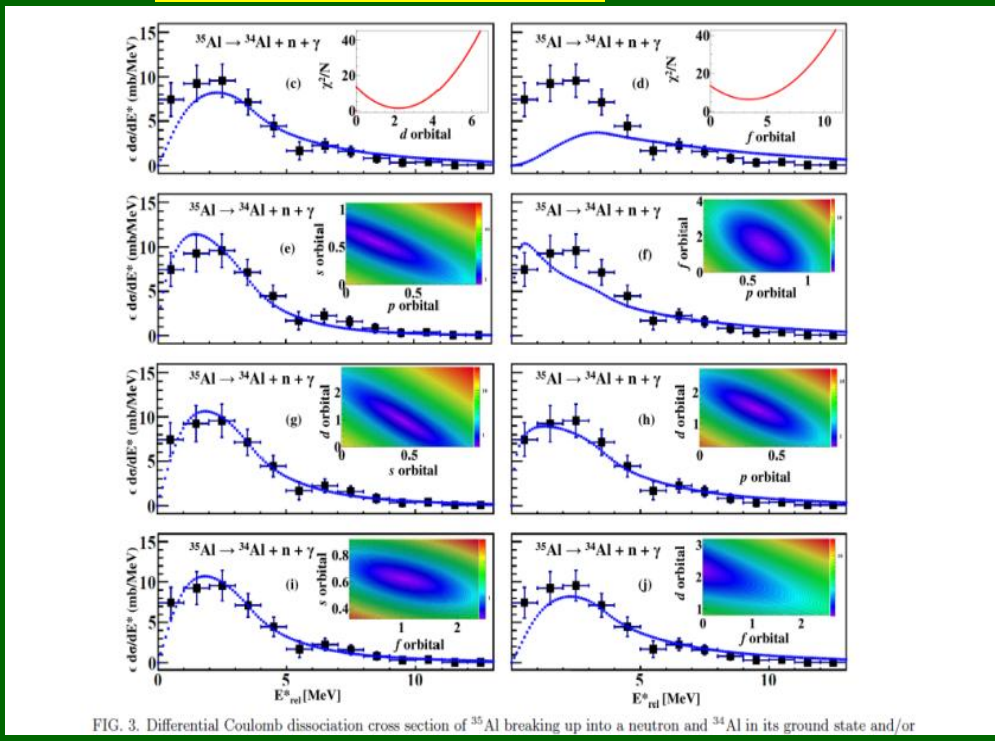
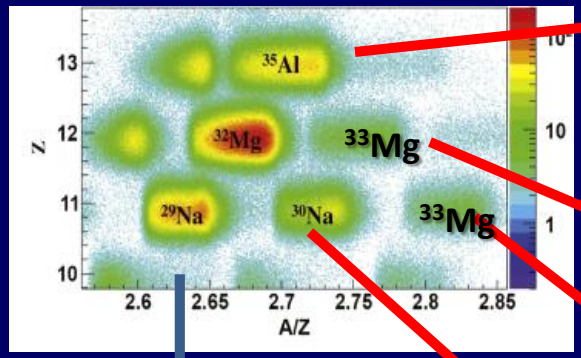


FIG. 3. Differential Coulomb dissociation cross section of ^{35}Al breaking up into a neutron and ^{34}Al in its ground state and/or

Ushasi Datta, CINPANP2018, 1st June, 2018

Disappearances of magic shell gaps



^{34}Al(gr./iso)⊗$\nu_{d,p,f}$

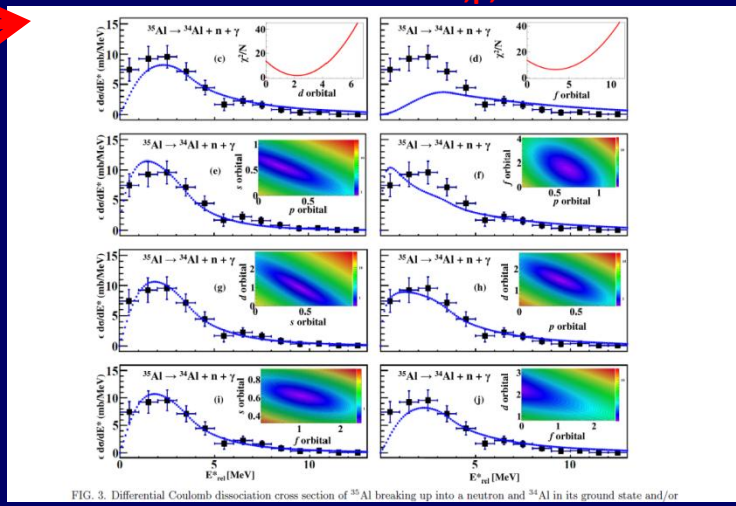
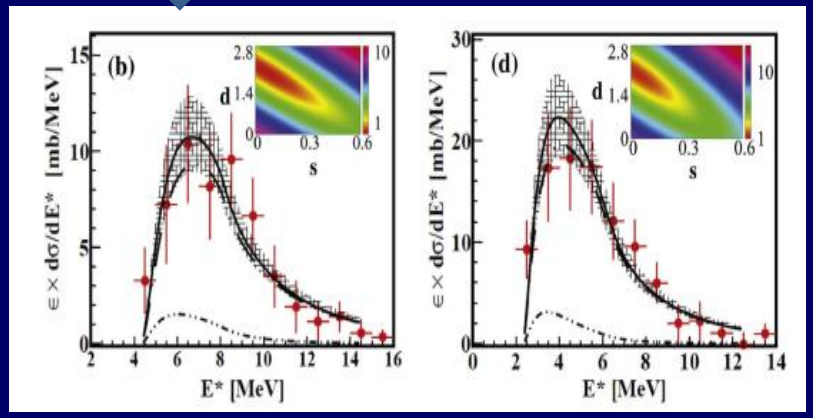
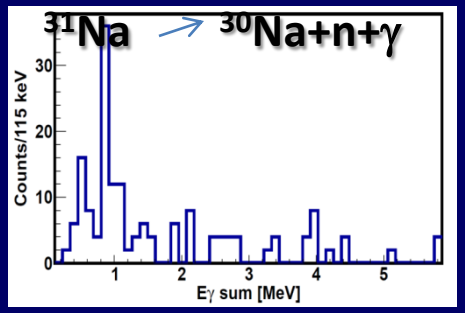


FIG. 3. Differential Coulomb dissociation cross section of ^{35}Al breaking up into a neutron and ^{34}Al in its ground state and/or

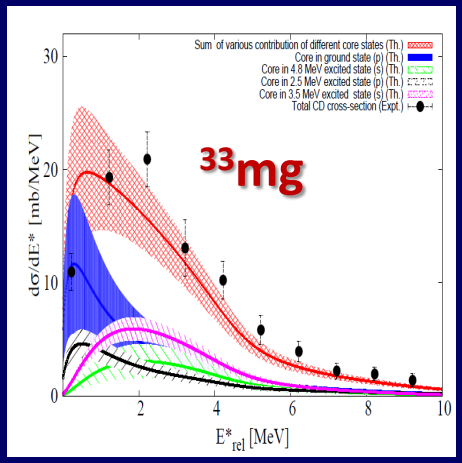
^{28}Na(gr.)⊗ν_d



^{29}Na(gr.)⊗ν_d



^{32}Mg(Ex.)⊗$\nu_{p,s}$



Rahaman et al. al.EPJ66, 02087 (2014)
Chakraborty et al.EPJ66, 02019 (2014)
Datta et al, PRC 94, 034304 (2016),
Rahaman et al, J.Phys.G 44, 045101 (2017)
Chakraborty et al, PRC 96, 034301 (2017)

Major part of ground state configuration is Multi-particle hole configuration across the shell gap.

Reduction and merging of N=20, 28

Advanced LIGO Constraints on Neutron Star Mergers and R-Process Sites

Capture cross-section of several unstable nuclei play key role in explosive processes

Indirect measurement ➡ **Coulomb dissociation**

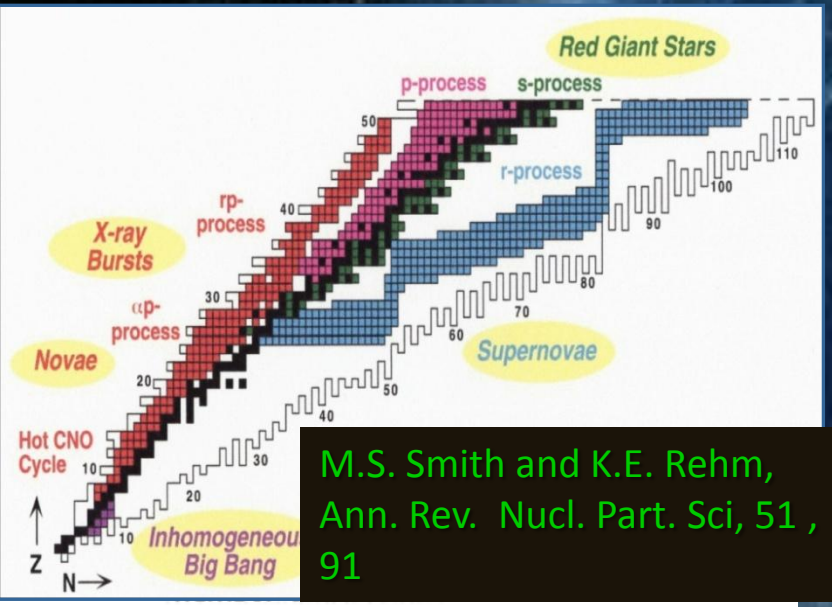
$$\sigma_\gamma = (2Ic+1)(2In+1) / 2(2Ip+1) \cdot K_{cm}^2 / k_\gamma^2 \cdot \sigma_{cap}$$

$$K_{cm}^2 = 2\mu E_{rel}/\hbar^2 , \quad k_\gamma^2 = Ex/\hbar c$$

G.Baur, et al.NPA458 , 188

C.Langer et al, Phys.Rev. C 89, (2014)
Type-I X-ray, $^{30}S(p,g)^{31}Cl$

U.DattaPramanik
Prog.Part.Nucl.Phys. 59, 183 (2007)



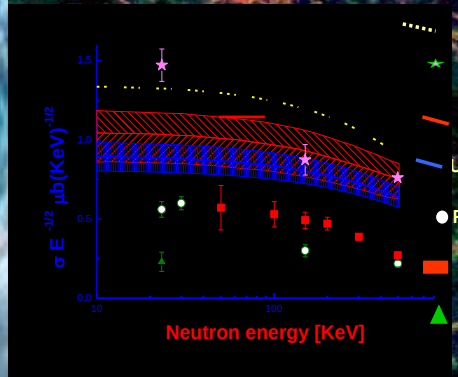
M.S. Smith and K.E. Rehm, Ann. Rev. Nucl. Part. Sci, 51 , 91

$^{14}C(n,\gamma)^{15}C$

*Breakout of n-induced CNO cycle..... M.Wiescher et. al. J.phys.G.25 R133

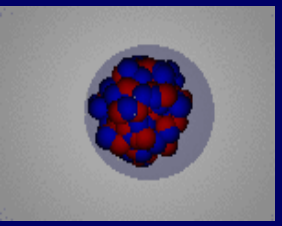
*Inclusion of light nuclei in reaction network of wind model enhances r-process heavy elements abundances .... M.Terasawa et al APJ562, 470, 2001

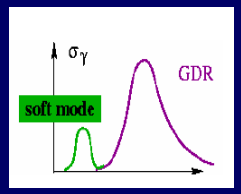
*Inhomogeneous big bang nucleosynthesis, production of A>14



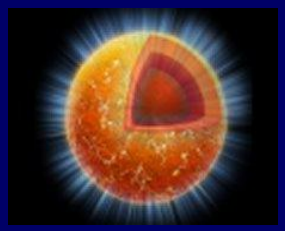
$^{14}C(n,\gamma)^{15}C$ capture cross-section is in agreement with direct and indirect measurement (CD) of RIKEN and GSI data .

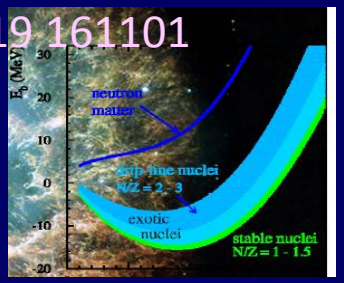
Low-lying dipole strength -PIGMY resonance—soft mode
Dipole polarizibility-neutron skin----neutron matter-neutron star

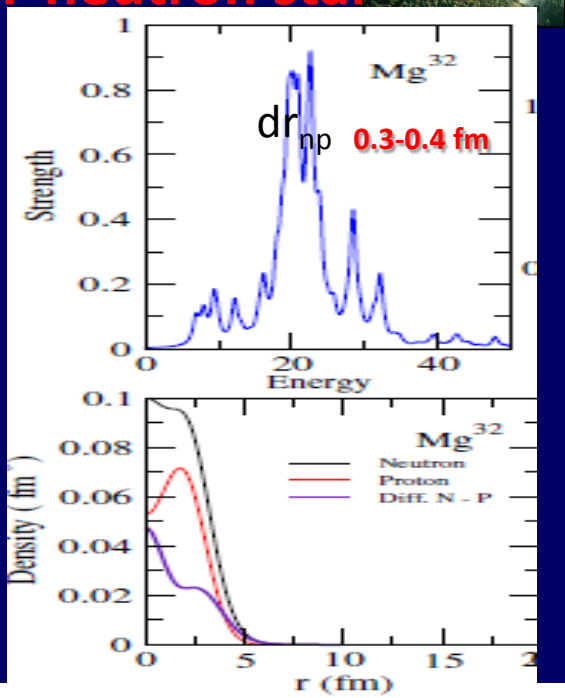




GW170817 PRL 119 161101



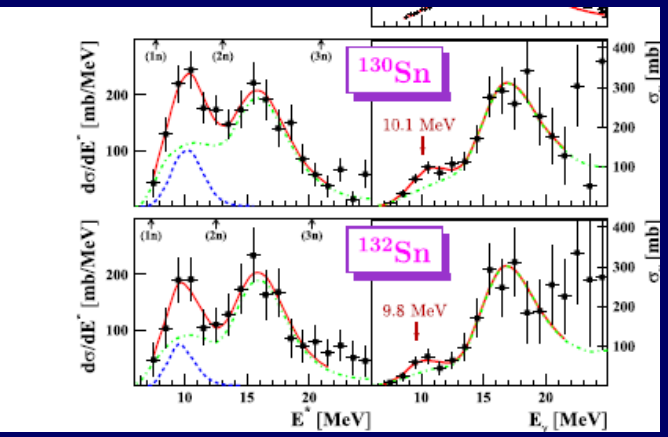


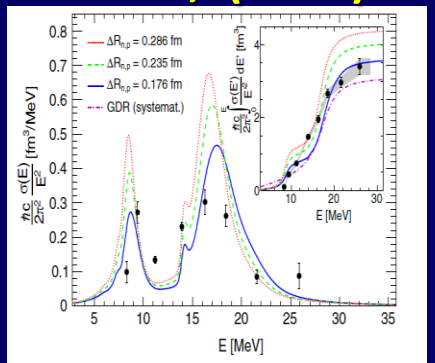


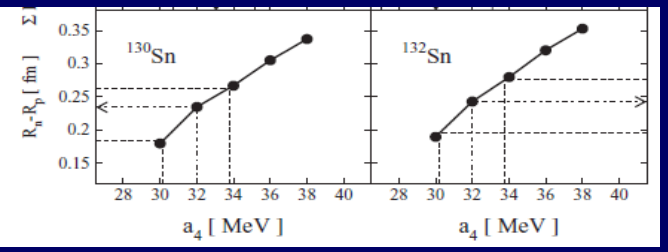
Neutron skin in ^{130,132}Sn,
Adrich et al, PRL 95, (2005),
Klimkiewicz et al, PRC76, (2007)

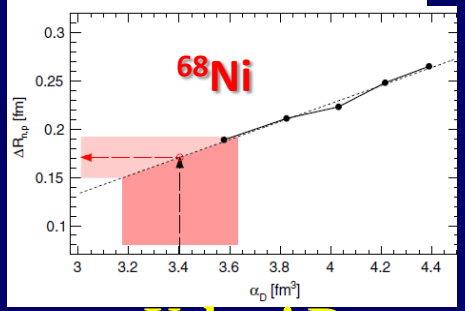
HI collision, Bettey's talk
PREX , JLAB, Riordan's talk

D. Rossi et al,
PRL111, (2013)

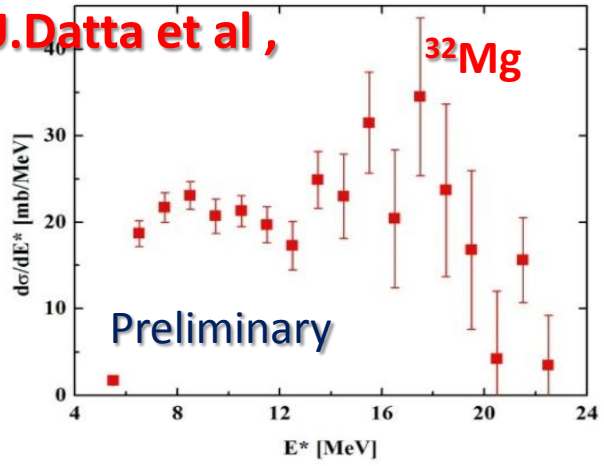








U.Datta et al , **^{32}Mg**



Summary and Future

A. Experimental data on shell evolution around the drip line is important for constraining and advancing our understanding the fundamental problem of nucleon-nucleon interactions, as predicted by theoreticians. Coulomb breakup data advanced our understanding "ISLAND of Inversion" neutron-rich nuclei. In some nuclei, we have shown first direct evidence of multi-particle-hole configuration. But complementary methods are equally important……Today Alan's talk, Tomorrow Gade's talk.

B. Experimental data on bulk properties of the exotic nuclei would improve our knowledge of mean field approximation and it is particularly important for some ingredients like density dependence symmetry energy etc.

C. Nuclear physics impact on Cosmic phenomena has been discussed . Indirect measurement for capture cross-section of loosely bound nuclei is an essential tool to understand nucleosynthesis process (like r-process) in explosive burning scenario. Measurement of neutron skin thickness will be an essential part for understanding dense cosmic object like neutron star.

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Thank You