Possible nuclear structure issues for nucleosynthesis

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Major scientific facilities in China

HIRFL-CSR, Lanzhou
Heavy Ion Res Facility + Cooling Storage Ring

LAMOST, Xinglong Observatory near Beijing
Multi-Object Fiber Spectroscopic Telescope

SSRF, Shanghai
Shanghai Synchrotron Radiation Facility

CSNS, Dongwan of Guangdong Province
Chinese Spallation Neutron Source

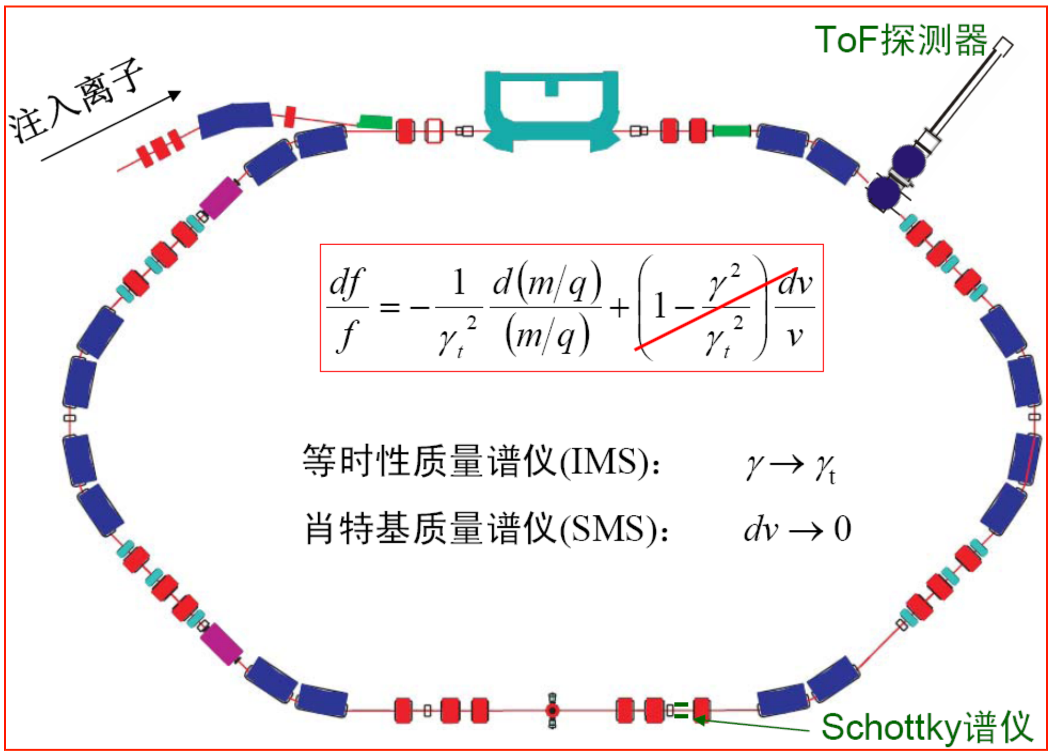
RUSSIA
KAZAKHSTAN
KIRGIZSTAN
MONGOLIA
HEILONGJIANG
JILIN
XINJIANG
LIAONING
INNER MONGOLIA
NORTH KOREA
GANSU
Beijing
PAKISTAN
Tianjin
Yellow Sea
QINGHAI
HEBEI
SHANXI
SOUTH KOREA
SHANDONG
Yellow River
CHINA
JIANGSU
TIBET
SHAANXI
HENAN
SHANGHAI
ANHUI
SICHUAN
NEPAL
CHONGQING
HUBEI
Yangtze River
ZHEJIANG
East China Sea
BHUTAN
JIANGXI
HUNAN
FUJIAN
GUIZHOU
INDIA
BANGLADESH
YUNNAN
TAIWAN
GUANGXI
Hong Kong
Macau
BURMA
VIETNAM
South China Sea
LAOS
0
400 km
HAINAN

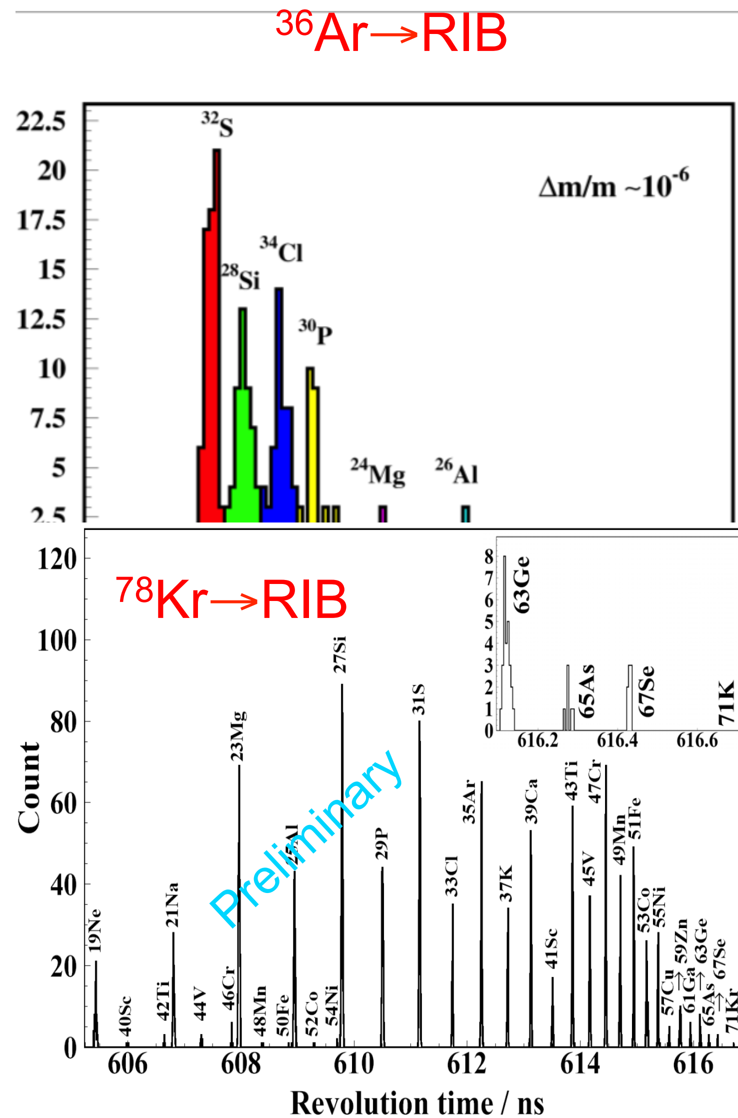

Lanzhou City

CSRe: Cooling storage ring

RIBLL2＋CSRe

Isochronous mass spectrometer





- End of 2007: test run
- End of 2008: 1st physics run
- Fall of 2009: results

Direct Mass Measurements of Short-Lived $A = 2Z - 1$ Nuclides ^{63}Ge, ^{65}As, ^{67}Se, and ^{71}Kr and Their Impact on Nucleosynthesis in the *rp* Process

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Mass excesses of short-lived $A = 2Z - 1$ nuclei ^{63}Ge, ^{65}As, ^{67}Se, and ^{71}Kr have been directly measured to be −46 921(37), −46 937(85), −46 580(67), and −46 320(141) keV, respectively. The deduced proton separation energy of −90(85) keV for ^{65}As shows that this nucleus is only slightly proton unbound. X-ray burst model calculations with the new mass excess of ^{65}As suggest that the majority of the reaction flow passes through ^{64}Ge via proton capture, indicating that ^{64}Ge is not a significant *rp*-process waiting point.

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NUCLEAR ASTROPHYSICS

Star bursts pinned down

One of the main uncertainties in the burn-up of X-ray bursts from neutron stars has been removed with the weighing of a key nucleus, ^{65}As, at a new ion storage ring.

Philip Walker

Understanding how the chemical elements formed in stars, and how their formation is related to observable astrophysical phenomena, requires close cooperation between those

role in determining the time evolution of the radiation burst. Yet, in some cases, it is simply not known whether or not a nucleus can keep hold of another proton. By measuring the mass of the arsenic

a so-called proton-unbound

ch a captured proton remains

unbound or only loosely bound to the nucleus — Xiaolin Tu and colleagues[1] have now shown that the germanium isotope ^{64}Ge is most likely not, after all, a waiting point in the evolution of X-ray bursts.

There is a long history of laboratory experiments being used to help understand

in the stellar environment. It sounds straightforward, but when the object of attention is ^{65}As (containing 33 protons and 32 neutrons) with a half-life of only 130 ms, nothing should be taken for granted. As they report in *Physical Review Letters*, Tu *et al.*[1] —

The core of the Lanzhou facility is the experimental cooler storage ring (Fig. 1), which is part of an accelerator complex at the Institute of Modern Physics. It is only the second storage ring of its kind in the world, the first being at the Helmholtzzentrum für Schwerionenforschung in Darmstadt, Germany[3]. There has been close cooperation between the two centres, and now the Chinese facility has produced its first high-profile results[1].

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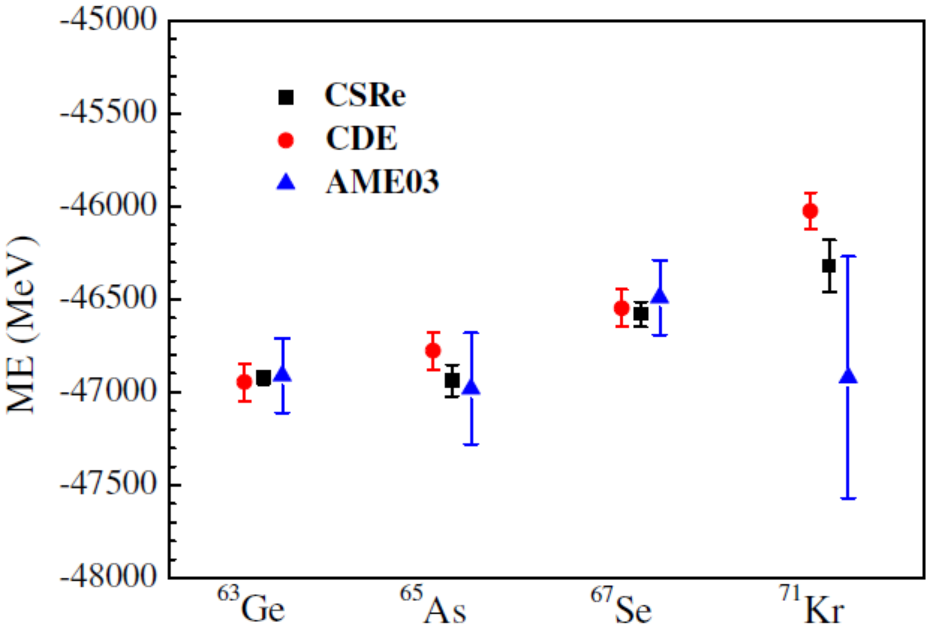
facility for nuclear physics: the cooler storage ring, now in operation at the Institute of Lanzhou, in western China.

How much the tiny nuclear structure changes can influence the nucleosynthesis results?

Mass measurement results

- Masses of these nuclei are measured for the first time.
- Current HIRFL-CSR results have similar error bars as CDE predictions.
- It confirms that CDE method is reliable at least for ^{63}Ge, ^{67}Se.
- It shows some differences for ^{65}As and particularly for ^{71}Kr.



Coulomb displacement energy (CDE)

Difference in binding energy of mirror nuclei

$$D(A,T) = BE(A,T_z^<) - BE(A,T_z^>)$$

Binding energy of the proton-rich nucleus $BE(A,T_z^<)$

Binding energy of the neutron-rich nucleus $BE(A,T_z^>)$

$$T = |T_z^<| = |T_z^>|$$

D(A,T) calculated with Skyrme Hartreee-Fock method

$$BE(A,T_z^<) = D(A,T)_{HF} + BE(A,T_z^>)_{\exp}$$

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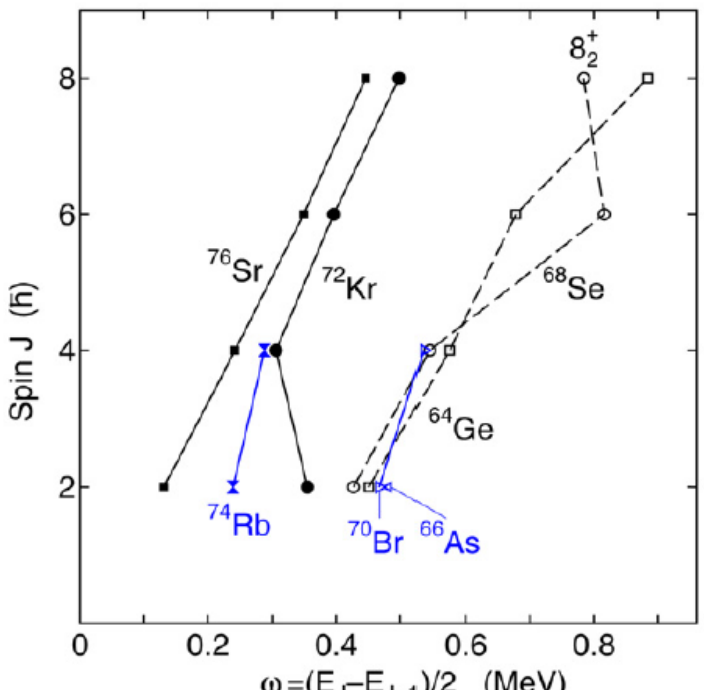
Phase transition in exotic nuclei along the $N = Z$ line

M. Hasegawa[a], K. Kaneko[b], T. Mizusaki[c], Y. Sun[d,e,*]

formation properly. Through analyzing the wave functions, we have concluded that the qualitative structure difference between the nuclei with $N = Z \leqslant 35$ and those with $N = Z \geqslant 36$ has the origin of the upper "gd" shell occupation. It has been discussed that the structure change is caused by a decisive breaking of the spherical shell model mean field and a formation of deformed mean field. In this sense, we have witnessed a basic mechanism of the phase transition to deformation in nuclei.



Important factors for a nuclear structure model calculation

- Single particle states (mean field part)
  - Reflect shell structure (spherical, deformed)
  - Adjust to experiment
- Two-body interactions (residual part)
  - Mix configurations (do not have in mean field models)
  - Transition probabilities are sensitive test
- Model space (configurations)
  - Large enough to cover important parts of physics
  - If not possible, introduce effective parameters

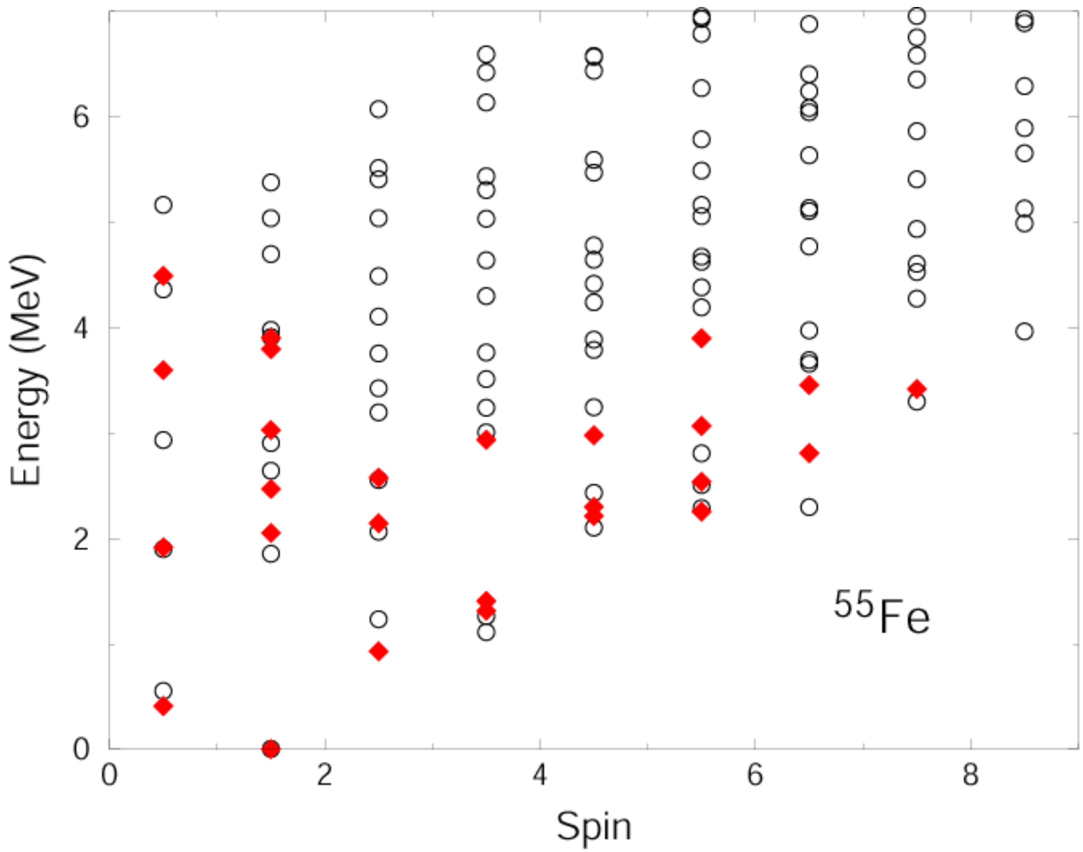
Ongoing projects

- Two shell model studies
  - Projected shell model (for well-deformed nuclei)
  - Large-scale spherical shell model (for near-spherical nuclei)

- Structures of neutron-rich nuclei
  - r-process interests
- Structures of proton-rich nuclei near the N=Z line
  - rp-process interests
- Structure of heavy, stable nuclei
  - s-process interests

Energy spectrum for ^{55}Fe: A projected shell model calculation

- Projected shell model calculation for ^{55}Fe energy levels



Spherical shell model with core-excitations

Large-scale shell model calculation with core excitations for neutron-rich nuclei beyond ^{132}Sn

Hua Jin (金华)[1,2], Munetake Hasegawa (长谷川宗武)[1,3], Shigeru Tazaki (田崎茂)[4], Kazunari Kaneko (金子和也)[5], Yang Sun (孙扬)[1,3,6*]

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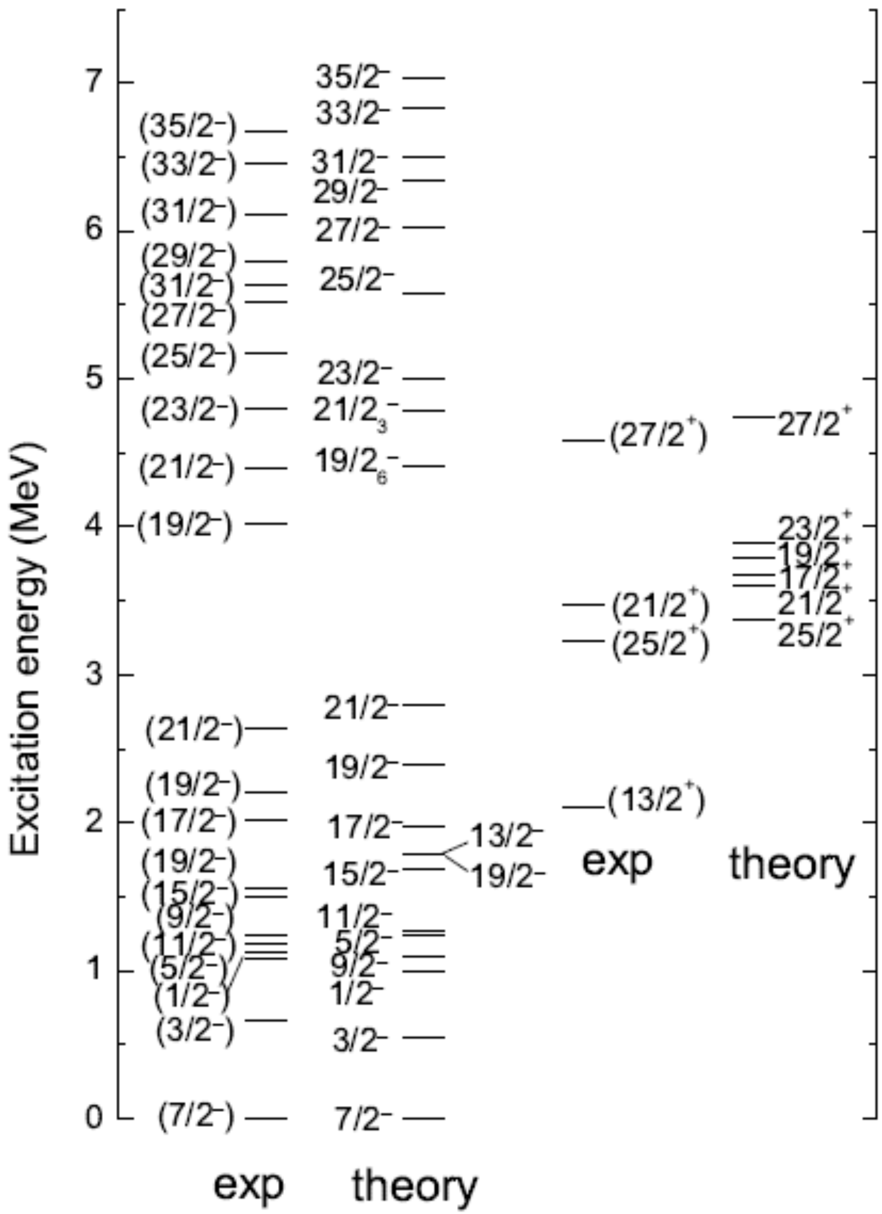
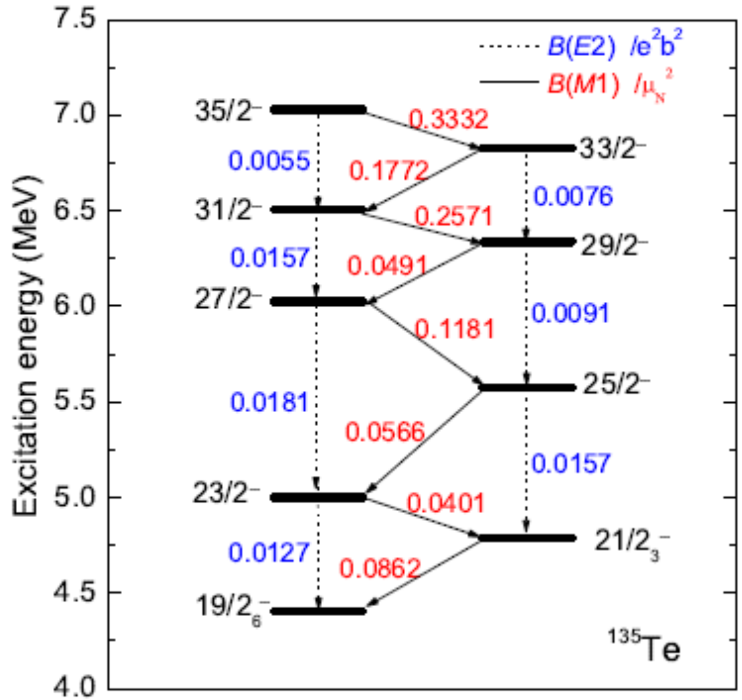
[6]*Department of Physics and Astronomy, University of Tennessee, Knoxville, Tennessee 37996, USA*

- Magic nature of ^{132}Sn has recently been confirmed by Jones et al. Nature 465 (2010) 454.
- Spectroscopy of valence nuclei with one particle in empty shells or one hole in completely filled shells provides direct information on single-particle structure.
- Spectroscopy of nuclei with two particles or two holes provides information on correlations between different kinds of pairs.

^{135}Te



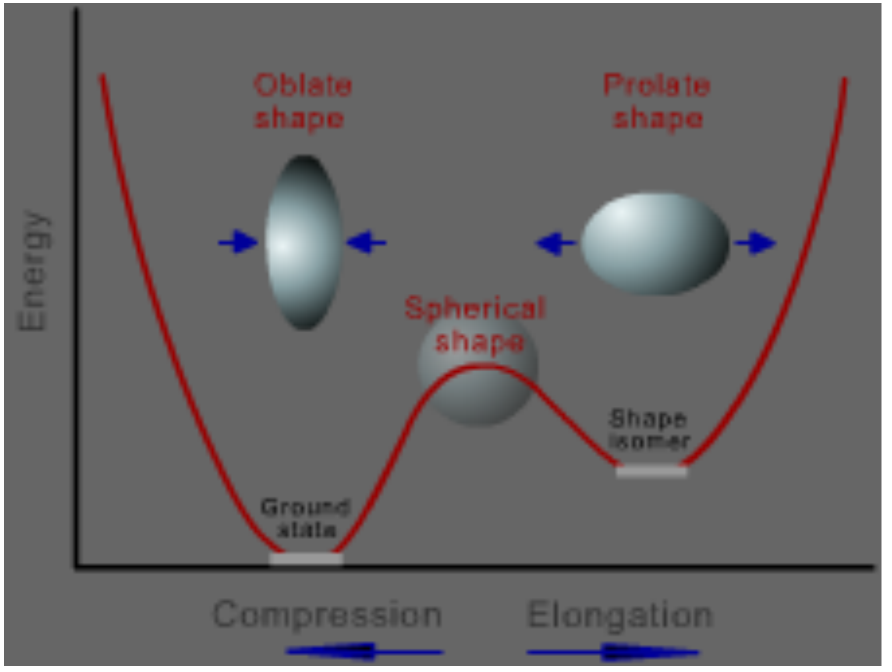


Shell model calculation considering particle-hole excitations show features supporting magnetic rotation bands.

Question of shape effect

In some nuclei, different shapes are known to co-exist near ground state.

Nuclear shape coexistence leads to shape isomeric states (excited states having relatively long lifetimes).

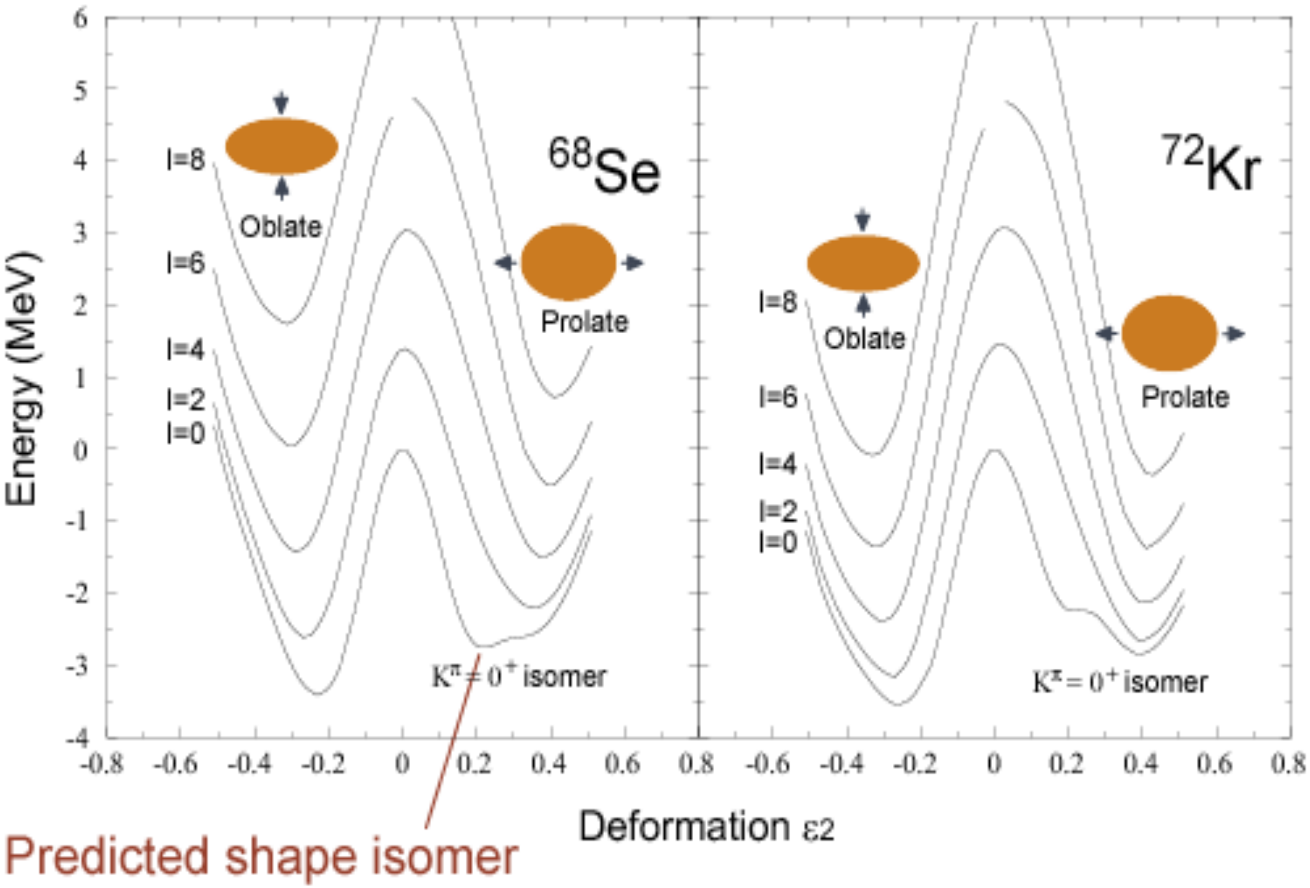


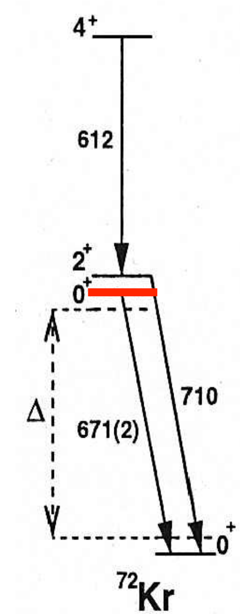
Nuclear isomers

- Bethe (1956): “An excited nuclear state which endures long enough to have a directly measurable lifetime is called an isomeric state.”
- Isomeric states occur because, to match the states to which it decays, it is difficult for a nucleus
  - to change its shape (shape isomer)
  - to change its spin (spin trap isomer)
  - to change its spin orientation relative to an axis of symmetry (*K*-isomer)

  Walker and Dracoulis, Nature 399 (1999) 35
- These states may behave like new nuclei in the reaction network.

Energies levels of ^{68}Se and ^{72}Kr

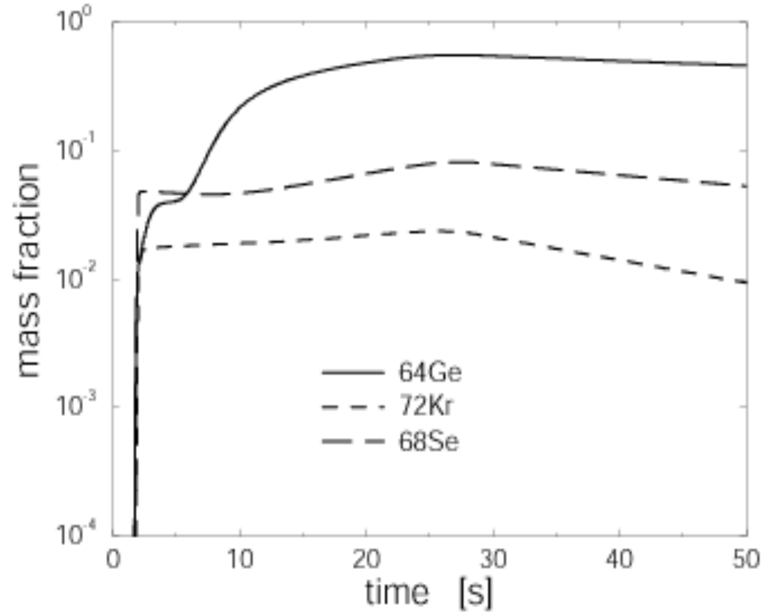




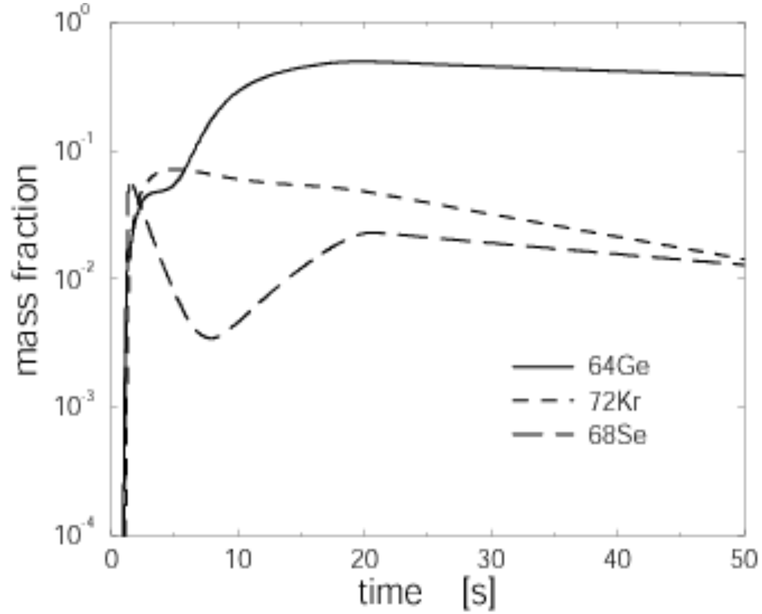
Bouchez *et al*, PRL (2003)

Isomer influence on abundances in X-ray burst

- It is possible that a flow towards higher mass through the isomer branch can occur (calculations using multi-mass-zone x-ray burst model)
  - Y. Sun, J. Fisker, M. Wiescher, *et al*., Nucl. Phys. A758 (2005) 765



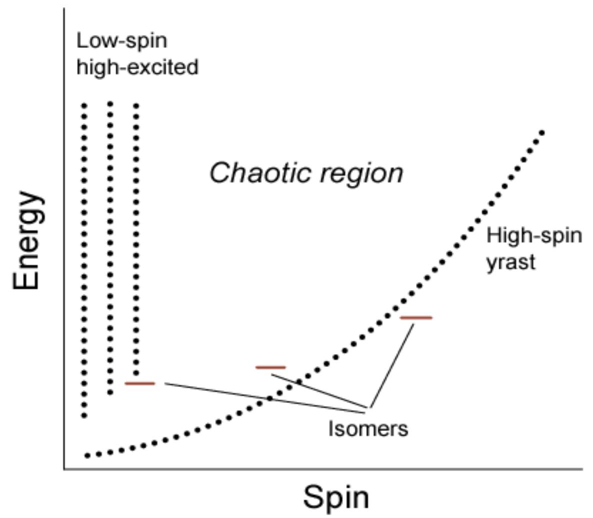
Without any possible isomer contribution



Full flow through isomers rather than g.s.

β-decay & electron-capture in stars

- Stellar weak-interaction rates are important for resolving astrophysical problems
  - for nucleosynthesis calculations
  - for core collapse supernova modeling
- Calculation of transition matrix element
  - essentially a nuclear structure problem
  - necessary to connect thermally excited parent states with many daughter states
  - for both allowed and forbidden GT transitions



Stellar enhancement of decay rate

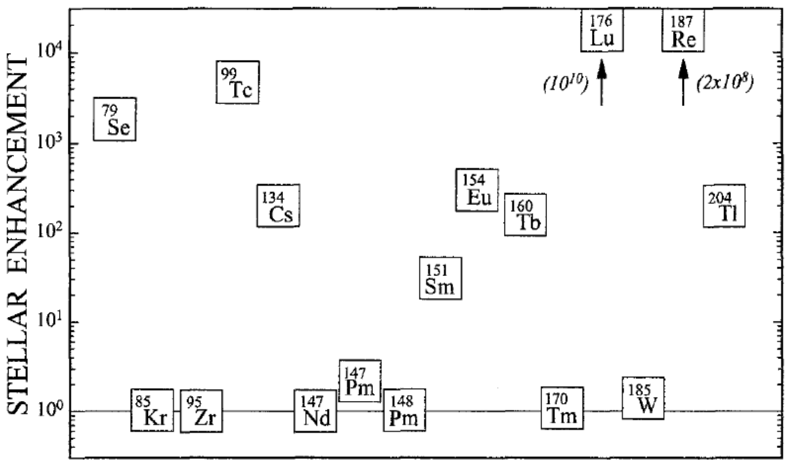
- A stellar enhancement can result from the thermal population of excited states

$$\lambda_\beta = \sum_i \left(p_i \times \sum_j \lambda_{\beta ij} \right)$$

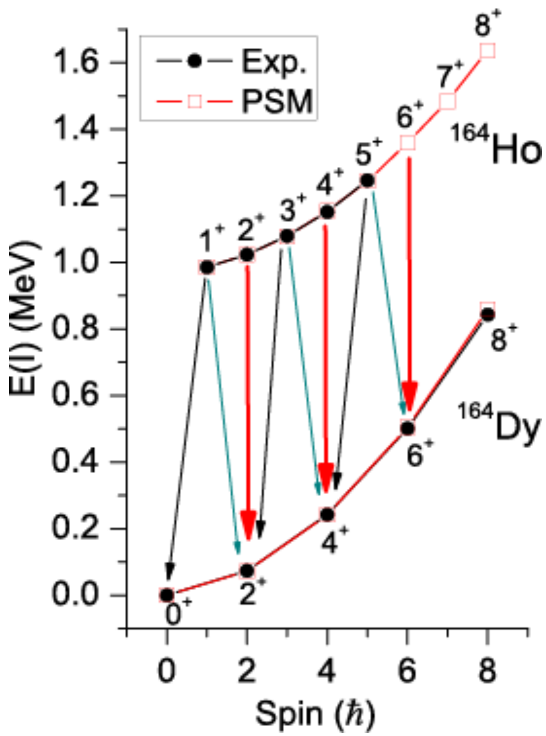
$$p_i = \frac{(2I_i + 1) \times \exp(-E_i / kT)}{\sum_m (2I_m + 1) \times \exp(-E_m / kT)}$$

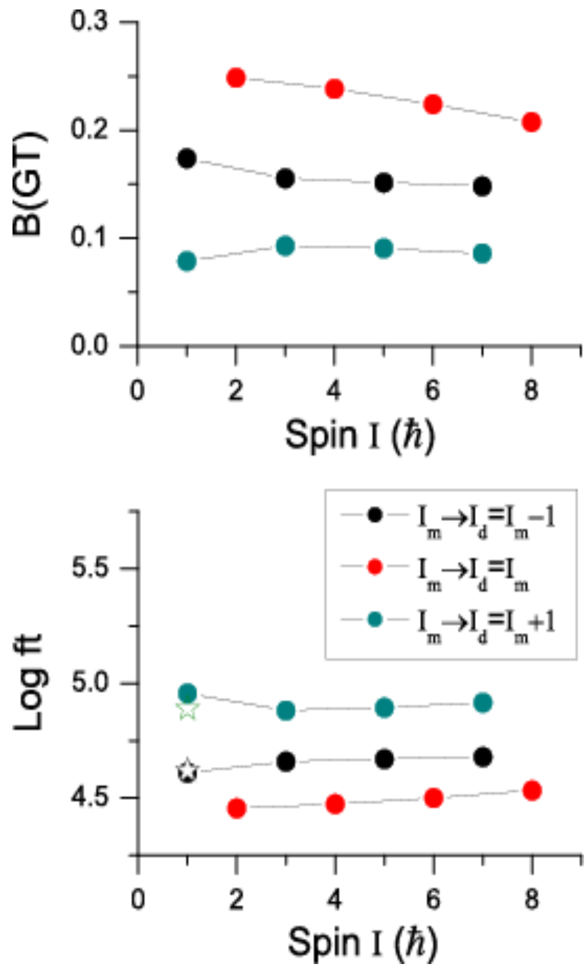
- Examples in the s-process

F. Kaeppeler,
Prog. Part. Nucl. Phys. 43 (1999) 419



B(GT) and log*ft* in ^{164}Ho → ^{164}Dy





Z.-C. Gao, Y. Sun, Y.-S. Chen, PRC 74 (2006) 054303

Nuclear matrix elements (future)

- To calculate quantities relevant to reactions, realistic many-body wave functions are needed.

  $$\langle\ A+1, I' \mid a^{+} \mid A, I\ \rangle, \qquad \langle\ A+2, I' \mid a^{+}\, a^{+} \mid A, I\ \rangle$$

- Preferably the wave functions are eigenstates of angular momentum and particle number, contain sufficient structure information in initial and final states.
- To perform shell model calculations and obtain the wave functions, one needs good
  - single-particle states
  - effective interactions
  - algorithms to construct shell model configurations

Summary

- Tiny nuclear structure changes may influence nucleosynthesis results
  - Example in nuclear mass calculations
  - Example with nuclear shape isomer
- Reliable shell model calculations for decay and nucleon-capture rates are needed
  - Workable models for any size of nuclei, deformed or spherical
  - Spectrum description is a crucial test for those models
- Particular nuclear structure changes may be more interesting
  - Deformation effect
  - Sudden changes in shell structure
  - Nuclear isomers