

Opportunities for low energy nuclear physics  
with rare isotope beam

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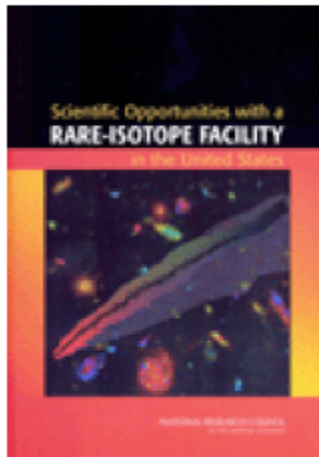
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**APCTP**

## Cotents

- Necessity for RIB
- Goals and topics
- Nuclear structure
- Astrophysics
- Fundamental symmetry and new physics
- Hadronic parity violation
- Summary

Based on...



**Scientific Opportunities with a Rare-Isotope Facility  
in the United States**

Rare Isotope Science Assessment Committee, National  
Research Council

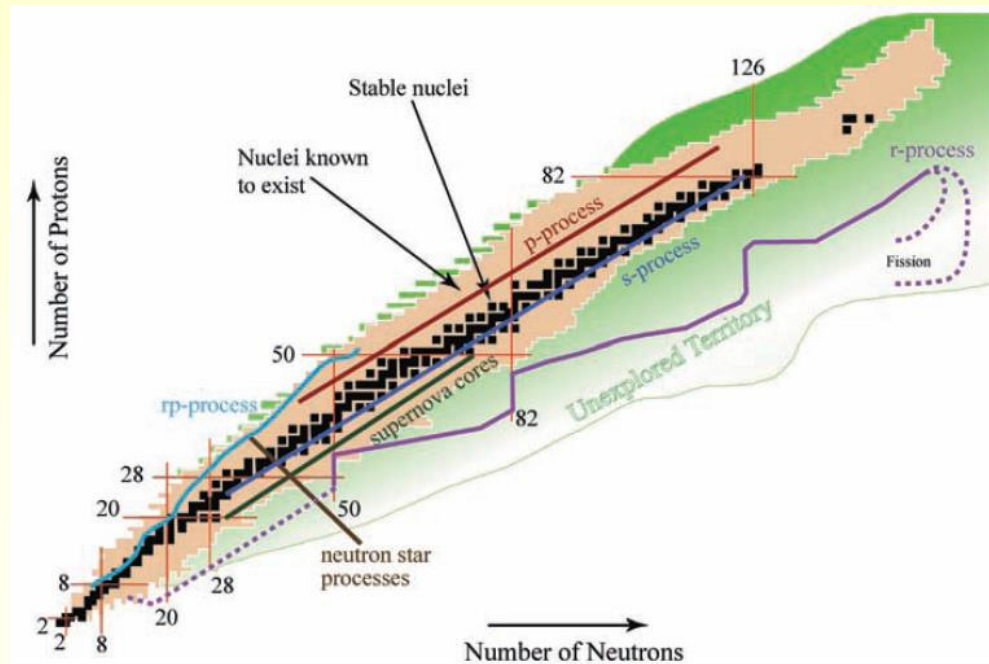
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## Necessity for RIB

- Well-known stable nuclei : ~ 300
- Total number of known : ~ 3,000



- Nuclear structure model : Fitted to stable nuclei
  - Unstable nuclei so far : Extrapolation of the models for nuclear interactions and structure
  - Direct information needs production of unstable nuclei and measurements of various phenomena
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- Explore a new science
  - Challenge for new technologies
  - Applications to other sciences

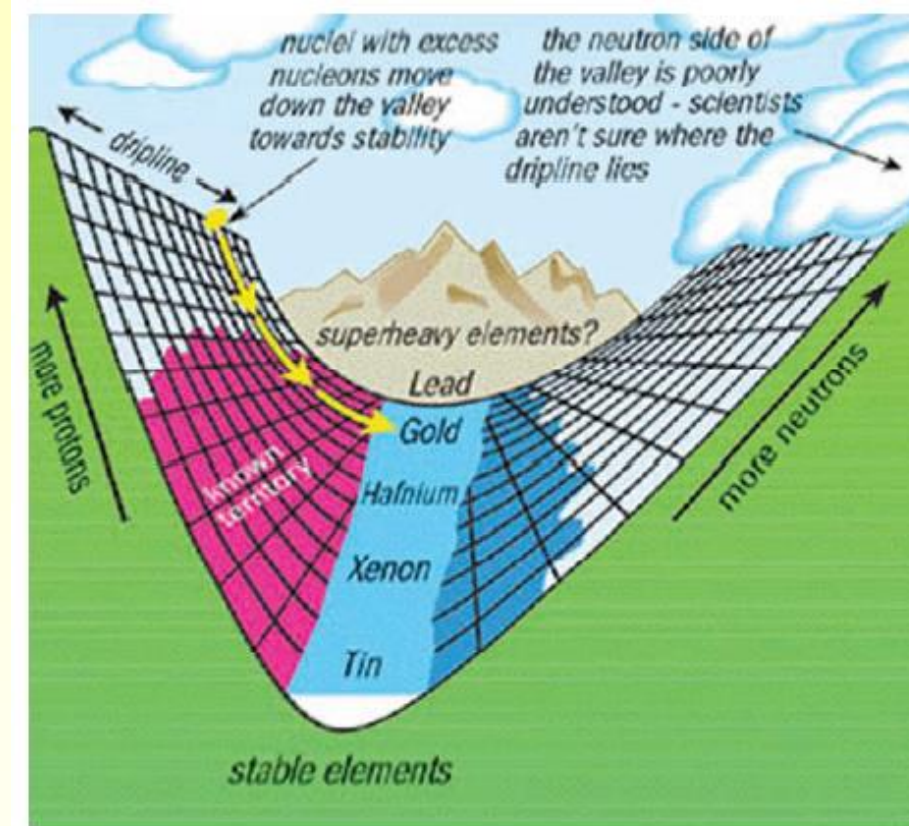
## Goals and topics

- Test the standard nuclear models : Verification and update of existing phenomenology
- Precise astrophysics : Provide realistic nuclear inputs to the processes in the various stellar environment
- Search for new physics and test of the standard model : Assumptions and predictions of the standard model

## Nuclear structure

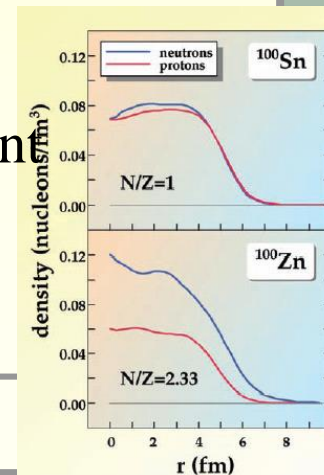
- Many tools for describing nuclei : Models constructed to explain observations
- How to justify the extrapolation to RI? : New theoretical methods (effective field theory, lattice QCD, advance of supercomputing...)
- RIB will provide data in entirely new mass regions to test traditional and new models and methods

## Easy access to neutron-rich nuclides





- Test the nuclear structure concepts
  - Probing the disappearance of shell structure : If exists, requires modification of mean field description of stable nuclei
  - Pairing and superfluidity : structure and the cooling of the neutron star
- Probing neutron skin
  - Nuclei with large neutron excesses : neutrons occupy weakly bound levels
  - Possible to model the exotic neutron-rich environment of the neutron star



- Probe the nuclear interaction model
- Building block : nucleon
- Building principle : NN interaction
- Modern NN interaction potential : fitted to  $\sim 4,300$  pp and np scattering data,  $\chi^2 \sim 1$
- What about nn interaction? : indirect way
- Isospin symmetry
  - $a_{np} \sim -23$  fm,  $a_{pp} \sim -17$  fm
- Neutron-rich nuclei will provide more direct information about nn interaction

- Creation of super-heavy elements
  - Koreanium?
  - Simulate infinite nuclear matter : get close to neutron star environment
  - Interest in longer-lived elements from the chemistry and atomic physics : highly relativistic inner electrons will affect the density distribution

## Nuclear astrophysics

- Determine the abundances of the elements and isotopes produced in stars and stellar explosion
- Understand energy creation and release mechanism in stellar environment
- Behavior of matter at extremes of neutron excess found in neutron star

- How were the elements from Carbon to Uranium created?
- Understanding the origin of the elements is mastery of the nucleosynthesis processes within different families of stars
- Elements found on earth : only a small fraction of the elements produced transiently along the reaction chain (unstable elements are bridge to stable elements)
- Iron in our blood : made in supernovae as radioactive  $^{56}\text{Ni}$

- How is the energy generated in stars and stellar explosion?
- Explosive stellar events : produce unstable nuclei
- Modern supernovae simulation : synthesis with 1,500 isotopes coupled about 15,000 possible reaction mechanisms
- More inputs necessary for complete understanding
- RIB : nucleosynthesis of heavy elements by r-, gamma- and rp-processes

- How would RIB help improve understanding of neutron star structure, supernovae and gamma-ray bursts?
  - Mean density of the neutron star  $\sim 3\rho_{\text{nm}}$
  - A few meters depth : sea of nucleon and electron  $\rightarrow$  negligible contribution to mass
  - Outer most crust : We get all the information from the outer crust
  - Far neutron-rich nuclei : important to probing the thermal and electromagnetic characteristic of matter at extreme density
  - Little experimental confirmation of the physics inputs in the models for outer crust

## Exotic Beams: An Urgent Need of the Nuclear Astrophysics Community

The key feature of an exotic-beam accelerator facility (such as a FRIB) for applications in nuclear astrophysics is its ability to produce high fluxes of unstable nuclei across a broad range of masses and particle-separation energies—it is the general-purpose nature of the facility that becomes its primary asset for nuclear astrophysics (see Box 2.3). Ultimately, one wants to understand the origin of *all* nuclei and then to use that understanding to diagnose stellar explosions and the chemical evolution of galaxies of all sorts. That is, in order to get leverage on the specific problem, scientists need first to sample and then understand the general case. Scientists have worked toward that goal for at least 50 years and have made some progress.



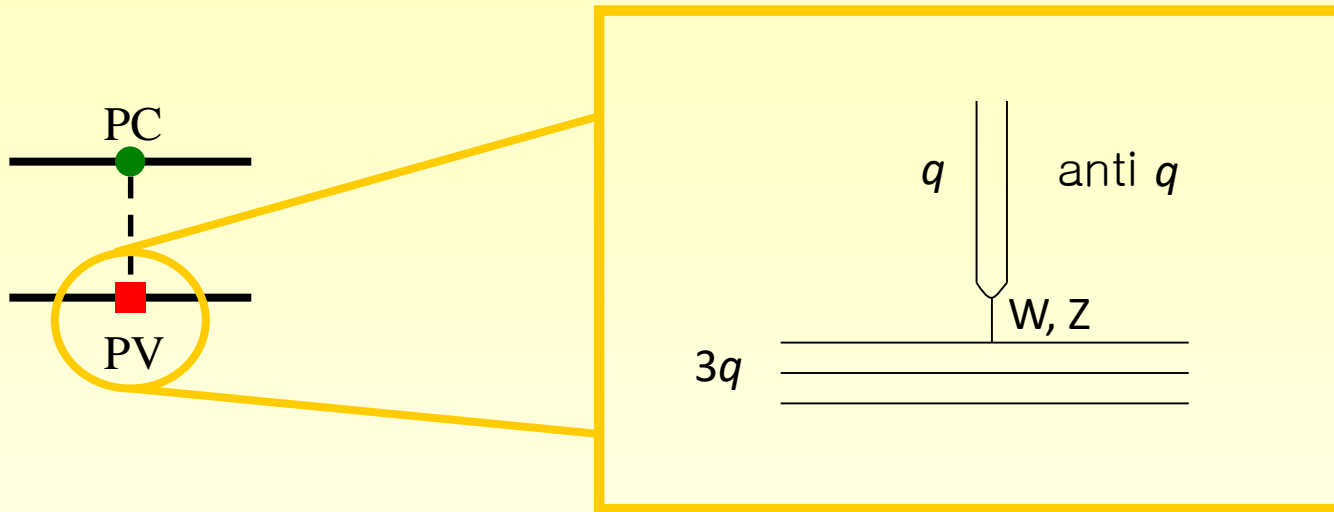
## Fundamental symmetries

- Many features of fundamental interactions discovered in nuclear physics experiments
  - Existence of the neutrino : nuclear beta decay
  - First observation of parity violation :  $^{60}\text{Co}$
  - First direct detection of the neutrino
  - vector/axial-vector structure of the weak interaction
  - Limit of the neutrino mass
  - Neutrino flavor mixing

- Matter-antimatter asymmetry in the universe
  - T or (CP) violation
  - Search for permanent electric dipole moment
  - Standard model : predicts negligibly small EDM
  - Most extensions of the Standard model generate much larger EDM
  - Existing EDM experiments : close the limits
  - Nuclei with enhanced CP violation effect :  $^{229}\text{Pa}$ ,  $^{223}\text{Ra}$ ,  
 $^{225}\text{Ra}$ ,  $^{223}\text{Rn}$

- Parity violating nuclear interaction
  - Weak interaction at hadron and nuclear level
  - 50 years after first observed, little progress yet
  - Anapole moment : spin distribution due to the PV interaction  $\sim A^{2/3}$  (A : mass number)
  - Only one measurement :  $^{133}\text{Cs} \rightarrow$  Inconsistent with theory or other PV experiments

## Hadronic parity violation



- Interaction type? : Meson exchange picture, spin, isospin structure, ...
- Weak meson-nucleon coupling constants? :  $\sim 10^{-8}$  of strong coupling, precise value, ...

■ Experiments

- 1972, Novosibirsk : PV polarization in  $np \rightarrow d\gamma$   
Inconsistent with PV potential at the time
- 1988, ILL : PV asymmetry in polarize  $np \rightarrow d\gamma$  Result  
 $= -(1.5 \pm 4.8) 10^{-8}$
- 2000 ~ 2007, LANL : Same as ILL, precision goal at  $10^{-8}$ ,  
Insufficient neutron flux
- 2007 ~ , SNS : Moving from LANL, on-going
- $d\gamma \rightarrow np$  : SPring-8, BES
- $nd \rightarrow t\gamma$  : TUNL, NIST (at SNS?)

■ Theory

- One  $\pi$ ,  $\rho$ ,  $\omega$  potential (DDH potential) : benchmark, 7 weak coupling constants
- Effective field theoretic derivation of the PV interaction (Zhu et al., 2005) : Pionful and pionless theories
- Calculate the observables with PV interactions  $\rightarrow$  obtain observables in terms of PV coupling constants : Compare with experiments
- Make use of ample versions of EFT : verify theory in terms of theory

## Summary

- Improve the existing theories and models
- Gateway to new physics
- Strong correlation with astrophysics
- Not so expensive (Gwa Cheon science museum ~ 450 billion Won)