3rd DITANET School on Beam diagnostics

Diagnostics for exotic beams

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Diagnostics for exotic beams

Exotic beams and how they are produces
Motivation (review of nuclear physics)
Information of interest
Specific problems
Methods and Solutions

Exotic beams and how are they produced

We determine between two kinds of exotic or radioactive ion Beams (RIB) according to the way they are produced:

- **In-flight production using a thin target**

  High energy heavy ion beam passing through a thin target leads to fragmentation of primary beam particles

- **Isotope-Separation On-Line (ISOL) using a thick target**

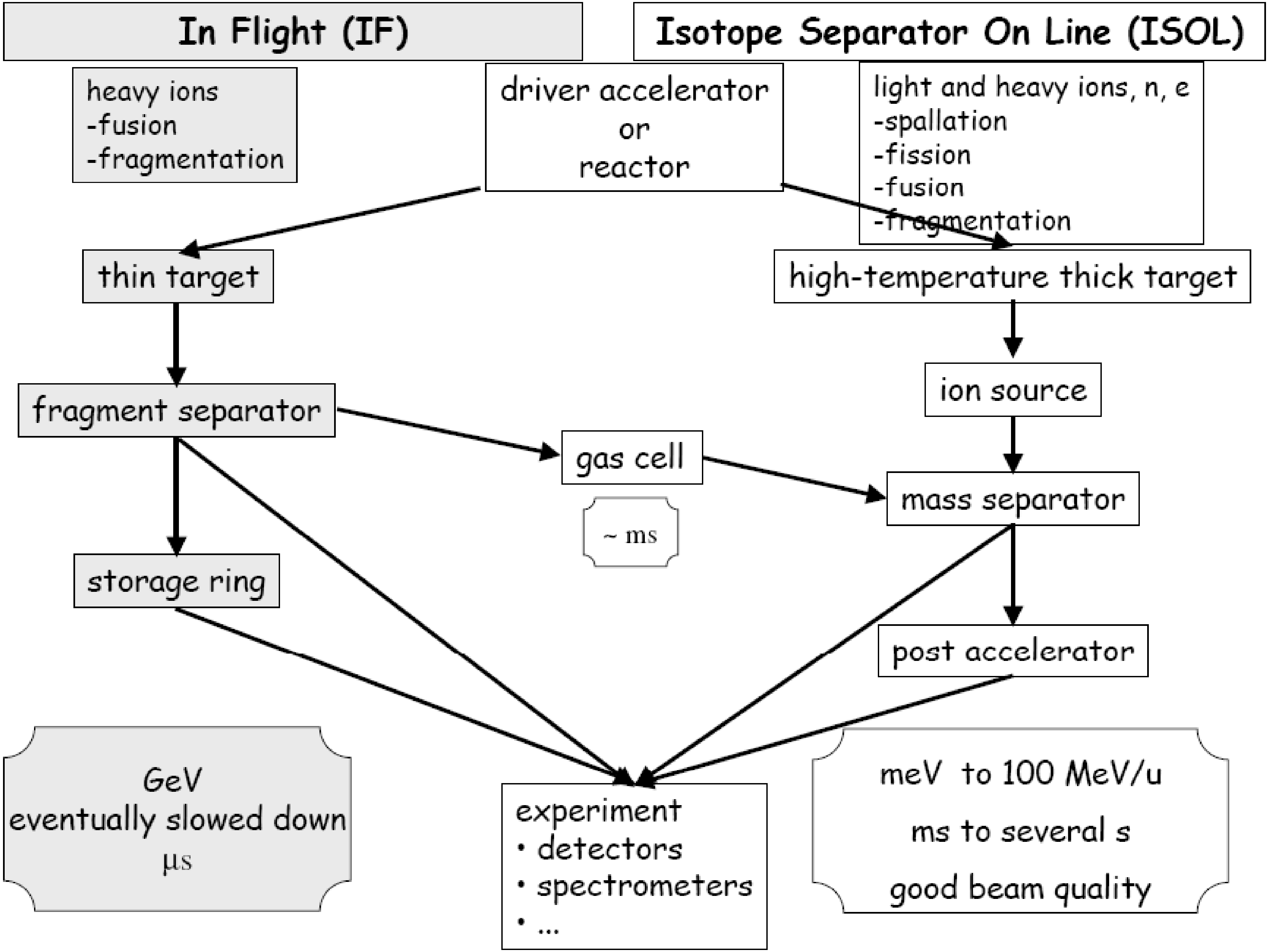
  When radioactive species are produced in a thick target, they must be extracted, ionized, separated, identified and finally accelerated. This requires a radioactive ion source, a mass separator and a post accelerator

In-flight production

- Fragmentation or fission of energetic heavy ion projectiles
- Fragments have nearly the same speed as incident ions
- Kinematically focused within a small forward angle
- Requires high projectile energy > 30 MeV/A up to some GeV/A for projectile-fission reaction (Uranium beam)
- Directly used as a RIB (after a fragment separator)
- Allows to study isotopes having half-lives down to ms or less
- No chemistry involved

On-line production (ISOL)

- Stopping the primary beam in the target
- Commonly used primary beams:
  - High energy protons
  - Medium energy heavy ions
  - Thermal neutrons (from a nuclear reactor)
- Reactions that occur in the target:
  - Projectile or target fragmentation
  - Fusion-evaporation
  - Fission
  - Spallation
- The exotic species must be extracted from the (hot) target, ionised and accelerated to give a RIB (keV up to MeV/A)
- Allows to study isotopes have half-lives down to tens of ms
- Evaporation process is sensitive to the chemical interaction between the exotic atom and the target


In Flight (IF)
Isotope Separator On Line (ISOL)
heavy ions
-fusion
-fragmentation
driver accelerator
or
reactor
light and heavy ions, n, e
-spallation
-fission
-fusion
-fragmentation
thin target
high-temperature thick target
ion source
fragment separator
gas cell
~ ms
mass separator
storage ring
post accelerator
GeV
eventually slowed down
μs
experiment
• detectors
• spectrometers
• ...
meV to 100 MeV/u
ms to several s
good beam quality

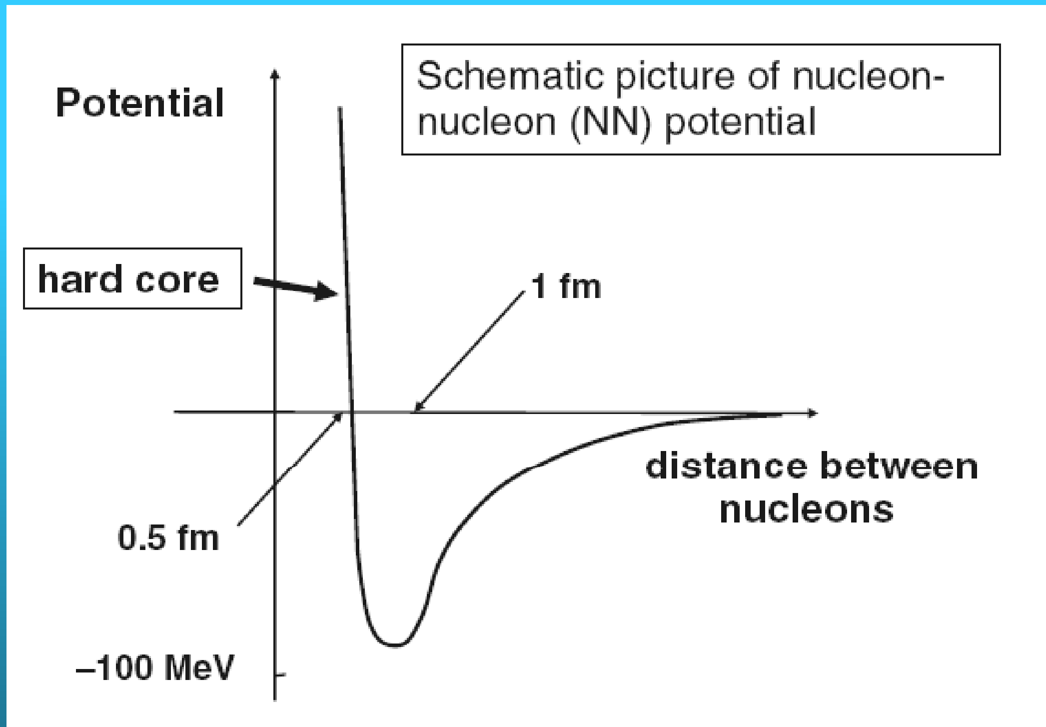
Motivation (review of nuclear physics)

Atomic Nuclei are quantum systems with finite numbers of strongly interacting fermions of two kinds (p and n)

•The strong interaction cannot be treated in a perturbative way

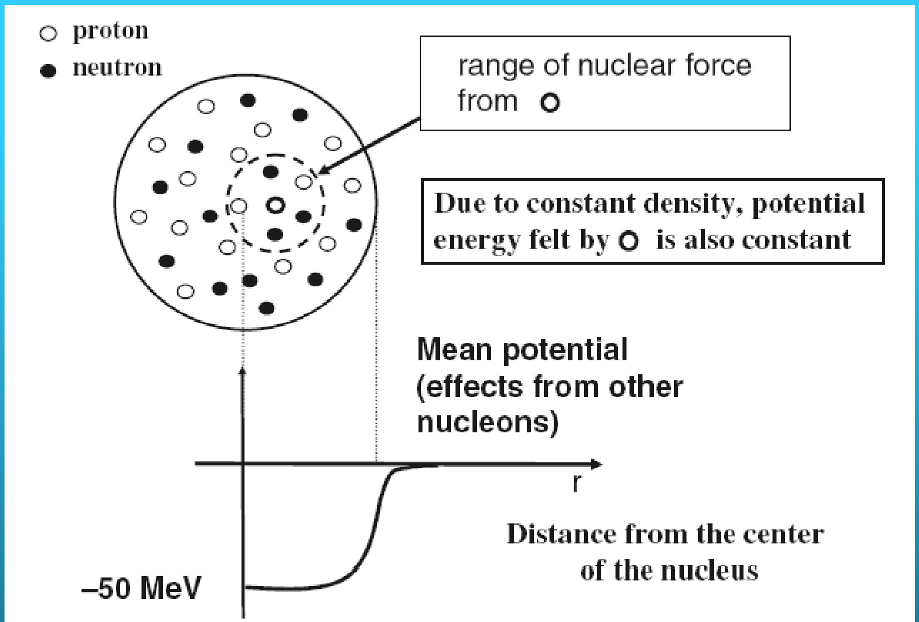
•The number of nuclei is to small for statistical methods

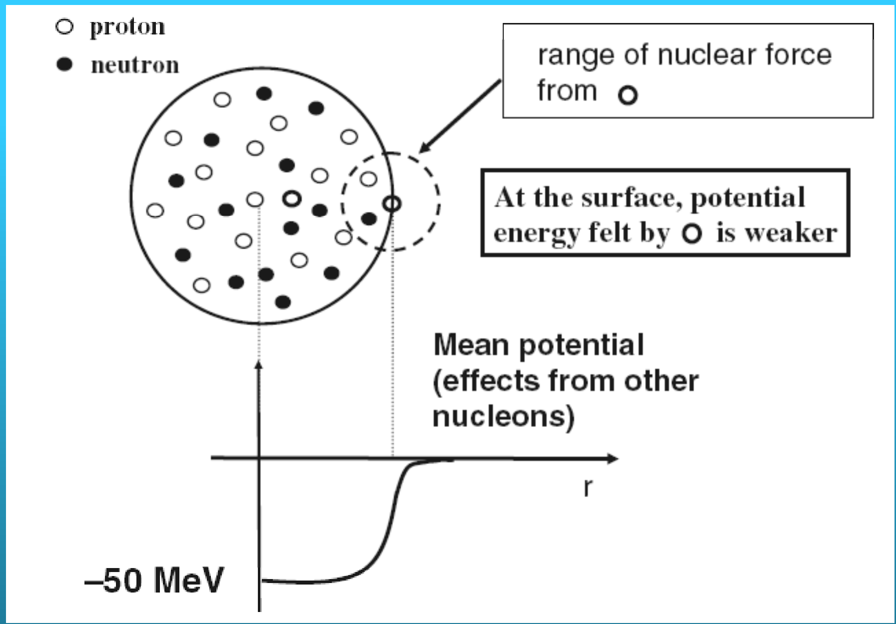
Starting form the bare nucleon-nucleon interaction, light nuclei (up to mass 10) can be described.



Motivation (review of nuclear physics)

In heavier nuclei the interaction between the nucleons are modified by the environment (other nuclei) they occur. The nucleon–nucleon interaction is very complicated, but can produce a simple mean potential. Nuclear mean fields can be generated in a self-consistent way by using effective two-body nucleon-nucleon forces.





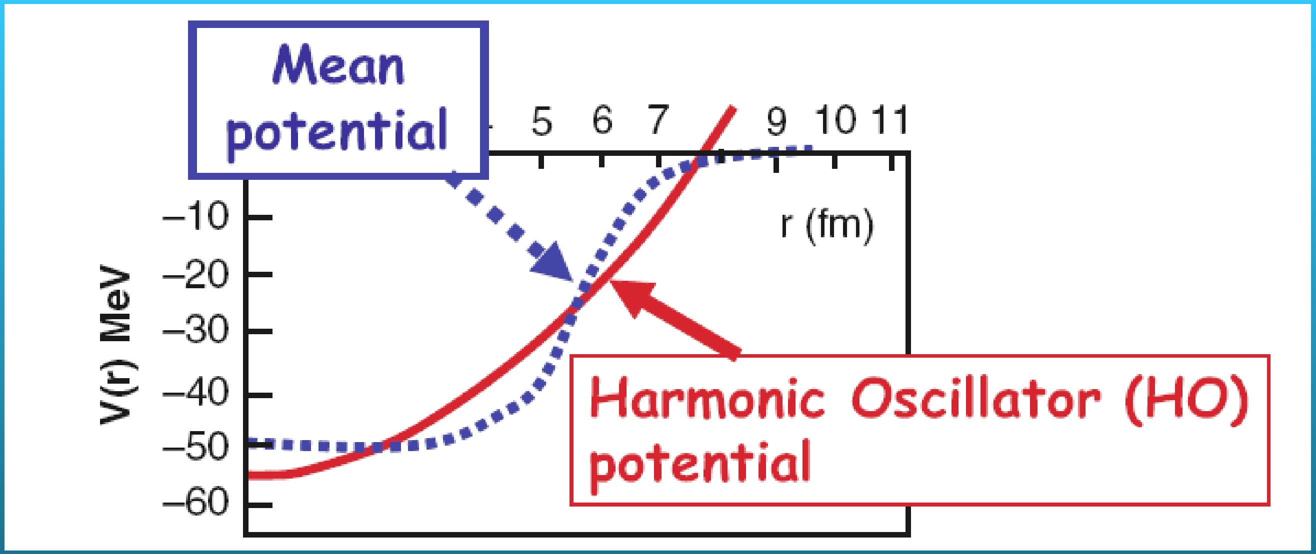
Motivation (review of nuclear physics)

The mean potential can be described, to a good approximation, in terms of the so-called Woods–Saxon (WS) potential. This is specified by three parameters: depth, radius, and diffuseness.

The eigenstates of the WS potential can be obtained only numerically. In order to make physics more transparent, a harmonic oscillator (HO) potential can be introduced

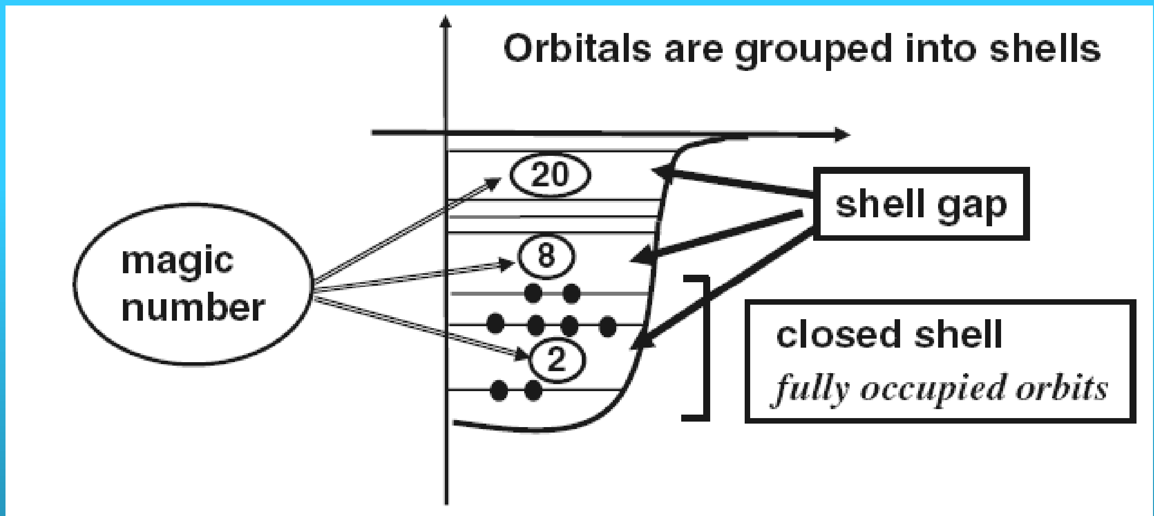
$$V_{HO} = m\omega^2 r^2/2 \ , \ (1)$$

where *m is the mass of the nucleon, ω is the oscillator frequency, and r stands* for the distance from the center of the nucleus.



Motivation (review of nuclear physics)

The nuclear shell model divides the nucleus into in inert core (closed shell) and a number of valence nucleons described as single-particle motion in the mean potential. This single-particle motion inside this potential can be solved. This is just an eigenvalue problem with the eigenstates corresponding to various orbital motions similar to electrons in a hydrogen-like atom. The eigenstate is referred to as an orbit.



The *horizontal lines indicate* single-particle energies (SPE's), which stand for energy eigenvalues of the orbits. The orbits form shells, and gaps between shells define magic numbers

Motivation (review of nuclear physics)

New techniques and increased computer power led to the description of medium heavy nuclei and also to the successful reproduction of collective effects in a number of nuclei. Although important progress has been made a number of crucial questions remain:

- **What are the limits for the existence of nuclei?**
- **How does the nuclear force depend on the proton-to-neutron ratio?**
- **How can collective phenomena be explained from individual motion?**
- **How to explain complex nuclei on the basis of simple building blocks?**

Most of the present-day knowledge of the structure of the atomic nucleus is based on the properties of nuclei close to the line of *β-stability where* the proton-to-neutron ratio is not so different to that of stable nuclei. But extrapolating this to the region far from stability is quite dangerous and already it is now clear that some of the 'basic truths' of nuclear physics have to be revisited.

Motivation (review of nuclear physics)

Important discoveries

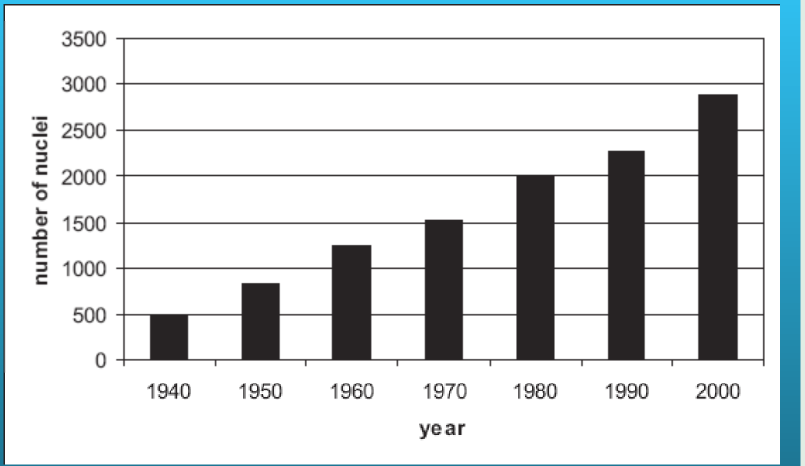
The high decay energy of exotic nuclei is opening up many decay channels and **new decay modes** (e.g.: beta-delayed particle emission)

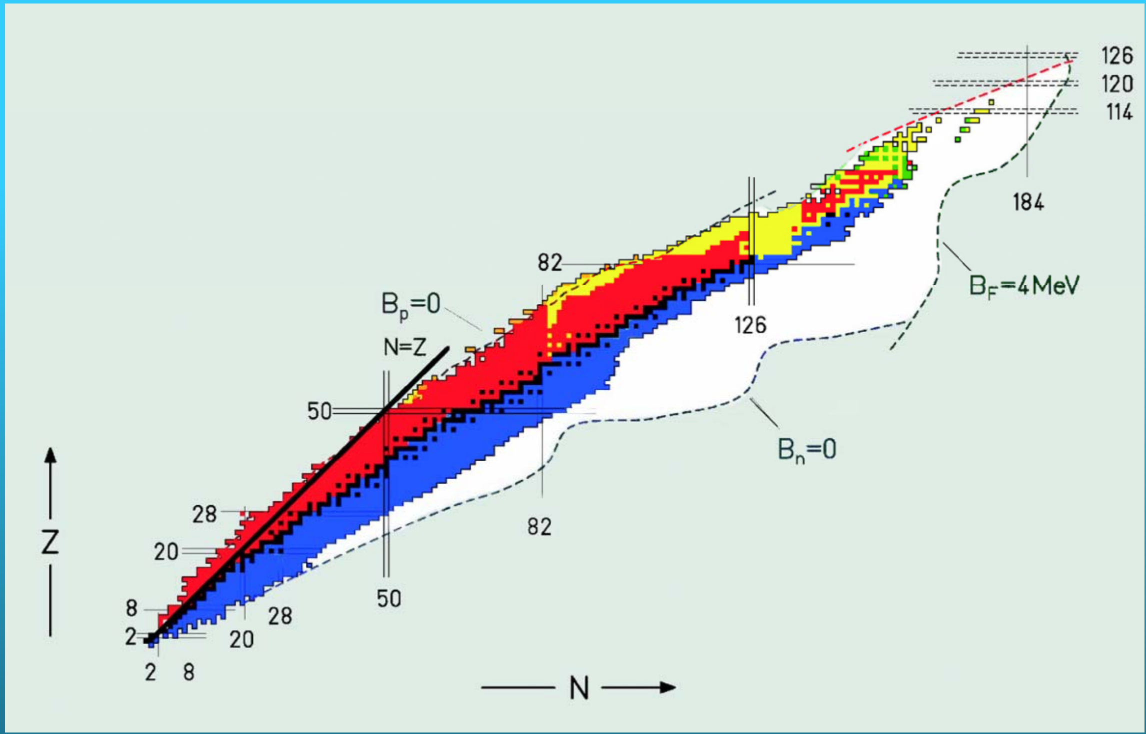
Groundstate properties:

- Proof of existence (or nonexistence)
- Half life, decay mode(s), Mass
- Spin and moments

Structural benchmarks:

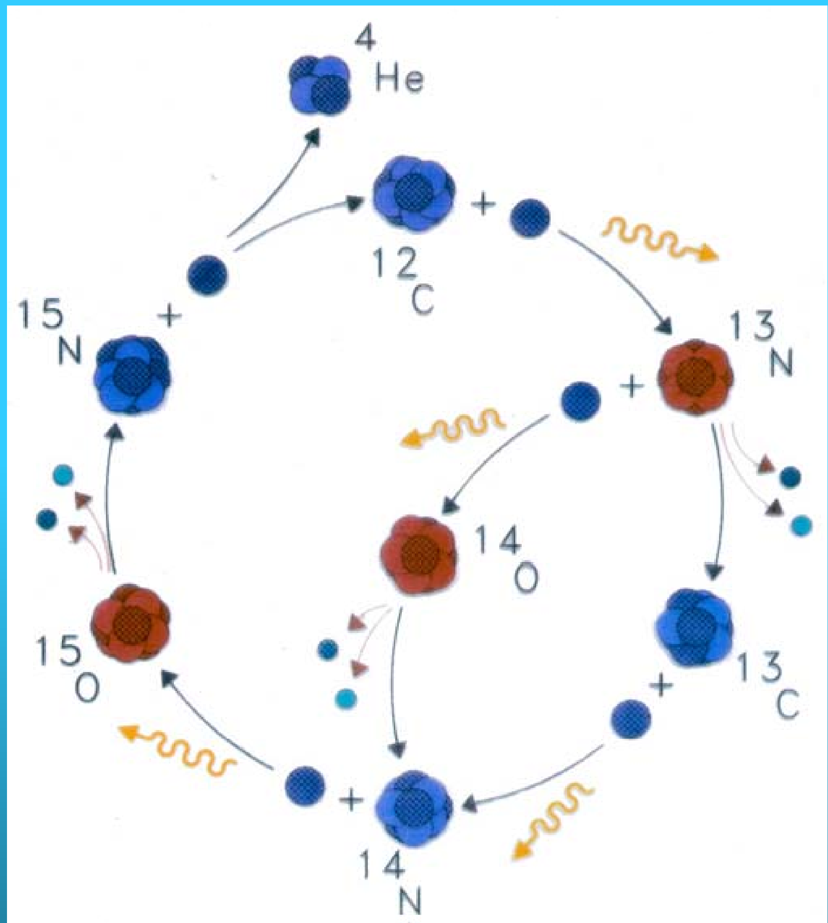
- Symmetry
- Transition and evolution





Motivation (review of nuclear physics)

Nuclear Astrophysics / Nucleosynthesis:
e.g.: CNO-cycle and hot CNO-cycle



Information of interest

Composition of the ion beam (maybe) unknown

Determination of the ions is necessary

What ions are produced (Isotope, Isomer)

How many ions are available/produced

What is their distribution in abundance, energy and space

Information of interest

Information needed:

- Beam position
- Transversal Beam Profile
- Longitudinal Beam Profile
- Ion velocity
- Ion momentum
- charge state
- Ion mass(es)
- Beam intensity (for a specific, separated (selected) isotope)

With this information we can determine the composition of the resulting ion beam (secondary or radioactive ion beam) and use this for the analysis of the resulting signals from the (second) target/experiment.

Specific problems (thin target)

- Fragments are usually fully ionized leave the target with nearly the same speed as the ions of the incident beam.
- Thin target acts like a stripper for both Initial ions and RI
- For a given Z_{beam} fragments with Z<(=) Z_{beam} are produced
- Isotopic width of the fragments is proportinal to Z
- Production yield is strongly dependant on the energy of the incident ions: $Y \sim E^{7/2}$
- Separation of the initial beam from the secondary one
- Two-stage fragment separator is needed
- An energy degrader ($\sim A^3/Z^2$) may be needed between the two separators in order to separate elements having the same magnetic rigidity (-> angular straggling, energy dispersion)
- High energy spallation products must be decelerated for analysis or nuclear reactions in a second target

Specific problems (thick target)

Primary beam can be besides heavy ions also protons, deuterons or
neutrons from a reactor and the target yields are normally higher than
those obtained by the in-flight technique.

- Radioactive ion source
- Separation of the ions, Wien filter, Thompson spectrometer
  - Sipmle magnet (200-400)
  - FOR ISOBARS WE NEED 20000-4000
  - Wien filter (Z/A), Thompson spectrometer (up to 1000 or more)
  - LAMS (Bunched beam, drift, debunching, magentic separation; 2000)
  - Identification via characteristic gamma-ray
  - If gamma is ambiguous, a chopper can be used to measure half-lives
- Beam intensity remains very low, often too low for defining the

Specific problems (accelerator/target)

Beam intensity of the primary beam should be very high

- Beam loading effects (reduced beam quality)
- Retune of the accelerator due to heavy beam load leads to smaller transmission and or dislocation of the beam
- Beam power is very high (radioactivity is very high)
- For in-line production, the beam spot must be as small as possible to limit the increase in emmitance due to straggling
- Power density in the target is very high (rotating beam or target)
- Target thickness must be optimized according to the primary and in case of in flight production also the secondary beam characteristics

Methods and Solutions

The beam diagnostics must be able to perform measurement on nano

down to sub-picoampere beams.

- Energy and charge state
- Position measurement
- Longitudinal diagnostics
- Radial distribution
- Characteristic radiation to identify
- Ion counting for cross section measurement (Partical detection and identification)

Thank you

References (Pictures and graphics):

M. Huyse, The Why and How of Radioactive-Beam Research, Lect. Notes Phys. 651, 1–32 (2004)
Otsuka, T.: Shell Structure of Exotic Nuclei. Lect. Notes Phys. 764, 1–25 (2009)

General literature:

Handbook of accelerator physics and engineering
Alexander Wu Chao, Maury Tigner ; ISBN 9810235005 (1999-2006

Interesting links used for this lesson and for further details :

http://www.triumf.ca/research/research-topics/rare-isotope-beams
http://www.euroschoolonexoticbeams.be/site/pages/lecture_notes
http://pro.ganil-spiral2.eu/laboratory/ganil-accelerators/spiral/tis