Spallation, multifragmentation and radioactive beams

Introduction to Nuclear Science

Simon Fraser University
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Outline

1. Energy in nuclear reactions

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2. High energy reactions induced by light ions

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Projectile energy per nucleon

- When exploring the impact of energy on nuclear reaction mechanism the initial energy of the projectile is often quoted in MeV per nucleon rather than in MeV. Let us explore why.

- We will assume a non relativistic projectiles

$$\begin{aligned} K &= \frac{1}{2}mv^2 = \frac{1}{2}Auv^2 \\ \frac{K}{A} &= \frac{1}{2}\frac{mv^2}{A} = \frac{1}{2}\frac{Auv^2}{A} = \frac{1}{2}uv^2 = \frac{1}{2}uc^2\left(\frac{v}{c}\right)^2 = \frac{1}{2}uc^2\beta^2 \end{aligned} \quad (1)$$

- The square root of the energy per nucleon is the speed of the projectile

$$\beta = \sqrt{\frac{2K}{uc^2}} = \sqrt{\frac{K\ [\text{MeV}]}{465.8\ [\text{MeV}]}} \quad (2)$$

Energy in nuclear reactions

- Based on the projectile's energy per nucleon nuclear reactions can be classified as
  - low energy, with $K/A \sim 5$ [MeV] at few percent of the speed of light
  - intermediate energy, with $K/A \sim 50$ [MeV] at ∼20 percent of the speed of light
  - high energy, with $K/A \sim 500$ [MeV] at ∼90 percent of the speed of light.
- The low energy reactions are these happening near the Coulomb barrier, these the reactions we discussed so far.
- Note that the high energy reactions are relativistic, they happen at the kinetic energy per nucleon comparable to the mass of a nucleon.
- Note also that Eq. 2 does not hold for high energy reactions and should be replaced by the relativistic energy-momentum relation.

Impact of available energy on the reaction mechanism

- To recognize the impact of the energy available in the centre of mass on the reaction mechanism let us calculate the reduced deBroglie wavelength which correspond to that energy.
- Since we need order of magnitude estimate let us assume a very heavy target and a very light projectile. In such a case the centre of mass can be approximated with the centre of the target.
- Let us than calculate the reduced deBroglie wavelength for the $p +^{209} Bi$ reaction at the proton energy of 5, 50, and 500 MeV (which for the proton with $A = 1$ is also MeV/A).
- Since we are only interested in the order of magnitude we will do the calculations non-relativistically (and we will end up being off by a bit for 500 MeV)

deBroglie wavelength for $p +^{209} Bi$

- The reduced mass is

$$\mu = \frac{A_T A_P}{A_T + A_P} u = \frac{209 * 1}{210} u \approx u \quad (3)$$

- The reduced deBroglie wavelength is

$$\lambda\!\!\!^{-} = \frac{\hbar}{p} = \frac{\hbar}{\sqrt{2\mu K}} = \frac{\hbar c}{\sqrt{2uc^2 K}} = \frac{197.3}{\sqrt{2 * 931.5 * K}} \ [\text{fm}] \quad (4)$$

- Thus for the proton with A=1

$$\begin{aligned}
\frac{K}{A} = 5\ [\text{MeV/A}] &\implies \lambda\!\!\!^{-} = 2\ \ [\text{fm}] \implies \lambda \approx 13\ \ [\text{fm}] \\
\frac{K}{A} = 50\ [\text{MeV/A}] &\implies \lambda\!\!\!^{-} = 0.7\ \ [\text{fm}] \implies \lambda \approx 4\ \ [\text{fm}] \\
\frac{K}{A} = 500\ [\text{MeV/A}] &\implies \lambda\!\!\!^{-} = 0.2\ \ [\text{fm}] \implies \lambda \approx 1.3\ \ [\text{fm}]
\end{aligned} \quad (5)$$

Comparison to the target radius

- The radius of ^{209}Bi is

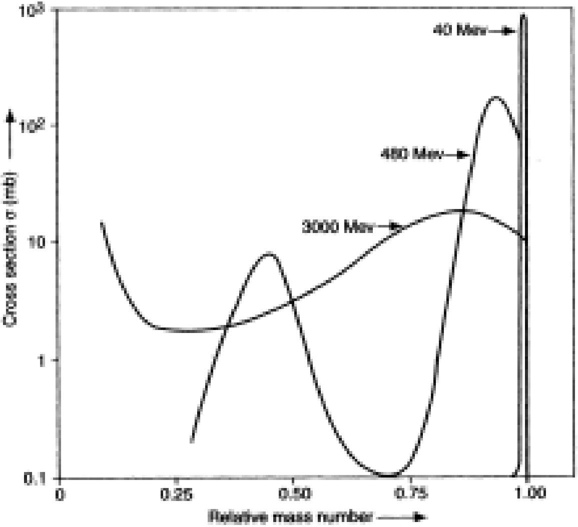
$$R_T = 1.2\sqrt[3]{209} = 1.2 * 5.9 = 7.1 \quad [\text{fm}] \tag{6}$$

- From the calculations on the previous slide
  - in low energy collisions a nucleon has a wavelength comparable to nuclear diameter
  - in intermediate energy collisions a nucleon has a wavelength comparable to nuclear radius
  - in high energy collisions a nucleon has a wavelength comparable to the radius of a nucleon.
- The above comparison is the key to the understating of high-energy reaction mechanism.

Why is the deBroglie wavelength significant?

- The deBroglie wavelength is a measure of the effective size of the projectile and its overlap with the target.
- In low energy collisions with the wavelength larger than the nuclear diameter the projectile interacts with the nucleus through the average nuclear force from all the nucleons within the nucleus.
- At intermediate energy the wavelength becomes smaller and the interactions is between the projectile and a subset of nucleons in the nucleus. Individual collisions between the nucleons of the projectile and nucleons of the target start to play a role.
- At high energies the size of the projectile is comparable to the size of a nucleon in the target and the reaction mechanism is dominated by individual nucleon-nucleon collisions between nucleons of the projectile and nucleons of the target.

Mass distribution in $p + {}^{209}Bi$ reaction at various energies

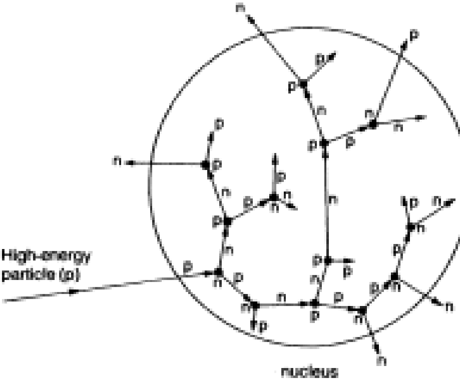


Mass distribution in $p + ^{209}Bi$ reaction at low energies

- At low energies the compound as well as direct reactions induced by light ions yield products which are closely concentrated around the target nucleus.

$p + {}^{209}Bi$ reaction at high energies

- At high energies a significant amount of energy is transferred into the nuclear system via a cascade of inter-nucleon collisions



Disintegration in light-ion high-energy reactions

- The inter-nucleon cascade transfer a significant energy into the nuclear volume
- The energy can be released in two ways leading to two distinctly different distribution of the reaction products.
- The excitation energy can be released by emission of a relatively small number of high-energy nucleons which leads to the reaction products which are target-like.
- The excitation energy can be released by splitting of the nucleus into two fragments of similar mass leading to the reaction products which are fission-like.
- Fission-like products are excited and may emit nucleons before reaching the ground state.

$p +^{209} Bi$ reaction at high energies

- Target-like and fission-like fragments from $p +^{209} Bi$ reaction at 480 MeV.

Spallation reaction

- At ultra-high proton energies of $\sim$3000 MeV the reaction mechanism changes.
- This can be seen from the fragment mass distribution which does not show the peak for fission-like fragments observed at lower energies.
- The fragment mass distribution is continuous, fairly uniform and shows an increase with decreasing mass indicating the presence of intermediate mass fragments.
- The reaction mechanism at these energies is called spallation.

$p +^{209} Bi$ spallation

- Fragment mass distribution and the enhancement of intermediate mass fragments in proton spallation $p +^{209} Bi$ reaction at 3000 MeV.

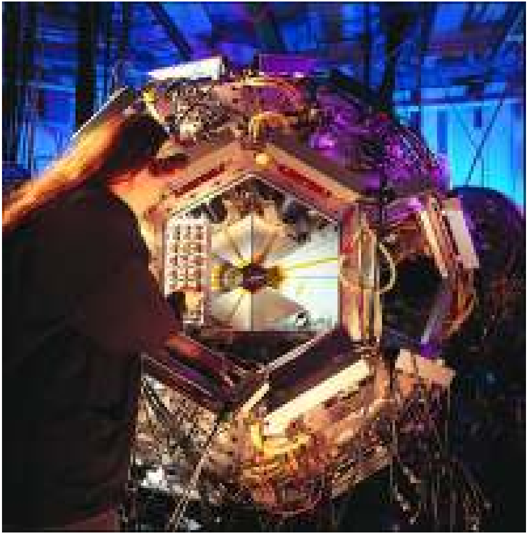
Multi-fragmentation

- The production of intermediate mass fragments prompted the development of a scenario for nuclear disintegration at ultra high energy in analogy to liquid-gas phase transition.
- If the collision is central (small impact parameter) the amount of energy transferred to the system is high enough to fully disintegrate it.
- This energy is transferred to the nucleus in a very short time and it is analogues to overheating a liquid droplet in a very short time.
- An overheated liquid droplet would vapourize and the vapours when cooled can condense again into smaller droplets.
- In analogy, the nucleus vapourizes, cools down and nucleons re-assemble into the intermediate energy fragments.

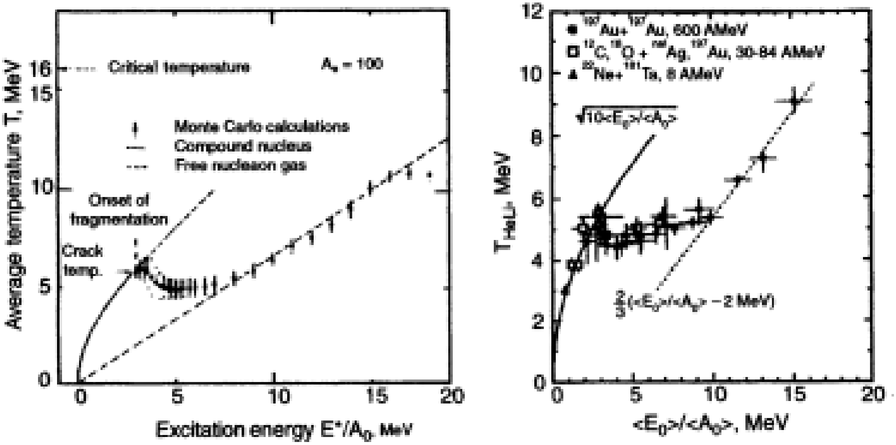
Multifragmentation in heavy-ion collisions

- Heavy ion collisions can transfer into a nuclear system much more energy than the spallation reactions.
- Thus the multifragmentation is expected to be even more pronounced in central heavy ion collisions.
- This conclusion prompted a significant research effort dedicated to studies of “nuclear vapourization” in nuclear reactions.
- These studies required very sophisticated detection system to identify the characteristics of the fragments from multifragmentation as well as to identify that collisions were central.
- The results of these studies are summarized by measurements of nuclear caloric curves (temperature vs. excitation energy) and identification of liquid-gas phase transition on nuclear phase diagram.

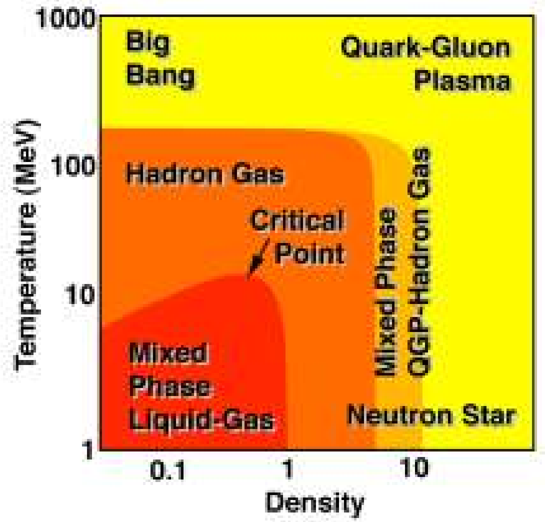
4π array for fragmentation study at MSU



Caloric curves in heavy ion reactions



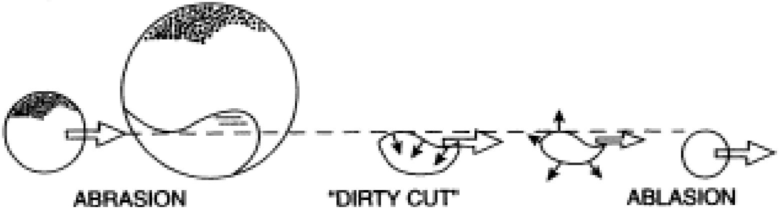
Nuclear phase diagram from heavy-ion reactions



Peripheral heavy ion collisions

- Peripheral (large impact parameter) collisions show a different reaction mechanism than the central collisions.
- The mechanism is that of abrasion and ablasion.
- At high energy the projectile shears off part of target in the overlap region between the projectile and the target nucleus (this is the abrasion step).
- The overlap sector undergoes multifragmentation.
- The non overlapping parts of the projectile and the target do not interact between each other and also do not interact with the fireball.
- The target- and the projectile-like fragments are excited through the surface energy, the surface is large compared to the optimal and the energy associated with the increased surface becomes internal excitation energy.
- The fragments de-excite in the ablasion step.

The abrasion-ablation in high-energy heavy ion collisions

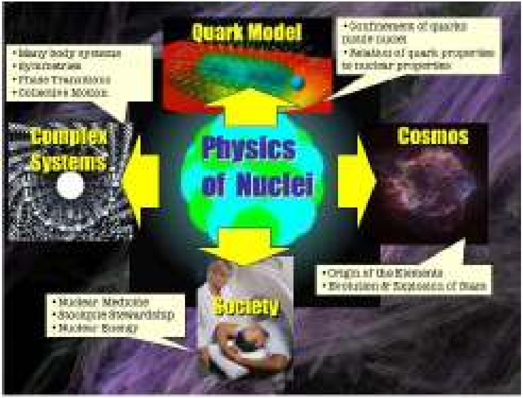


Multifragmentation in high-energy heavy ion collisions

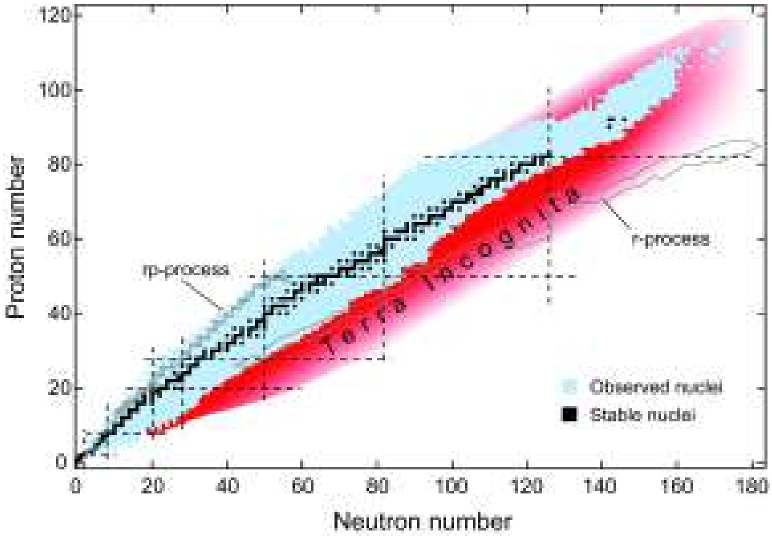
- The overlap region in high-energy heavy ion collision becomes a highly-excited "fire-ball" which undergoes multifragmentation.

High energy collisions and isotope harvesting

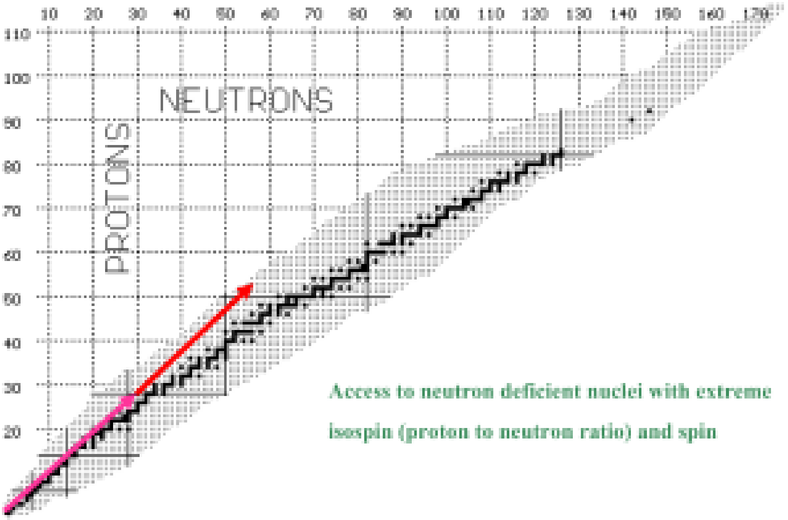
- High energy collisions produce a broad range of products
- These reactions can be used to harvest isotopes of interest to fundamental science, medicine, industry and homeland security.



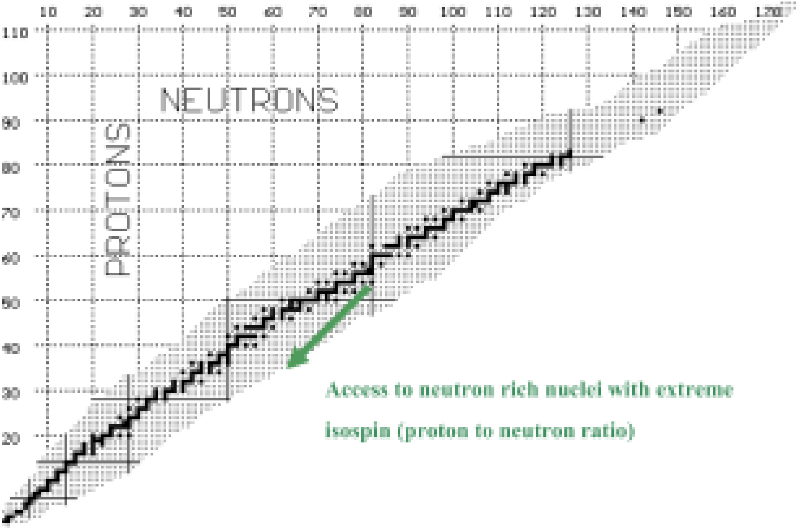
Nuclear Terra Incognita



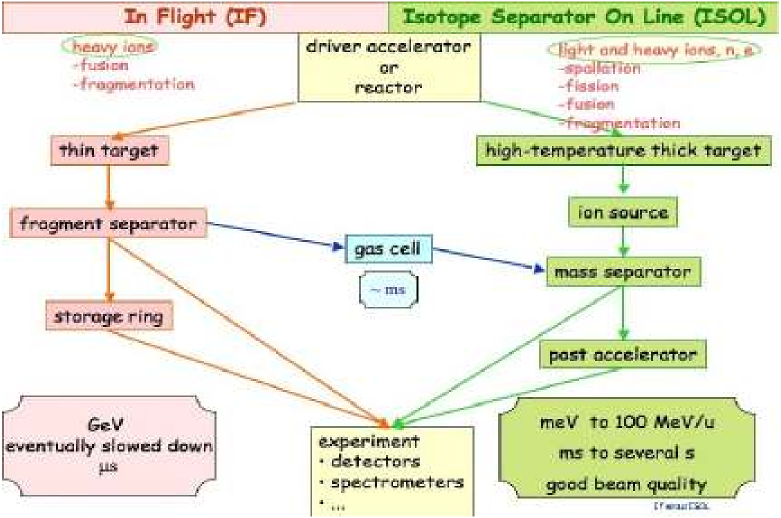
Fusion


NEUTRONS
PROTONS
10 20 30 40 50 60 70 80 90 100 110 120 130 140 150 160 170
110 100 90 80 70 60 50 40 30 20
Access to neutron deficient nuclei with extreme
isospin (proton to neutron ratio) and spin

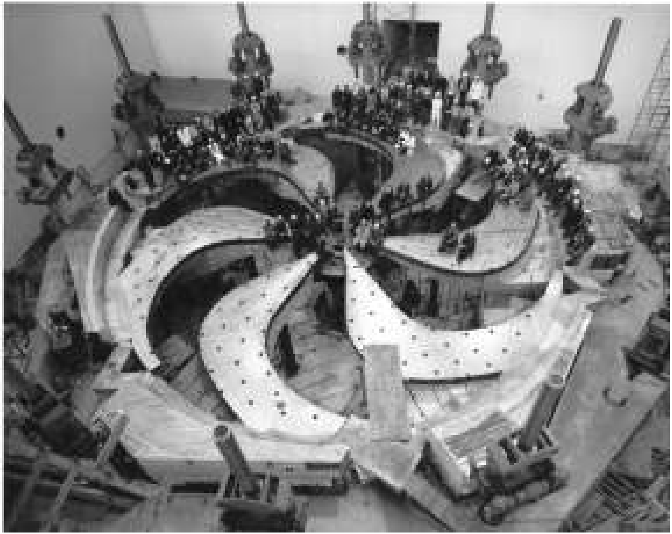
Spallation,fragmentation,fission



Production or rate isotopes

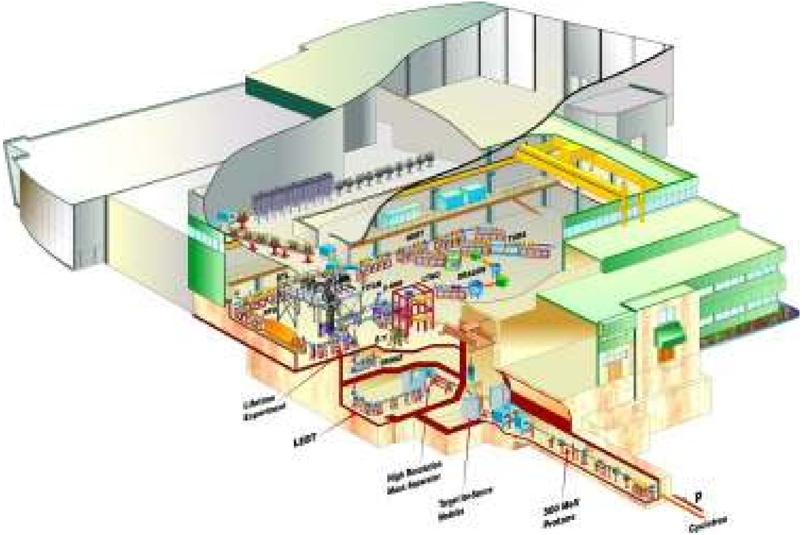


The world's largest cyclotron at TRIUMF



The world's largest cyclotron at TRIUMF

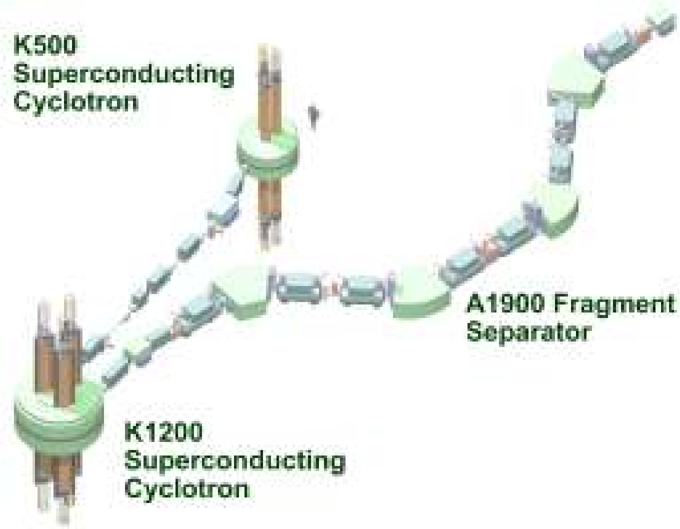
ISAC-II at TRIUMF



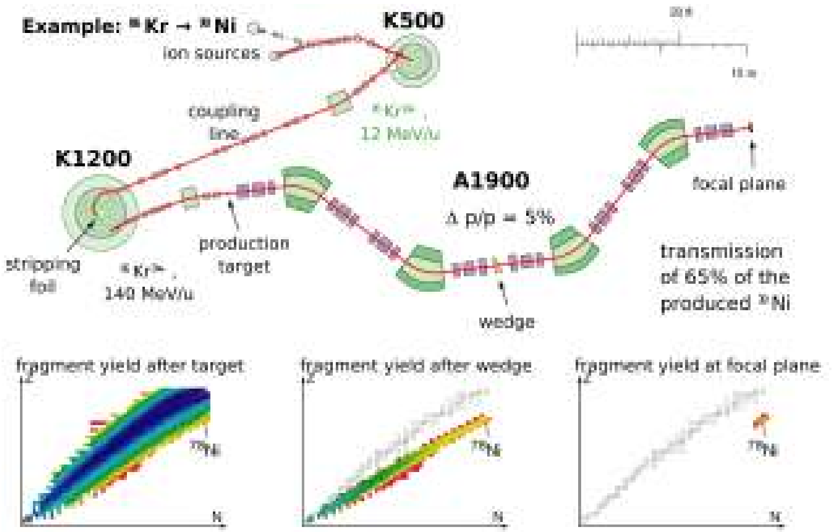
ISOL beams and facilities

- ISOL beams are good quality with small positional and angular divergence and good energy resolution.
- These beams are ideal for astrophysics, reaction and structure studies near the Coulomb barrier.
- The ISOL method, however, is very chemically selective, some elements easily emerge from the target, while other do not emerge at all. The chemistry of the target sets the limitation for the whole facility.
- ISOL facilities other than ISAC at TRIUMF are: HRIBAF at Oak Ridge National Laboratory in US, ISOLDE in CERN, Switzerland, and GANIL in France.

Coupled Cyclotron Facility at NSCL/MSU



In-flight production of rare-isotope beam at NSCL



Fast beams and facilities

- Rare isotope beam have energy near that of the primary beam.
- Beams are good for experiments that use high energy reaction mechanisms
- Luminosity (intensity x target thickness) can be large since targets can be thick.
- Individual ions can be identified
- Efficient, fast (100 ns), chemically independent separation
- Production target is relatively simple
- Fast beam facilities other than the NSCL are RIKEN in Japan, GANIL in France and GSI in Germany.