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Conceptual Design Project: Accelerator Complex for Nuclear Physics Studies and Boron Neutron Capture Therapy Application at the Yerevan Physics Institute

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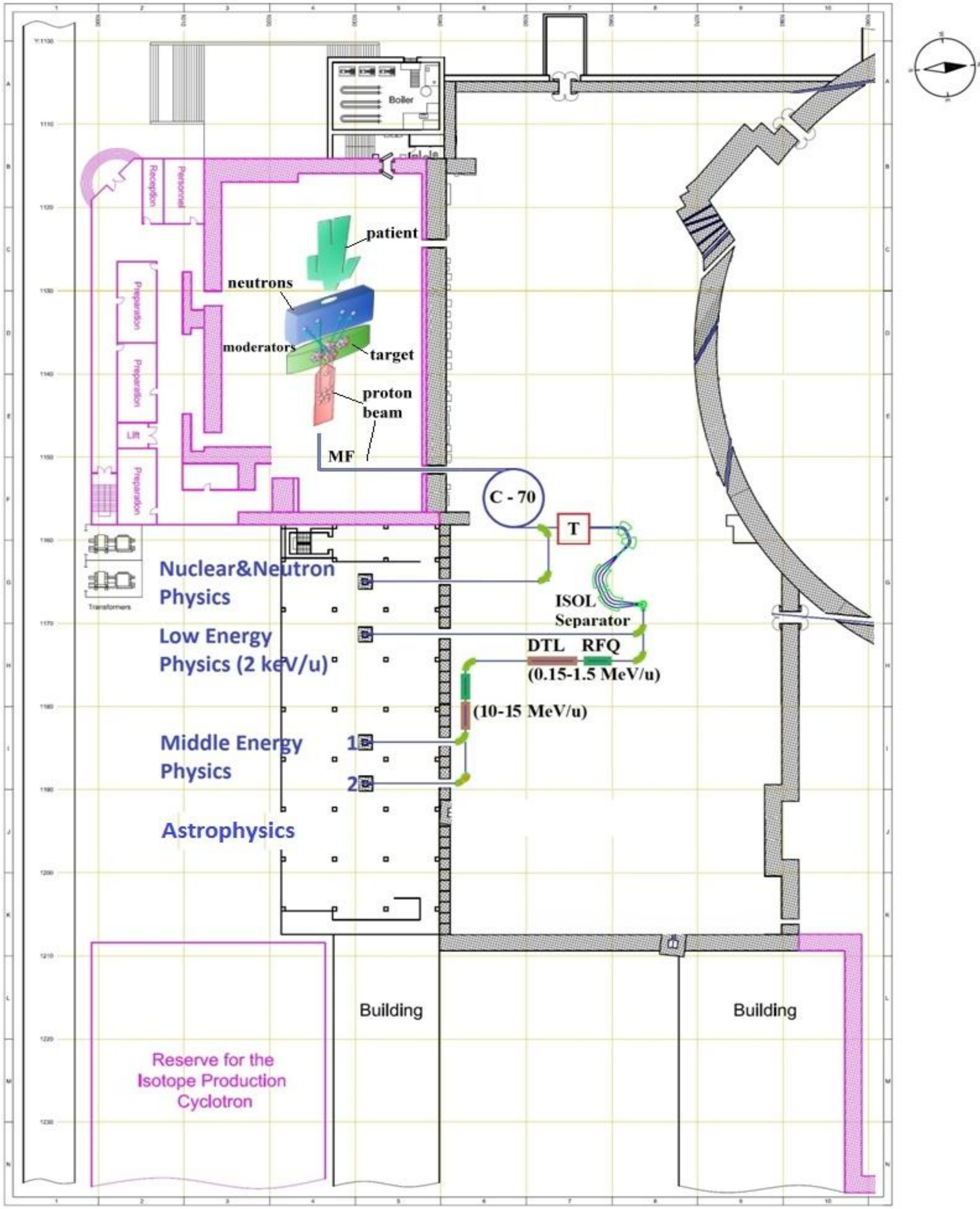
Introduction

- The study of nuclear physics with the RIBs is important in order to determine the limits of existence and the properties of nuclei far from the stability valley, around the neutron and proton drip-lines and in the super heavy region. Such exotic nuclei could show new phenomena and new types of nucleonic aggregation.
- Understanding of some important astrophysical problems. In the stellar nucleosynthesis, indeed, the *r-process* involves nuclei close to the neutron drip line that will be directly accessible with the RIBs.
- Understanding of the basic law of nature, testing the standard model and the fundamental conservation laws.

Cyclotron C70 for Nuclear Physics Studies and BNCT



The beam characteristics of cyclotron C70

Cyclotrons	Proton		Deuteron		Alpha	
	Extracted Energy (MeV)	Beam Intensity (μA)	Extracted Energy (MeV)	Beam Intensity (μA)	Extracted Energy (MeV)	Beam Intensity (μA)
C70	30-70	1000	15-35	50	70	35

The *proton, deuteron and ^{4}He beams* from *C70 IBA Cyclotron* will bombard a thick Uranium target to produce RIB's by means of Isotope Separation by On Line (ISOL) technique.

Beam Production

The proton, deuteron and ^{4}He beams during interaction with uranium target will produce a variety of intense beams of nuclei far from beta stability line. After mass separation the secondary beam (including RIB's) with energy 2 keV/u will be produced.

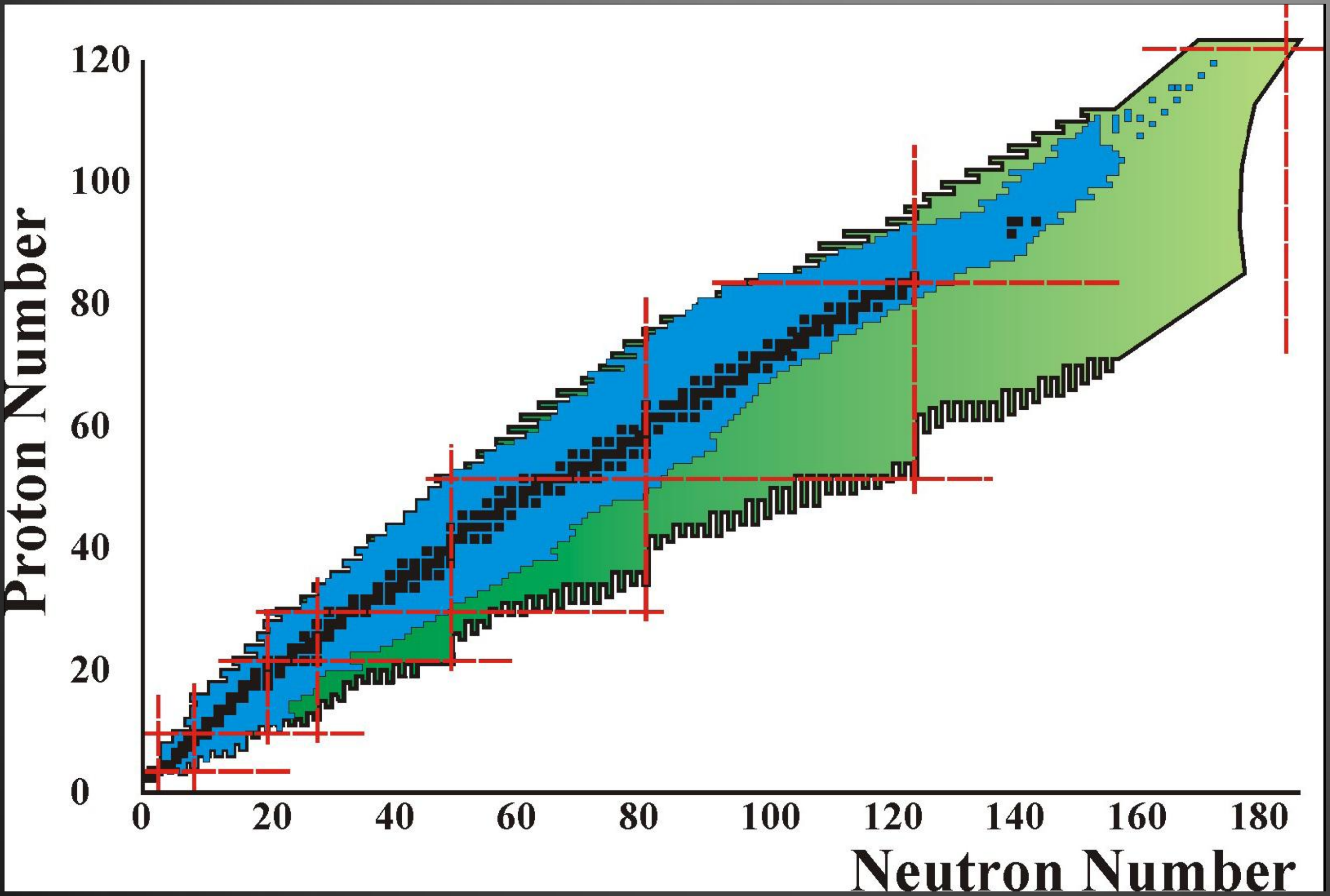
Basic specifications

Input beam	
Energy	**2 keV/u**
Ion mass	**A ≤ 30**
Ion charge	**1**
Beam current	**< 1 μA**
Beam emittance (100%)	**≤ 50 mm mrad**
Accelerated beam	
Output energy range	**0.15 MeV/u ≤ E ≤ 1.5 MeV/u** **1.5 Mev/u - ~ 10 MeV/u**
Resolution E/E	**≤ 0.1 %**
Duty factor	**100 %**

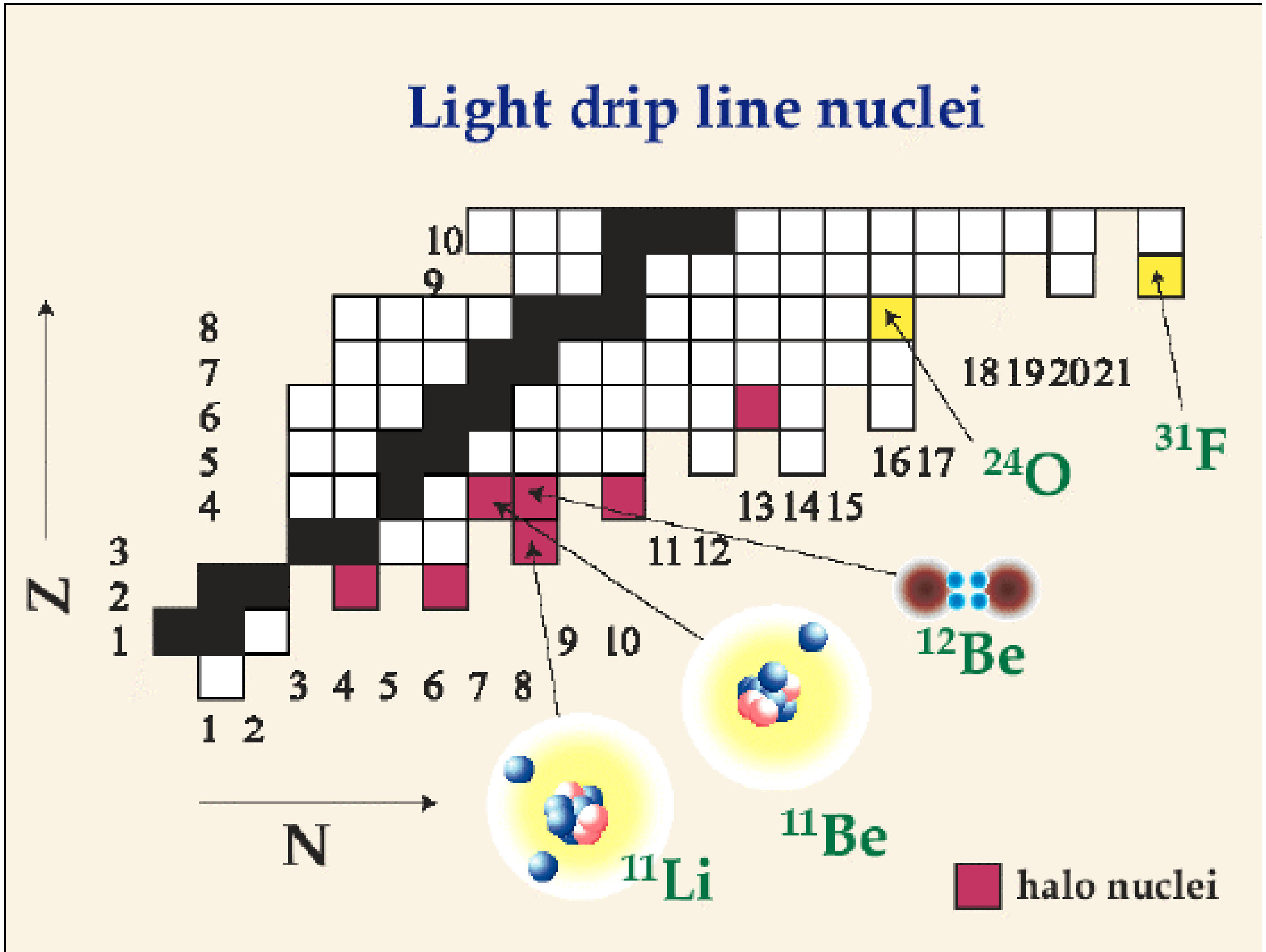
Importance of RIB's

The nuclear physics with Radioactive Ion Beams is important to determine the properties of nuclei Far from the stability valley, around the neutron and proton drip-lines and in the super heavy region.

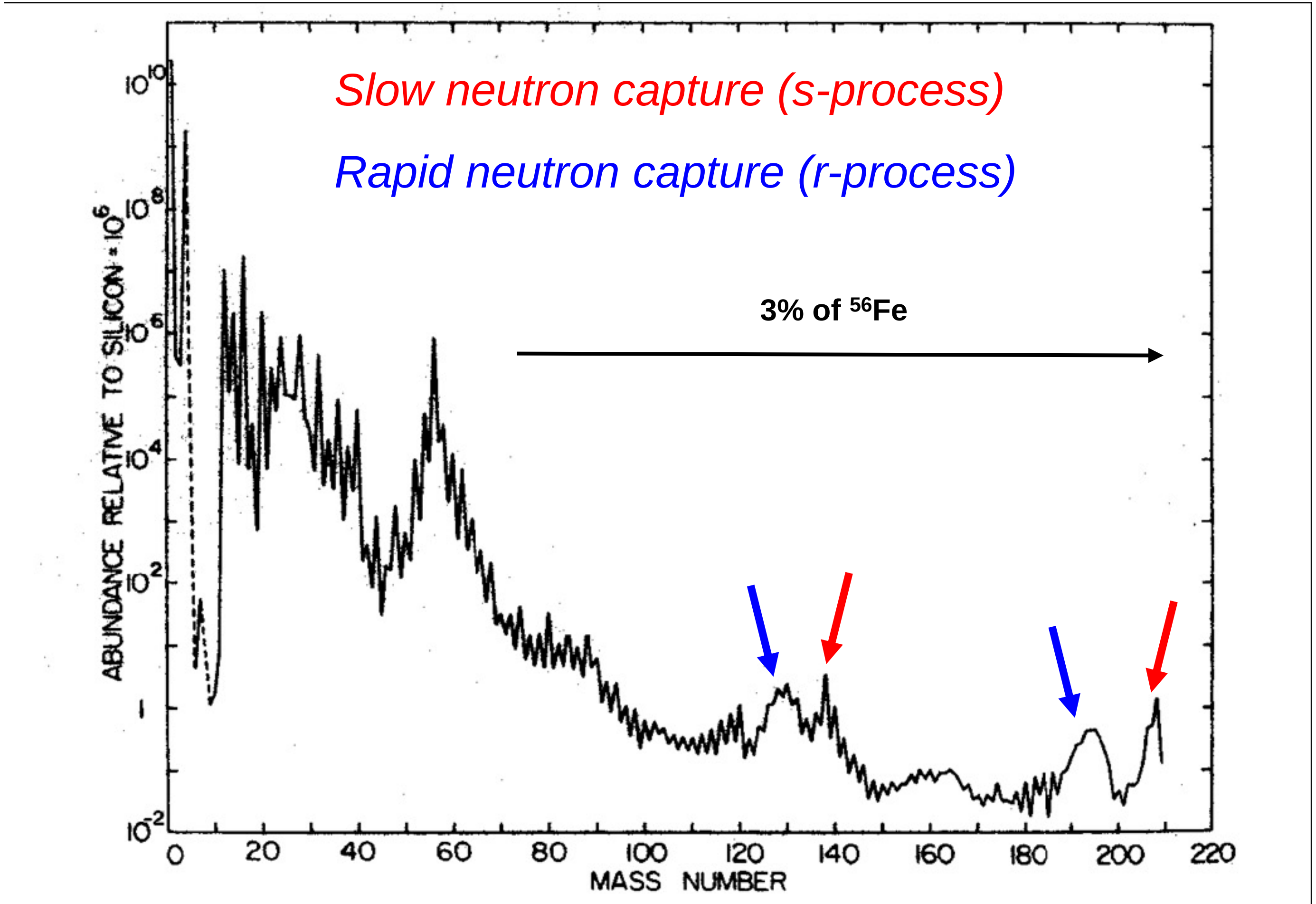
Two areas of study (the high and low energies) of the nuclear matter are strongly related and are complementary: at high energy the nuclear physics strives to derive the properties of hadrons from those of quark and gluons, at low energy the nuclear physics strives to derive the properties of the nucleus from those of nucleons.



The black squares represent the stable nuclei. These nuclei form the valley of stability. The blue region indicates the shorter-lived nuclei produced in laboratory. The green region represents the incognita region up to the drip lines. Red vertical and horizontal lines show the magic numbers as known today near the stability valley.



The neutron drip line has been explored only up to oxygen (Z = 8), where the heaviest particle stable isotope has 16 neutrons. The heaviest known isotope of fluorine (Z = 9) has 22 neutrons. Therefore one additional proton binds at least six neutrons. Purple squares indicate the known halo nuclei and a very elongated "dimer" configuration has been found for ^{12}Be.



The solar system abundance of elements as function of the mass number. Two neutron capture process are responsible for the synthesis of elements heavier than iron. The slow neutron-capture accounts for the peaks indicated by the red arrows, whereas the rapid neutron-capture accounts for the peaks indicated by the blue arrows.

Charged particle reactions are responsible for the nucleo-synthesis chains that populate nuclei up to iron. Beyond the iron region, the Coulomb barrier is to high for such processes and the heavier nuclei are formed by reactions induced by neutrons.

The rapid neutron capture (r-process) together with the slow neutron capture (s-process) are the main nucleosynthesis processes that are effective in populating the heavy elements.

- ***The s-process* operates close to the stable nuclei where the time between sequential neutron capture reactions is longer than the lifetime for β-decay. The neutrons are produced in stars by charged particle induced reactions and the cross sections for neutron capture reactions (σ) are usually quite large, (σ = 100-5000 mb) for low energy neutrons. Nuclei with small cross section (closed shell nuclei) have a large lifetime τ and form a 'bottleneck' resulting in the s-process abundance peaks .**

In the r-process the neutron capture has to occur much more rapidly than β-decay.. When the r-process starts there are many neutrons available for capture and some seed nuclei as ^{56}Fe. A seed nucleus starts to quickly capture neutrons getting heavier and heavier until reaching a nucleus with binding energy so small that the capture rate is balanced by photodisintegration. At this "waiting point" the neutron capture stops and the nucleus is transformed via β-decay to a nucleus with higher separation energy where the neutron capture can start again.

at a given proton number the abundance is concentrated in the waiting point nucleus. More slow is the decay more abundant is the nucleus. Nuclei with a neutron magic number are therefore "waiting points", where the neutron capture slows the β-decay to stability dominates.

Beam parameters depends on research topics

Research group	Research topics	Energy & current of RIs
Nuclear Structure	❖ Exotic nuclei near the neutron & proton drip line ❖ Isomer research	• Unstable: $_{20}$Ca, $^{84}_{32}$Ge, $_{36}$Kr, $^{132}_{50}$Sn, $_{54}$Xe • Stable: $^{76}_{32}$Ge, $^{86}_{36}$Kr, $^{136}_{54}$Xe, $^{238}_{92}$U 0 ~ 70 MeV/u, > 0.1 nA (10^9 pps)
Nuclear Astrophysics & Nucleosynthesis	❖ Breakout reaction from Hot-CNO cycle to rp-process ❖ Nucleonsynthesis contribution of isomers ❖ Important constraint on core-collapse supernova model	• Unstable: $^{15}_{8}$O, $^{26m}_{13}$Al, $^{45}_{23}$V, $^{62\text{-}66}_{32}$Ge, $^{46\text{-}52}_{12}$Mg, $^{132}_{50}$Sn, $^{134}_{52}$Te, $^{140,144}_{54}$Xe, $^{194\text{-}196}_{75}$Re, $^{198,202}_{77}$Ir, $^{95}_{69}$Tm • Stable: $^{23}_{11}$Na, $^{134\text{-}135}_{55}$Cs 0~10 MeV/u and few hundreds MeV/u 0.1 nA ~ 1 μA (10^6 ~ 10^{13} pps)

* Notation: Stable, neutron-deficient, neutron rich Ris

** Yong Kyun Kim "Utilization of Intense Rare Isotope beam at KoRIA", KIAS Workshop, Nuclear and Particle Physics at KoRIA and BSI,

Nuclear Matter	❖ Symmetry energy in astro- and nuclear physics ❖ Neutron skin thickness ❖ Isovector giant dipole resonance ❖ Collective flows in HI collisions, and etc.	• All ions from H to U, (H, $^{132}_{50}Sn$, $^{140}_{54}Xe$, $^{238}_{92}U$) 0 ~ 70MeV/u, > 10^9 pps
Medical & Bio application	❖ Effect on human body by HI ❖ Radiobiology research with HI beams ❖ Radiation therapy with HI beams ❖ Industrial applications with HI beams	• Unstable: **$^{11}_{6}C$** • Stable: p, $^{4}_{2}He$, $^{12}_{6}C$, $^{16}_{8}O$, $^{20}_{10}Ne$, $^{28}_{14}Si$, $^{35}_{17}Cl$, , $^{40}_{18}Ar$, $^{48}_{22}Ti$, $^{56}_{26}Fe$, $^{131}_{54}Xe$ 10 ~ few hundreds MeV, 0.1 nA ~ 1 μA
RI Material Research	❖ Elastic Recoil Detection (ERD) system	• Unstable: ^{8}Li, ^{11}Be, $^{15,19}_{8}O$, $^{17}_{10}Ne$, $^{62}_{30}Zn$, $^{77}_{33}As$, $^{99}_{41}Nb$, $^{99}_{43}Tc$, $^{100}_{46}Pd$, $^{117}_{48}Cd$, $^{111,117}_{49}In$, $^{131}_{52}Te$, $^{140}_{59}Pr$, $^{172}_{71}Lu$, $^{181}_{72}Hf$, $^{187}_{74}W$, $^{199}_{81}Tl$, $^{204}_{83}Bi$ few tens keV ~ 10 MeV, 15~30 nA

* Notation: Stable, neutron-deficient, neutron rich RIs

Applications

The high intensity neutron source with rate of 10^{14} n/s will provide an epithermal neutron beam flux of 10^9 n/cm^2·s at least for BNCT.

Another very attractive application of neutron beams is Boron Neutron Capture Synovectomy (BNCS) on the base of the reaction $^{10}B(n,\alpha)^7Li$ for the treatment of rheumatoid arthritis, i.e. inflamed tissues in joints.

BNCT is a radiation therapy. A boronated substance is injected in the patient body, and then the patient is irradiated with thermal or epithermal neutrons. Because of the high ^{10}B thermal/epithermal neutron capture cross section (3837 barn), the nuclear reaction

$^{10}B(n,\alpha)^{7}Li$

is likely to occur. The nuclear reaction fragments thus produced

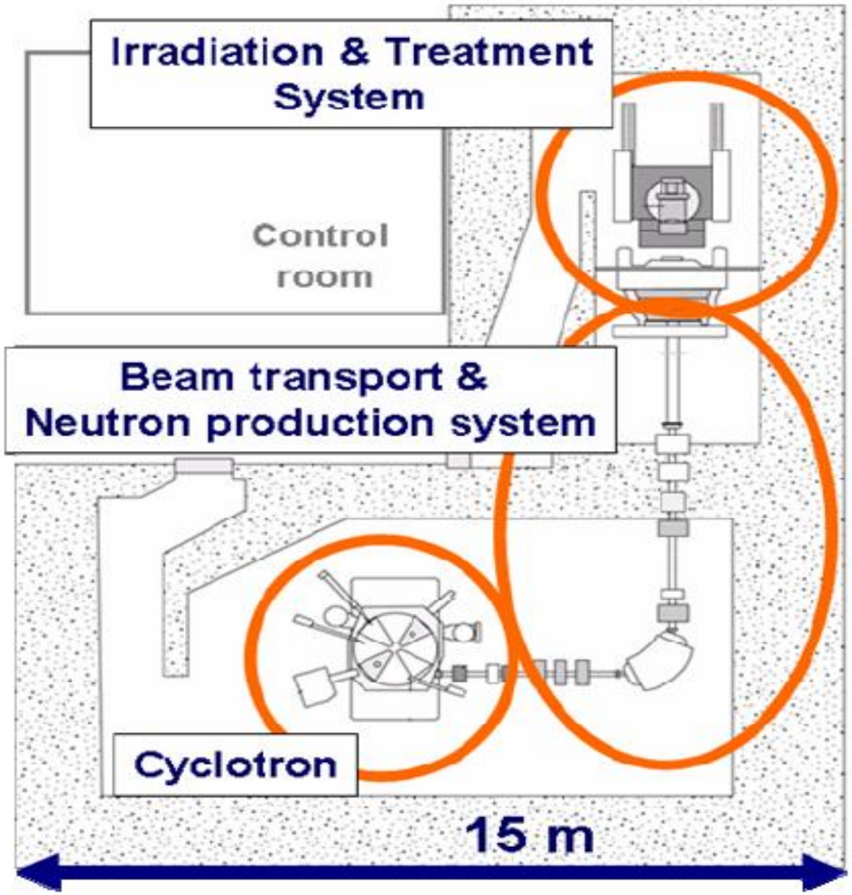
(^{4}He of 1.47 MeV and ^{7}Li of 0.84 MeV)

are densely ionizing charged particles, the ranges of which in soft tissues

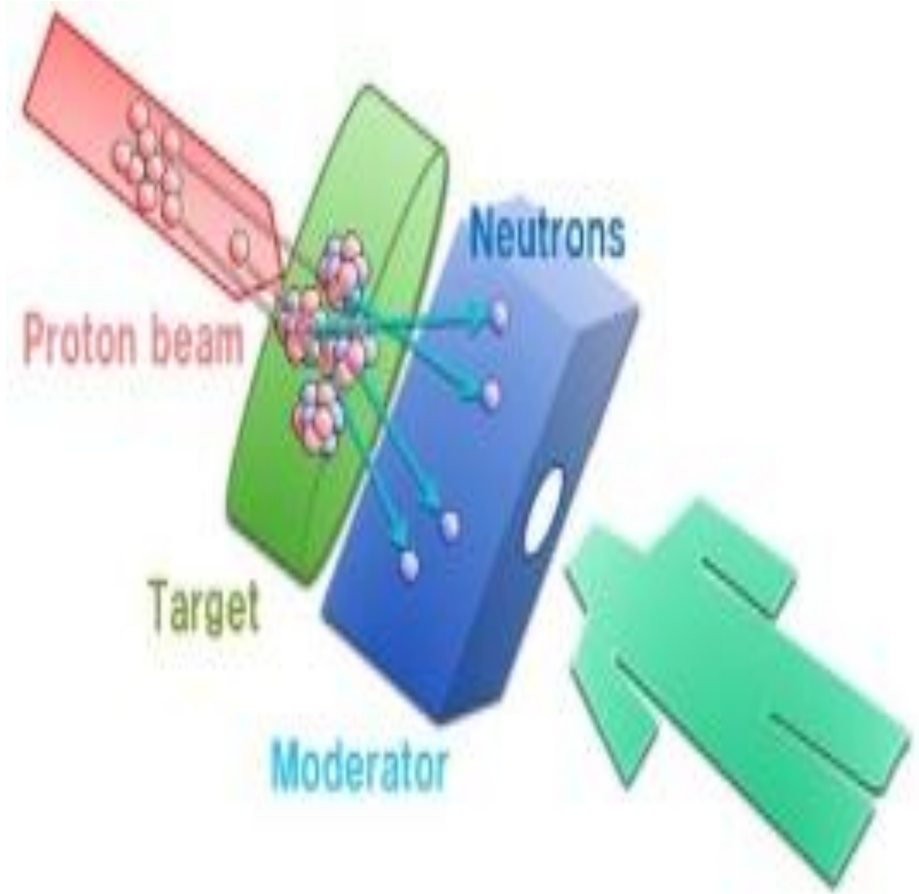
(~8 µm for α particle, 5 µm for the lithium ion)

are as short as a cell diameter (~10 µm).

Epithermal neutron beam facility for treatment of Boron Neutron Capture Therapy



Layout of cyclotron based neutron source KURRI



The schematic drawing of BNCT system

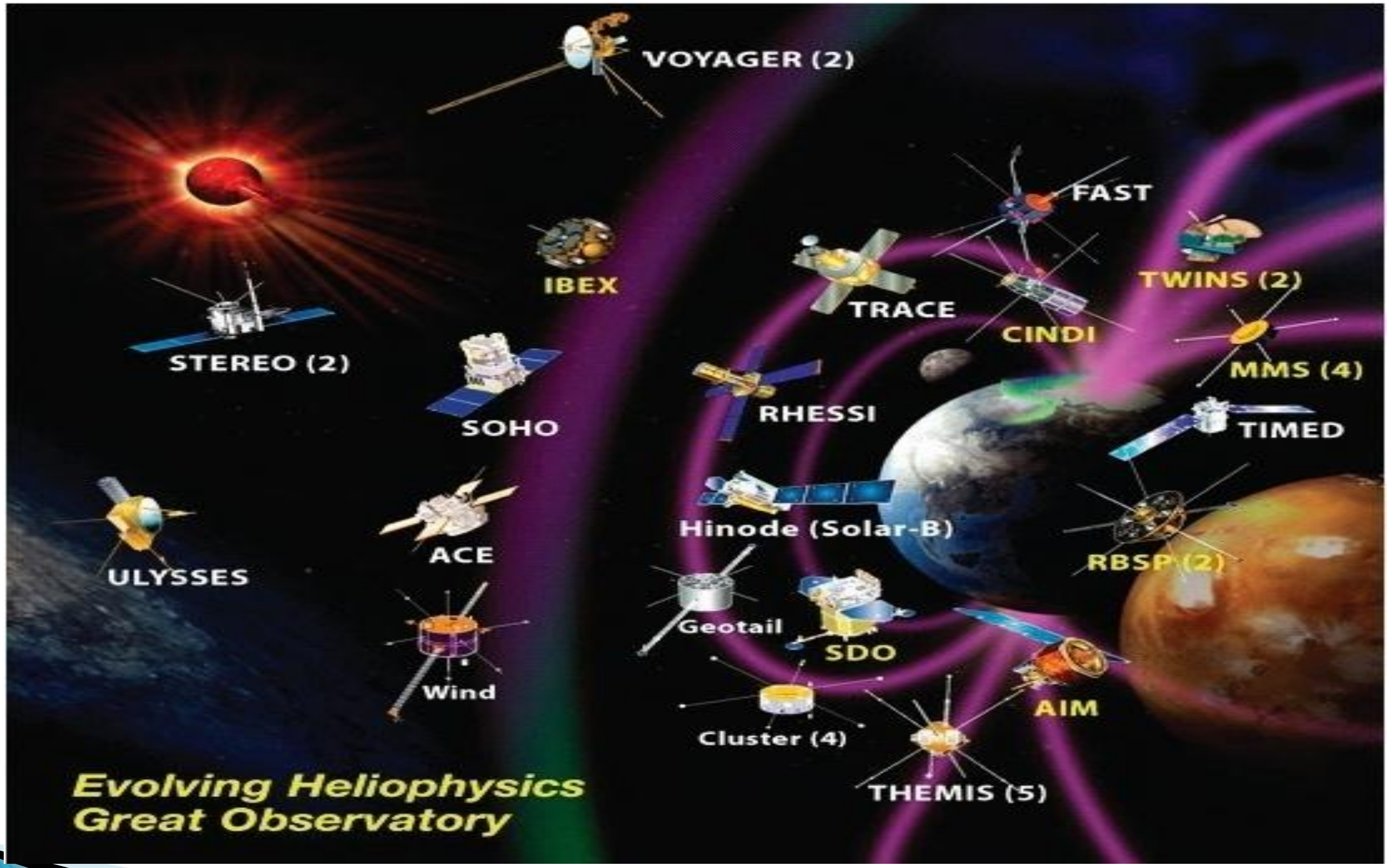
Isotopes production

Also the cyclotron C70 opens great opportunities for the production of a number of isotopes for diagnosis and therapy. Some of the main isotopes that can be produced in the C70 are also very popular in nuclear medicine

(^{111}In, ^{201}Tl, ^{67}Ga, ^{103}Pd and ^{123}I).

In conclusion, the planned facility will offer unique opportunities to extend the radiobiological activity program in Armenia taking advantage of the availability of protons and neutrons in a wide energy range.

Neutron and proton irradiation facility for interdisciplinary applications.
Space Radiation - Demand for ground tests.



The Earth science satellites in orbit.

The YerPhI Complex Accelerator Facility after its full scale construction could be involved in the program of investigations:

- ***Radiation hardness of the new electronic products***

- ***Properties of radiation monitors for space and laboratory Applications***

- ***Basic mechanics of radiation effects in semiconductors***

- ***Space radiation environment by on-earth simulations***

Nuclear Waste Transmutation and Incineration

In the proposed project, experimental facility allows the possibility to measure the neutron capture cross section for fission products

^{99}Tc, ^{129}I and ^{135}Cs

and for transuranic elements Np, Am, Cm, Pu with different energy neutrons and develop technology for radioactive waste transmutation.

Radiolysis

Water radiolysis through α radiation will provide the highly active chemical radicals that could enhance corrosion of the barriers, or lead to the formation of chemical complexes of which migration speed could be much higher than expected.

These topics will be studied with the help of Cyclotron C70 α beam, the energy of which will be higher than what is available today.

Thank You for Attention