Project for Heavy Charged-particle Beam Multi-purpose Use

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I. Project for Heavy Charged-particle Beam Multi-purpose Use

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A brief summary is given for the results of multi-purpose use of a cyclotron and RI in past two decades. This report presents as well a preliminary planning of further development by introducing the facilities, being under construction or consideration, and scientific motivations.

CYRIC (Cyclotron and Radioisotope Center) was established in 1977 as an institution for carrying out research studies in various fields by the use of a cyclotron and radioisotopes, and also for training researchers of Tohoku University for safe treatment of radioisotopes and radiation. The CYRIC cyclotron is a variable energy AVF machine with a K value of 50 MeV; being capable of acceleration protons up to 40 MeV, deuterons to 25 MeV, α-particles to 50 MeV, and He-3 particles to 65 MeV.

During the past two decades, refereed 501-papers written in English have been published in scientific journals in the world. Ninety-six dissertations for D.Sc.(37), D.M.(38), D.Eng.(11), D.Agr.(6), Pharm.D.(2), etc. have been accepted based on the research in CYRIC, while 154-thesises for master's degree have been presented.

Based on the successful results of the 20 years-long multi-purpose use of Cyclotron and Radioisotopes, replacement of the present cyclotron with a larger dimension K=130 MeV one, and construction of experimental facilities have been authorized by Japanese government in 1998 and 1999 financial years.

Since 1979, we have an apparatus for fast neutron time-of-flight analysis equipped with a 40m long flight path, an electromagnetic isotope separator (EMIS) for on-line and off-line uses, and an x ray detection system for atomic physics and for element analysis by PIXE method. Fully automated positron emitter labeled compound synthesis systems is installed for the studies of biology and medicine. A positron tomograph ECAT-II was installed in 1981. Another four-rings PET(PT931) and TOF type PET (PT711) scanners were installed in 1986 and 1987, respectively. Since 1983 school year, these scanners have been extensively used for clinical researches; for cancer diagnosis and for brain researches, etc., supported by steady operation of the cyclotron, and by reliable supply of short-lived positron emitter labeled compounds. Recently, a system of the high-resolution positron-emission tomograph SET 2400W-S has been installed.

With fast neutron time of flight measurement, we have explored isospin- and spin-isospin excitation in nuclei by (p,n) charge-exchange reactions at 35 MeV. Our interests have been focused on: (1) Isospin mixing effect in the width of IAS, (2) 0^+ to 1^+ Gamow-Teller type transition, (3) Stretched particle-hole excitation, and (4) 0^+ to 0^- or $\Delta J^\pi = 0^-$ pion-like transition. These works have established a research field of spin-isospin excitation of nuclei in low energy (p,n) reaction. In addition, spectroscopic works by the (d,n) reaction have been carried out to investigate single particle nature of nuclei. Atomic and molecular physics with charged particles from an AVF cyclotron started at CYRIC exploring inner-shell ionization mechanism, results have been and extended over applications with the particle induced x-ray emission (PIXE) method for element analysis.

Researches using an EMIS equipped with a tape-transport and an ion-guide systems are: (1) Discovery of the heaviest two "mirror-decay" nuclei, ^{57}Cu and ^{59}Zn.(2) Implantation of radioactive isotopes to make good-quality samples for precision measurement of conversion-electrons up to the atomic valence shells to derive the Mössbauer isomer-shift scales $\Delta R/R$. Researches in the field of nuclear spectroscopy, using perturbed angular correlation (PAC) and perturbed angular distribution (PAD) methods with a magnet, are measurement of fifteen samples of magnetic-moments of nuclear isomeric-states. In a field of solid-state physics, PAC measurements, after EMIS for acceleration of Rl, have been carried out to examine the orientation and magnitude of the electric field gradient created by a vacancy at Rl-probe impact. Efforts to accelerate light heavy-ion has been continued for further application to scattering experiments. Heavy ions of ^{12,13}C, ^{15}N and ^{16}O were extracted successfully, and used for elastic scattering on ^{28}Si at small angles in order to obtain total reaction cross-sections model independently.

Using 36-MeV α-particles with an energy degrader system to obtain an uniform depth distribution in the specimen, He implantation effects on mechanical properties of a number of composites have been studied to apply these composites on structural materials of a fusion reactor. As a new type of isotope effect in metal acetylacetonates, time-dependent isotope effect in recoil implantation was studied, and it was found that the decay products ^{99m}Tc and ^{96}Tc tended to form pertechnetate in comparison with the direct nuclear reaction product ^{95}Tc, by water soluble species of Tc nuclides produced by the (d,xn) reaction on Mo. Further recent topics in RI-production with 12-MeV protons and 16-MeV deuterons is insertion of radioactive atoms in C_{60} and C_{70} fullerenes. Such endohedral fullerenes ^{7}Be@C_{60}, ^{127}Xe@$C_{60,70}$ and ^{79}Kr @$C_{60,70}$ and their dimers were detected.

With the neutron facilities in CYRIC, neutron dosimetry and monitoring were studied, and activation and spallation cross-sections have been measured. Also investigated were neutron absorption and leakage for purposes of radiation shielding. By combination with clinical PET studies, absorbed dose in humans due to intravenous administration of positron emission radiopharmaceuticals were measured.

One of major programs has been instrumental development of positron emission tomograph and automated labeling system of radiopharmaceuticals with cyclotron-produced positron emitters for nuclear medicine as listed in the following Table.

Nuclide	Radiopharmaceuticals	Imaging Target
C-11	[^{11}C]Methionine	Tumor
	[^{11}C]Doxepin	Histamine H_1 receptor
	[^{11}C]Nemonapride(YMO9] 51-2)	Dopamine D_2 receptor
	[^{11}C]Benztropin	Muscarinic acetylcholine receptor
F-18	[^{18}F]FDG	Energy metabolism in brain, heart and tumor
	[^{18}F]FDOPA	Presynaptic dopamine synthesis
	[^{18}F] Fluorodeoxyuridine	tumor
O-15	[^{15}O]Oxygen	Cerebral oxygen consumption
	[^{15}O]Carbon dioxide	Cerebral blood flow
	[^{15}O]Carbon monooxide	Cerebral blood volume
	[^{15}O]Water	Cerebral blood flow

These tracers have been successfully applied to several clinical researches including diagnosis of malignant neoplasms and neuro-pshyhiatrical diseases. The measurement of whole-body metabolism is an especially powerful technique not only for early and qualitative diagnosis (tissue characterization) of cancer but also for optimization of rational treatment and its evaluation. We were the one of the first research groups to have revealed neuronal receptor dysfunction in dementia of Alzheimer' s type. Research of central histamine H_1 receptors has been extensively investigated in our institute with collaboration of department of cellular pharmacology, school of medicine. Imaging analysis showed that H_1 receptors increased in the epileptic foci, which possibly reflects important role of histamine neurons in metabolic suppression of electrically over-discharge.

Development of a new PET with three-dimensional (3D) data acquisition and 3D-reconstruction capability was another success of our engineering group. 3D-reconstruction time was only 1 min for 63 sliced volume, which we believe a world record. Increase of sensitivity of this PET prompted us to apply this technique for sport science. Regional metabolic activation of muscles as well as in brain by physical exercise was successfully imaged.

We investigated the change of various neurotransmitter and receptors in the brain of several experimental models such as MPTP-induced Parkinsonian mice, 6-hydroxydopamine -treated rats, rats or gerbils subjected to cerebral ischemia and aged rats. Our results indicate that the dysfunction of neurotransmitter receptor systems plays a key role in the age-related neurodegenerative processes of several experimental animal models. Thus, these experimental study may provide an important information in age-related neurodegenerative diseases, such as Parkinson's and Alzheimer's disease.

1. AVF Cyclotron

Figure 1 illustrates a layout of the new AVF cyclotron and injection- and extraction-lines. Ion sources are located on the under ground level, then ions are injected upward into the central acceleration-region through an inflector. There are two modes of acceleration: one is positive-ion acceleration, being extracted at R=930 mm by a deflector, while negative ions are accelerated up to a radius of 680 mm corresponding to K = 50 MeV in magnetic rigidity, then stripped their electrons by a carbon foil, thus being extracted through the residual magnetic field as shown in the figure.

A negative ion source is located on the BF1 floor just below the accelerator. A conventional type Electron Cyclotron Resonance (ECR) source is installed in another room on the same BF1 floor, while a more high-power ECR course are under consideration. The conventional one is planned to be used for RI beam acceleration of light-heavy ion.

In the positive-ion's straight line through the first switching dipole-magnet, a
beam-emittance
measuring-port are equipped for tine tuning of the cyclotron to match acceptance of the beam transport system. One of the special features of our transport is beam time-sharing by a dipole-magnet with alternating current, by which a beam is injected into all beam courses available in a time interval of several seconds. Utilizing this equipment, a long-shift experiment and short-time radioisotope production may be possible simultaneously.

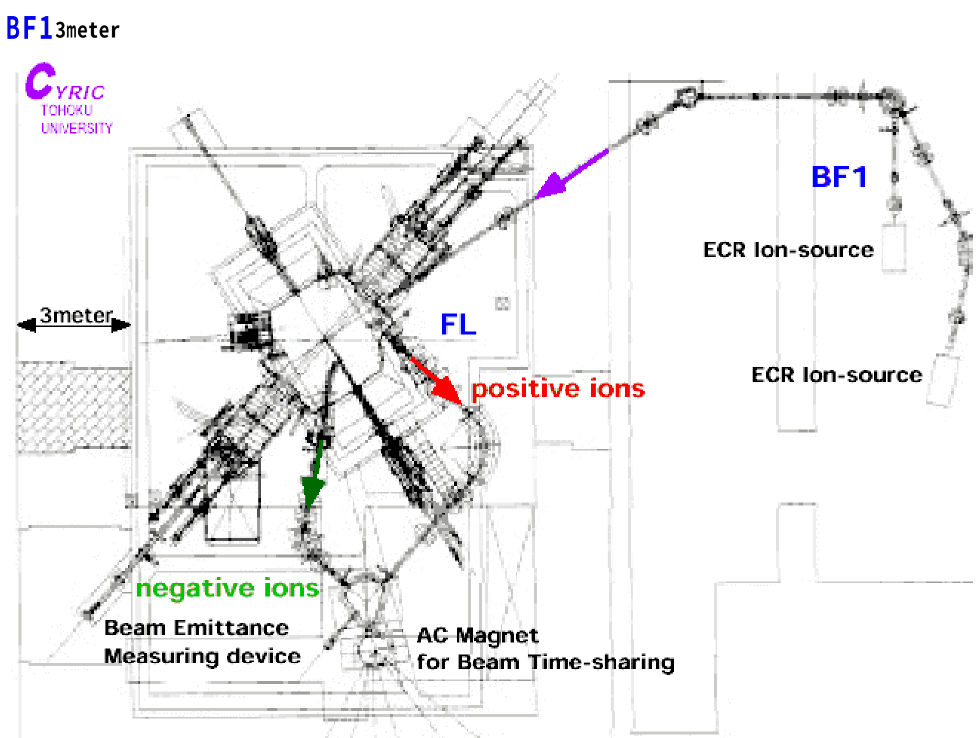

Fig 1. Layout of the new AVF cyclotron and injection- and extraction-lines.

Tables 1 and 2 list the specifications and beam characters of the new cyclotron.

Table 1. Specification of the new AVF cyclotron.

Electromagnet System		
	Weight	200 ton
	Extraction Radius	923 mm
	Number of Sector	4
	Max. Average Induction	19.6 kG (over Hill)
	Main Coil Power	230 kW
	Number of Trim Coil	12 pairs
Radio-Frequency System		
	Number of Dee's	2
	Frequency	11-22 MHz
	Max. Dee Voltage	50 kV
	Max. RF Power	70 kW x 2
External Ion Source		
	Negative ion	Cusp-type
	Positive ion	ECR, 10GHz
		ECR, 14GHz

Table 2. Beam energies of the new AVF cyclotron.

a) Positive ion acceleration.

Accelerated Particle	Energy (MeV)	Beam intensity(μA)
p	10-90	50
d	10-65	50
^{3}He	20-170	50
^{4}He	20-130	50
^{12}C	20-397	5p
^{14}N	20-463	5p
^{16}O	20-530	5p
^{20}Ne	20-662	5p
^{32}S	20-698	3p
^{40}Ar	20-744	3p
^{84}Kr	20-695	3p
^{129}Xe	20-748	1p

a) Negative ion acceleration.

Accelerated Particle	Energy (MeV)	Beam intensity(μA)
p	10-50	300
d	10-25	300

2. Beam Swinger and Large Solid-angle Neutron Detection System for Time-of-Flight Experiments

As one of the main facilities of the new System for Heavy Charged-particle Multi-purpose Use in CYRIC, construction the beam swinger, being capable for rotating the beam axis from -5deg. to 145deg. with K= 130 MeV, is under progress. The other new feature of this system is the neutron detector matrix, being located at a distance of 44 meter after the neutron flight path, and consisting of 32 pieces of the counter which contain 50 litter of liquid scintillater in its total volume.

This system may be a powerful tool to investigate isospin and spin-isospin excitation in nuclei through the (p,n) reaction in a wide range of incident proton energies. With energetic and high-intensity monochromatic neutron beams, neutron scattering experiments with high sensitivity provide a new field to explore charge-symmetry and charge-independent character of the nuclear forces, and to work with other engineering studies.

Figure 2 shows a lay out of the beam swinger and detector matrix.

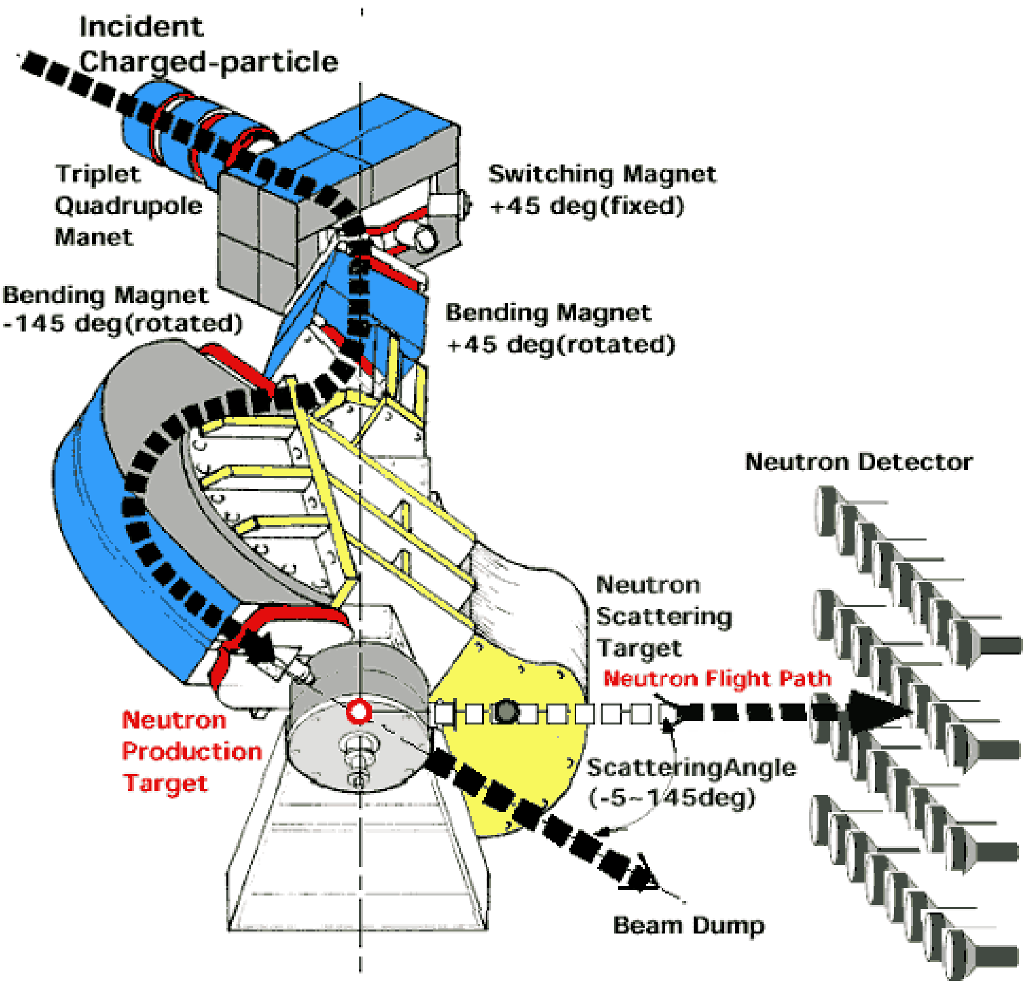

Fig. 2. Lay out of the beam swinger and detector matrix.

3. On-line Electric and Magnetic Isotope-separator

Study for unstable nuclei provide us with information of such nuclei that have decayed in the course of history of universe by producing them artificially with an accelerator or reactor. Energetic and high intensity charged-particle are considered to be the best candidate to explore such unstable nuclei far from the stability line. Many facilities in the world are oriented to the accelerated charged-particles, heavy-ions especially, for this purpose. On the other hand, production of unstable nuclei by neutrons may be more efficient, though it has been limited to a few cases with nuclear reactors due to the experimental difficulties to combine neutron beams with an on-line electromagnetic isotope separator.

The new cyclotron at CYRIC provide us with a sufficient high-intensity neutron beam to investigate unstable nuclei close to the neutron drip-line, together with the on-line electromagnetic isotope separator (EMIS) equipped with the ion-guide ion-source, and the high-speed tape-transport system. The additional powerful equipment is a high-resolution and large solid angle gamma ray detection system consisting of three pairs of four hold clover-type pure-Ge crystal, each of which is surrounded by 12 pieces of BGO Crystal. Figure 3 shows a layout of EMIS together with the new Ge-detector ball.

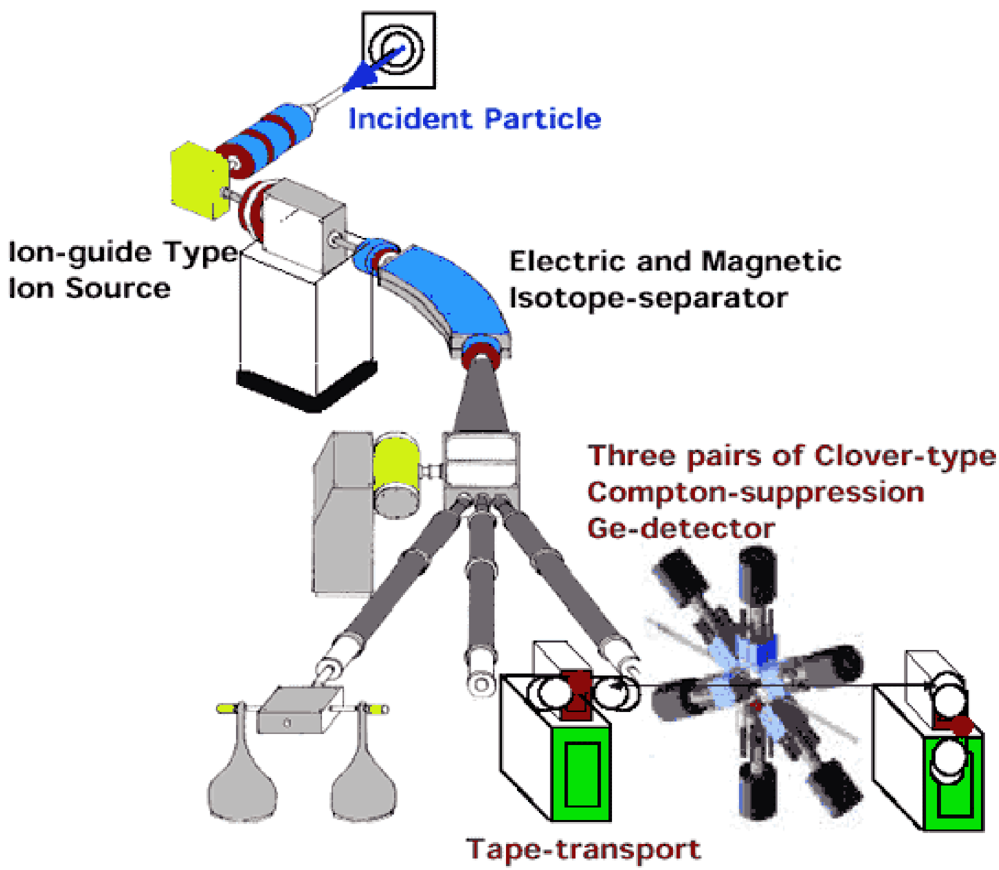

Fig. 3. Layout of EMIS, tape-transport and Ge-ball .

4 . High-energy γ -ray Detection System

The system is capable for detecting and analyzing high-energy γ-rays, up to e. g. 500 MeV, and neutral mesons produced by nuclear reactions. It contains 148 pieces of CsI crystal, the volume of each detector being 1000 cm^3 , and they are segmentaized into four blocks so as to cover a half p-radian in solid angle. The minimum internal radius is 55 cm. These four blocks are mounted on a stem, and each block is separately removable.

Equipped on a beam course of the K=130 MeV, AVF cyclotron facility of CYRIC, this system is applied for studies of high energy γ-rays production by energetic heavy ion impact up to the maximum energy kinetically allowed, and h- and p-mesons production energetically available. Thus, this system is expected to explore interesting phenomena of *coherent extreme* in nuclei. It should be noted that the beam transport system with time-sharing AC magnet is expected to work efficiently for such an experiment with quite rare events. Figure 4 shouws a schematic view of the CsI crystal high energy γ -ray detector.

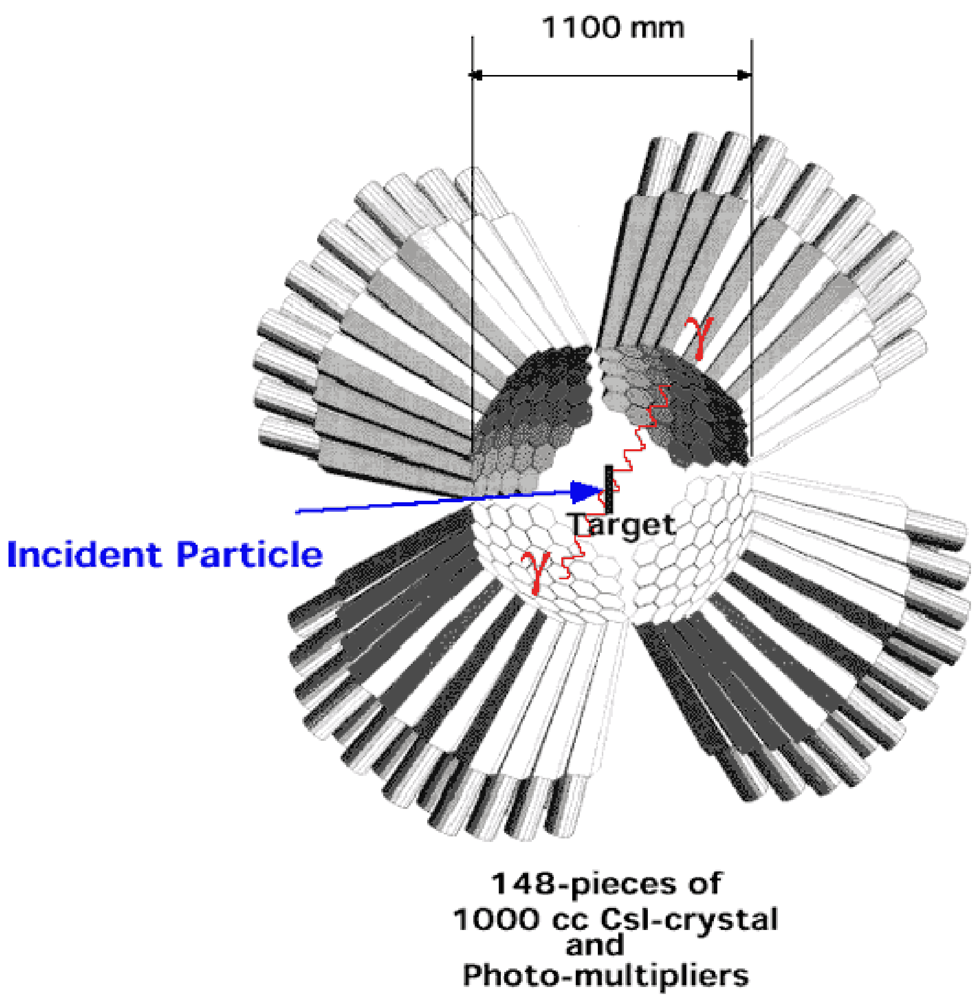

Fig. 4. Schematic view of the present CsI crystal high energy γ -ray detector.

5 . Neutron-life and Neutron-induced Reaction Analyzing Facility

Energetic and high-intensity charged particle beam, negative ion beam in particular, provide as well high-intensity white and monochromatic neutron beam, thus enabling us to carried out a number of neutron induced experiments. The main part of the .spectrometer is the electromagnet which have been used as that of our old K=50 MeV, AVF cyclotron. Charged particles emitted from different points along with the plane perpendicular to the incident direction have a focal plane, where a detector array as calorie meter is located.

A challenging project with this large solid angle magnetic spectrometer and high-intensity monochromatic neutron beams is measurement of the life-time of neutrons in flight. Accurate and comprehensive neutron life-time data are of crucial importance for current science including astrophysics, cosmology, particle and nuclear physics, etc.

Monochromatic 30-MeV neutrons are produced, then they flight through the 20m-long evacuated tube, reaching to the spectrometer in an average flight-time of ~1 msec. One neutron per hour may change to a proton. The neutron flight time, measured in a resolution of 10^{-3} is used to identify protons from neutron-decay. The most important point for this experiment is to measure the total amount of neutrons with sufficient accuracy as high as several 0.1%. Figure 5 shows a cross-sectional layout of the facility.

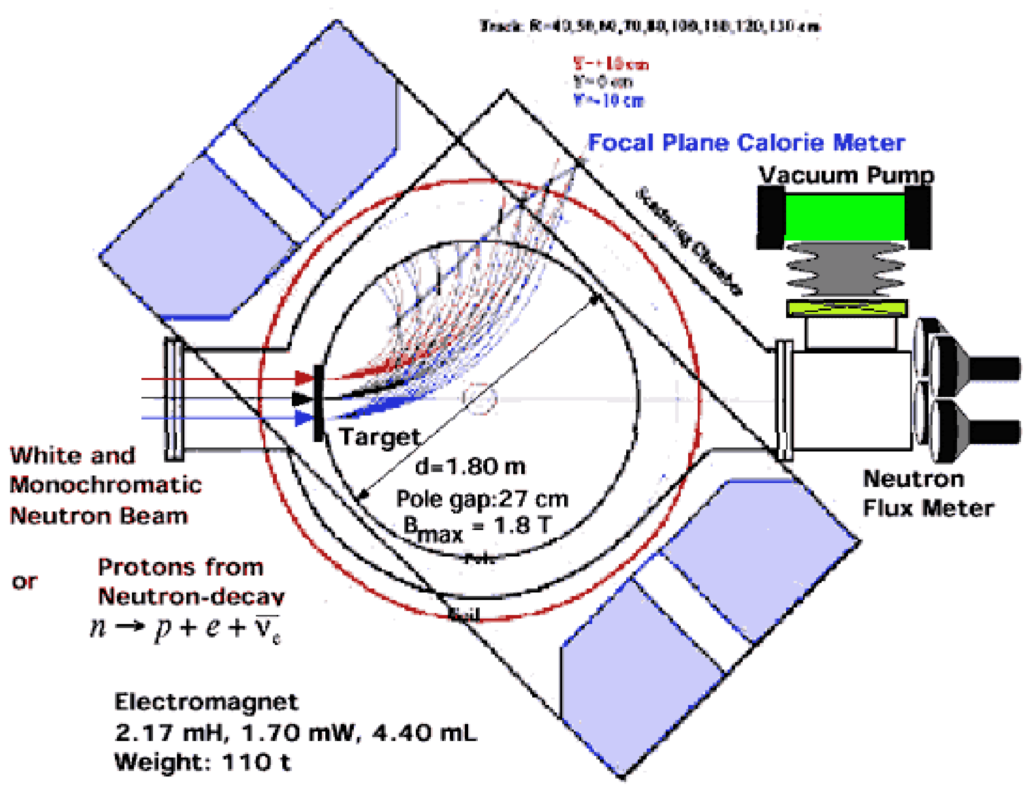

Fig. 5. Cross sectional view of magnetic spectrometer and neutron flux meter.

6 . High Intensity Thermal and Epi-thermal Neutron Source

High intensity proton and deuteron beams by the negative ion acceleration mode provide a good place for production of thermal and epi-thermal neutrons. Recent development of high intensity charged-particle accelerator make it possible to use such a neutron beam with almost equivalent intensity as that by a nuclear reactor.

Figure 6 shows a target and moderator system to produce thermal and epi-thermal neutrons from high-energy neutrons by a configuration of Al/Pb, Iron, graphite, heavy-water, and Bi, etc. Of course, there should remain a lot of developing studies to thermalize several tenth MeV neutrons to thermal ones. Especially, minimization of high-energy neutron background is the most important point in these studies.

Utility of high-intensity thermal and epi-thermal neutrons may spread over many research fields, in which activation analysis combined with that by PIXE for medium and heavy elements, and radiography for light elements may be good candidates. Final goal of application of these neutrons is that for the study of Boron Neutron-capture Cancer Therapy (BNCT). Even limited to selective melanoma therapy, collaborations among physicists, pharmacologist, radiologist, and medical scientists are essential. This project is under consideration, being discussed in a working-group organized in CYRIC.

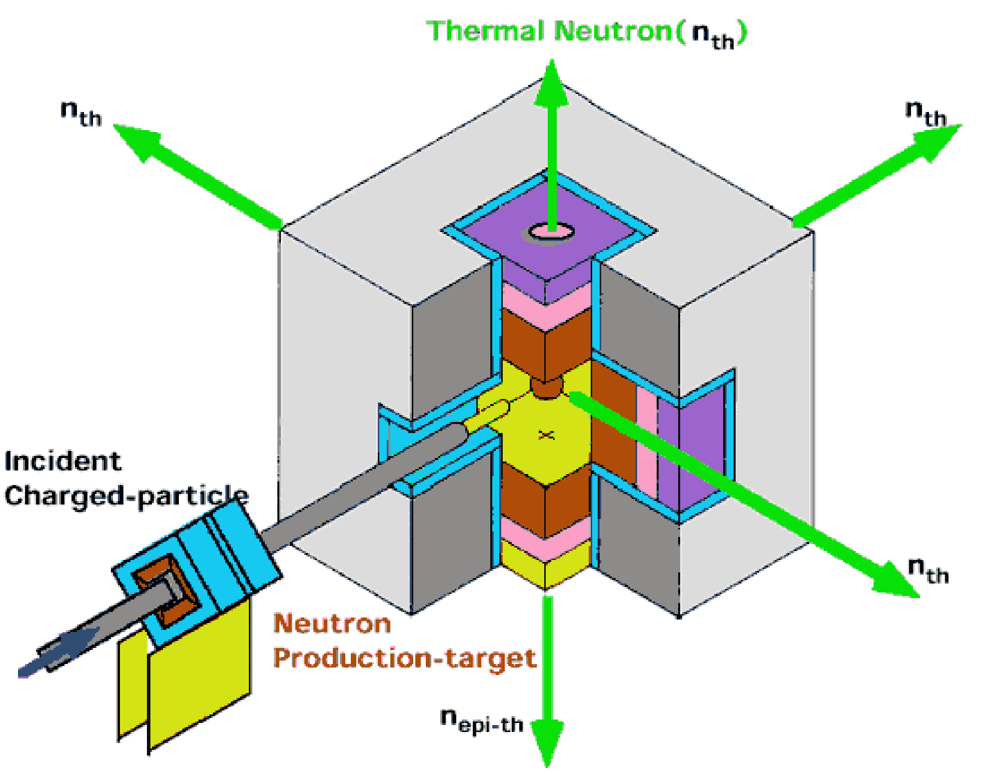

Fig. 6. Sketch of thermal and epi-thermal neutron source.

7 . **Medical Research by Simultaneous Synthesis of Multiple Radiotracer**

Energetic beams may open a new field for production of radiotracers through, for example, (p,xn,yp) reactions on medium and heavy nuclei. With the additional small-size cyclotron already working, multiple production of radionuclides is possible.

Simultaneous measurement of cerebral blood flow gives an estimate of regional tracer delivery and thus improves accuracy of the receptor quantification. For quantitative assessment of neuronal transmitter and receptors, neuronal receptor quantification are made by ^{11}C-labeled receptor ligand and ^{15}O-labeled water are produced, respectively, by K=130 and K=120MeV cyclotrons. As such quantitative evaluation of clinical neuro- psychiatricaldiseases such as dementia, other degenerative disease and psychosis will be carried out. The ^{45}Ti nuclide is suitable for antibody labeling thanks to a longer half-life and high affinity with proteins. Intravascular radioactivity of ^{45}Ti can be connected by measurement of tissue vascular fraction using [^{15}O]carbon monoxide which tightly binds to hemoglobin. Cancer diagnosis using radiolabeled monoclonal antibody may be performed with ^{45}Ti-monoclonal antibody and [^{15}O]-CO produced by K=130 and K=12 MeV cyclotrons, respectively. Figure 7 shows a flow-Chrat for nuclear medicine by PET and related facilities.

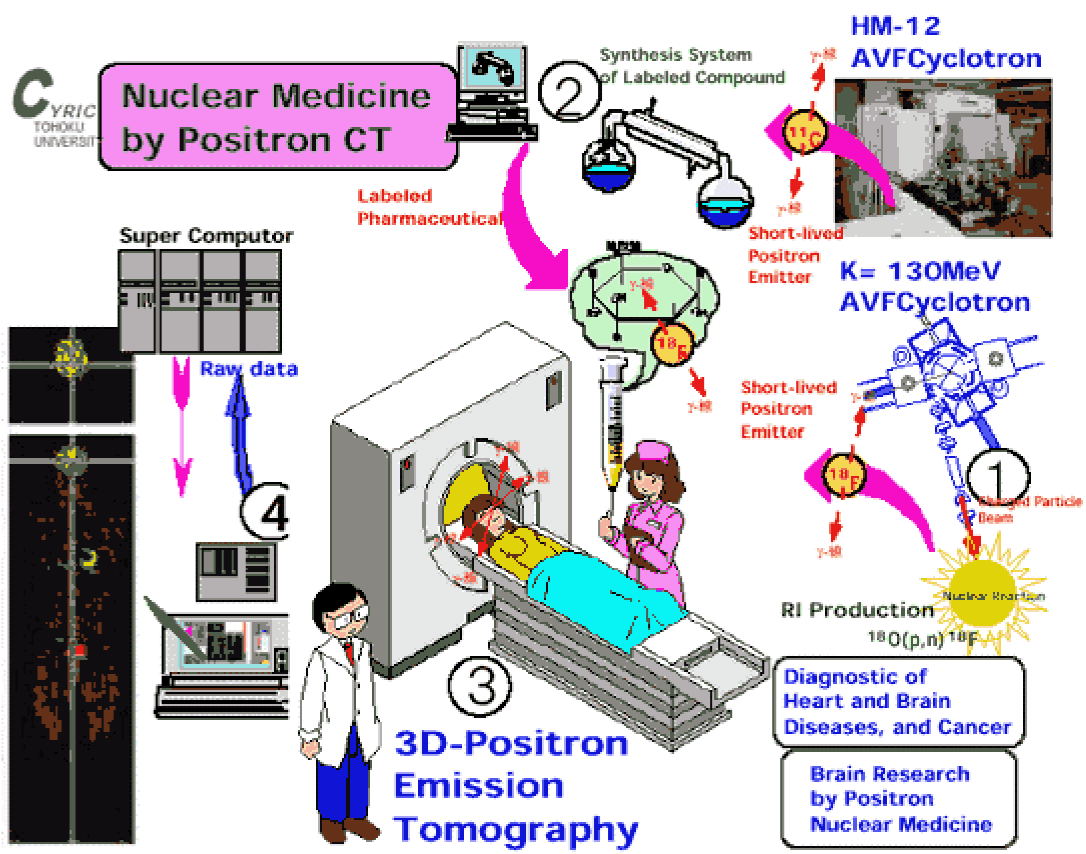

Fig. 7. Illustration for nuclear medicine by PET and related facilities.

As a summary, a layout of building and facilities for “Project for Heavy Charged-particle Beam Multi-purpose Use” are illustrated in the next page.

System for Heavy Charged-particle Beam Multi-purpose Use