

ROLE OF CYCLOTRONS IN RECENT NUCLEAR PHYSICS

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1 RI BEAMS AND CYCLOTRON

Human knowledge is often biased by limited information and science is not free from this problem. In nuclear physics, studies had been restricted to essentially the stable nuclei that have well balanced ratio of proton and neutron numbers.

Recent development of RI beams has revealed this bias and provided the possibility to study structure of unstable nuclei that are very neutron rich or proton rich. New types of nuclear structures have been discovered and nuclear physicists are working hard to understand those new features. It is widely thought among nuclear physicists that we need to formulate a new model of atomic nuclei that can explain the structure of nuclei, stable and unstable nuclei, based on rigorous many-body theory.¹⁾

Nuclear physics is also essential for understanding our existence through the synthesis of elements. All the elements on earth were synthesized through nuclear reactions in the evolution of the universe. To understand the nucleosynthesis we need to understand, what is the limit of the nuclear existence, what properties do nuclei have, and how do they interact each other. To understand those fully we need the basic rule behind many body systems. It means that the whole nuclear physics knowledge is necessary to understand how all elements have been synthesized.

Since Rutherford, studies of nuclei were made by scattering of particles and observation of decays. In nuclear physics scattering could be made only among stable nuclei and elementary particles except a few cases such as a beam of ^3H . Because of that reason, even nucleon density distributions in nuclei could not be studied for unstable nuclei. It is only after the invention of RI beams when the nuclear distributions of short-lived nuclei start to be studied. Immediately after the first use of RI beams has discovery of a new structure, the neutron halo, been made. RI beams definitely provided revolution in nuclear studies. In addition the method of producing RI beams itself provided a powerful tool for expanding the chart of nuclei.

RI beams provide a new class of beam. Use of heavy ions provided the wide variety of elements and mass into nuclear physics. Also a large angular momentum could only be carried into nuclei by heavy ions. Now, with use of RI beams, one can change the combination of isospin in nuclear reactions. It is essentially the freedom to

change the ratio of protons and neutrons in nuclei that could not be made with stable nuclei.

In addition to nuclear physics, RI beams provide many new directions and means for scientific research and practical applications. These require high-intensity and high-quality beams over wide energy and isotopic ranges. Study of reactions relevant to nucleosynthesis need energies below 1A MeV, while investigation of nuclear density distributions requires beam energies of several hundred A MeV or higher. Nuclei at the limit of existence i.e. near the drip lines have expected lifetimes in milliseconds, so that fast production and delivering of RI beams is essential. At present, however, no single method exists for producing RI beams that fulfills all these requirements. Instead, two methods are used

One is the in-flight method and the other is re-acceleration method using isotope separator on line (ISOL). The In-flight method, sometimes called the Fragmentation method, in which a primary stable heavy-ion beam is broken into fragments in a thin production target. A fragment separator selects radioactive fragments of interest, and delivers them to the experimental area. The ISOL method, in which an accelerator or a nuclear reactor yields a beam of charged particles or neutrons that is sent on a thick target to produce radioactive nuclei. The radioactive species thereby produced are transported by a transfer tube to an ion source, and the resulting ions are separated by an isotope/isobar separator, post accelerated and sent to the experimental area.

The In-flight method provides fast production of RI beams and thus the nuclei or isomers of lifetime as short as 1 μs can be separated and used for further reaction studies. Also no elemental restriction exists in this method. A weakness of the In-flight method is the quality of beam. Because of reaction recoil, the RI beam usually has momentum spread as large as a few percent and has a large emittance. In contrast, the ISOL method provides high-quality beam directly from an accelerator. However the extraction of an isotope from the target requires relatively long time and it is extremely difficult to obtain a beam of nuclide with lifetime shorter than 100 ms. Also an extraction of RI from a target is strongly affected by the chemical character of the elements.

A new combined method has been proposed recently. In this method, in-flight separated RIs are stopped in the He gas cell. In the gas cell, rf trapping field and DC drift field are applied to guide the ions of RI to the small exit. Since the stopping time and extraction time is shorter, it

is expected that the short-lived isotopes can also be reaccelerated after the extraction. It is also expected that an elemental dependence of the extraction efficiency be less severe.

Among those method, RI beams produced by the in-flight method provided an important role for discovery of new structures of nuclei near the neutron dripline. This paper describes thus studies though the in-flight method below.

In all method, cyclotrons play important roles all over the world. The advantages of cyclotrons for in-flight method are; high beam intensity with DC operation and the micro-bunch that gives additional identification and separation methods of RI beams. One of the limits of cyclotron at this moment is the energy of beam. Although RI beam can be produced efficiently with a heavy-ion beam of energy higher than 100A MeV, the most efficient production could be made with energy of a few GeV per nucleon. A cyclotron cannot provide this energy under the present technique. A synchrotron can easily provide this energy range of heavy ions but the intensity would be much weaker than that delivered from a cyclotron.

2 RENAISSANCE IN NUCLEAR PHYSICS

Among the many recent studies, I present here the several basic findings in nuclear structure to show the change in nuclear structure physics. More details and more subjects of interests would be found in review papers and in recent conference proceedings.²⁾

2.1 Expansion of Nuclear Chart

The separation method of RI beam provides an extremely efficient method of production and identification of new isotopes far from the stability line. In fact, nuclei near the proton and neutron driplines have been discovered recently. Before the invention of RI beam method, the known neutron dripline was only up to Li. Now we consider that we have reached the neutron dripline up to oxygen. Proton dripline has been extended

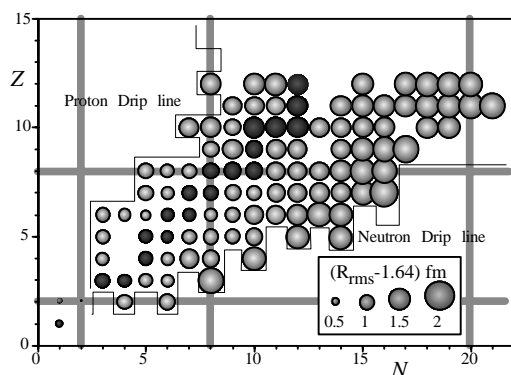


Figure 1. The root-mean-square radii of matter distribution of light nuclei.

now to Ge, As region. The increase of known nuclide in the last decade is remarkable. Newly planned facilities such as NSCL upgrade in MSU and the RI Beam Factory in RIKEN are expected to discover hundreds of new isotopes.

2.2 New structures of nuclei

New structures such as neutron halos and neutron skins have been discovered by the use of RI beams.³⁾ These structures are pressing nuclear physicists to reformulate the nuclear theory.

2.2.1 Nuclear Radii

Radii of nuclei have been determined for unstable nuclei since the first use of High-energy RI beams. Interaction cross sections of RI beams on nuclear target provide the tool for determining radii of matter distributions in nuclei.⁴⁾ Figure 1 shows thus determined effective root-mean-square radii. The matter radius increases as one move away from the valley of stability. It is clearly seen that the radii of isobars are different, and thus break the well-known $A^{1/3}$ rule of the matter radius. The radius is always larger for larger isospin. Sudden increases of radii are seen in nuclei near the neutron drip line. These sudden large increases show formation of the neutron halos. Neutron halos are also observed as narrow momentum distribution of the projectile fragment of those nuclei.

The gradual, but faster than $A^{1/3}$, increase of matter radii along Na isotopes reflects the formation of thick neutron skin. Although direct evidence is only from Na isotopes, where matter radii and proton radii have been separately determined⁵⁾, analysis of charge changing cross section also support the formation of neutron skin in other neutron rich nuclei.

From studies of nuclear density distribution of stable nuclei, three common properties were known. They are;

1. The half density radius of nuclei is proportional to $A^{1/3}$: $R_{1/2} = r_0 A^{1/3}$,
2. Surface diffuseness is constant,
3. Proton and neutron distributions are proportional even if the number of protons and neutrons are different.

Those were considered to be common for all nuclei and used as the base of the nuclear models such as shell model. For example the nuclear potential is described by the equation,

$$U = Vf(r) + V_{ls}(\mathbf{l} \cdot \mathbf{s}) r_0 \frac{1}{r} \frac{d}{dr} f(r)$$

where $f(r)$ is the so-called Woods-Saxon type radial function,

$$f(r) = \left[1 + \exp\left(\frac{r-R}{a}\right) \right]^{-1}$$

The radius R and diffuseness parameter a have the values,

$$R = r_0 A^{1/3}, \quad r_0 = 1.25 \text{ fm}, \quad \text{and} \quad a = 0.65 \text{ fm}.$$

The potential for protons and neutrons differ only by the depth of the potential, V and V_{is} . No change is necessary for $f(r)$ function.

Studies of unstable nuclei, however, show all those rules are broken as seen in the Fig. 1. The R is not only a function of A but also depends on the Z/N ratio, or on N and Z . A large change of surface diffuseness is seen in a halo nucleus. The R for protons and neutrons is different.

These new information indicates that the radial function $f(r)$ should be different for protons and neutrons, namely $f_p(r)$ and $f_n(r)$ with different values of R and a . So far no handy parameterization has been given for unstable nuclei. Collections of much more data are necessary to form the general potential shape.

Why such difference occurs? Figure 2 is the bucket model to explain it. This bucket represents the potential of nucleus in some extent. If one fill a conical bucket buy liquid, the radius of the top surface is proportional to $V^{1/3}$, where V is the volume of the liquid. Now, suppose two types of liquid (proton and neutron) are separated by a wall with small leaking holes. A stable nucleus is described as the right-hand-side bucket. Although the depth of the bucket is shallower for protons because of the Coulomb interaction, protons and neutrons are filled up to the same level. Therefore, none of them leaks into the other part. It means beta decay does not occur and thus the nucleus is stable. In his case the radii of proton and neutron are same because the top level is same.

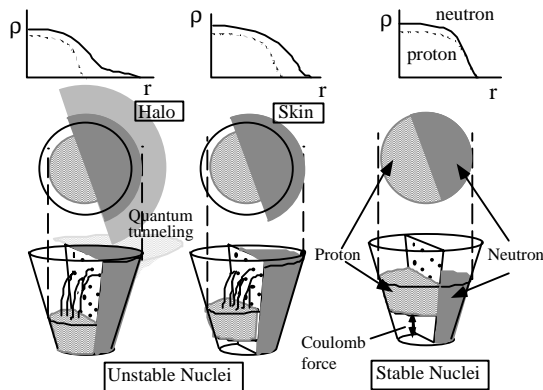


Figure 2. Bucket model of nuclear radii to show why neutron skins and halos appear only in unstable nuclei. Density distributions of nuclei are also shown on the top of the figure.

On the other hand a neutron rich nucleus has different surface level. The neutrons are filled to a much higher level as seen in the central bucket in the figure. Neutrons leak into protons, so that beta decay occurs. In this case, the radius of neutrons is larger than that of protons as easily seen in the figure. Therefore neutron skin is

formed commonly in unstable neutron-rich nuclei but not in stable nuclei.

When neutrons are filled up very close to the rim of the bucket, the quantum tunneling occurs and neutrons extend outside the bucket to a long distance. This is the neutron halo as seen in the let-hand-side bucket.

The neutron skin is the effect of global nucleon distribution but the neutron halo is a new type of quantum tunneling effect. One of the well-known tunneling effects is the alpha decay. An α particle tunnels through the potential barrier and go out from a nucleus. The α particle never comes back into the nucleus. In the neutron halo, however, the tunneling occurs in a bound state. A neutron tunnels out far from the potential to the place where no potential exist. However this neutron does not leave the nucleus. As an example halo neutrons in ^{11}Li stays inside the potential only less than a few tenth of the time.

The discovery of neutron halos and neutron skins removed the restriction in imagination of the nuclear forms. Recently a molecular structure with covalent bond has been observed. A halo nuclei ^6He plays an important role in the formation of covalent bond. In ^6He the last pair of neutrons is bound by less than one MeV. In contrast 20 MeV is necessary to remove a neutron from the α core in ^6He . Moreover the last neutrons are in $p_{3/2}$ orbital and four neutrons can be in the orbital. A covalent bond type molecular structure was firstly suggested from an inelastic scattering experiment of ^{12}Be .⁶⁾ Recent experiment confirmed the rotational band associated with a large deformation and thus confirmed such a state.⁷⁾ This type of state can be connected like a chain and ultimately may form a long chain, a nuclear polymer.

2.2.2 Magic Numbers

Magic numbers (2, 8, 20, 28, 50, 82, 126) indicate the shell structure of nuclei and are important building block of nuclear models. A nucleus with magic proton or neutron number bounds stronger than the neighboring nuclei. In particular a nucleus that has both proton and neutron magic numbers is called as doubly magic nuclei and is extremely important. Magic numbers are considered to be independent from each other for proton and neutron, namely a proton magic number stays constant even a neutron number changes and vise versa. However recent studies in nuclei far from the stability line show that magic numbers are dynamically changing in neutron rich nuclei.

The first example is the neutron magic number 20. It was known from isotope-shift measurements that Na isotopes near and on $N=20$ are deformed and thus magic number may be disappearing.⁸⁾ Recent studies of Coulomb excitation with RI beam clearly showed a disappearance of $N=20$ magic number for Z below 12. One of the important results of it is a non-existence of, supposedly a doubly magic nucleus, ^{28}O . In addition,

recently, it is found that $N=8$ magic number also disappears for $Z < 5$. It is also reflected to no binding of ^{10}He , another supposedly double-magic nucleus. Those are only two places where neutron magic numbers are tested at very neutron-rich region. In both regions, which means in all studied neutron-rich regions, magic numbers disappear. Do all magic numbers disappear in neutron-rich nuclei and the shell structure dissolves?

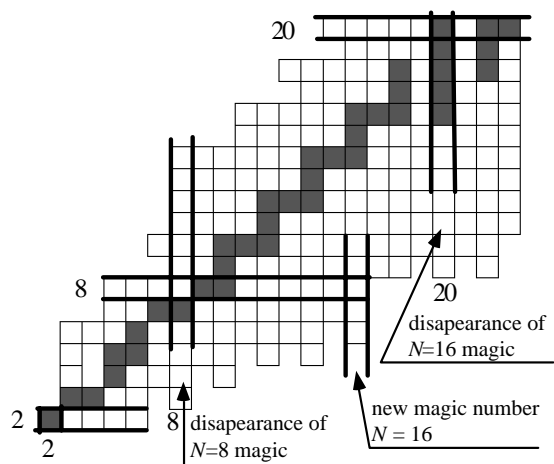


Figure 3. Disappearance of magic numbers $N=8$ and 20 are seen in neutron rich nuclei. New magic number $N=16$ appears in neutron rich nuclei.

In the last year, a new magic number $N=16$ has been discovered in neutron rich region. It was found from an anomaly in nuclear radii and confirmed by the systematic analysis of the binding energy of surrounding nuclei. The neutron number 16 is right in the middle of the s - d shell in the traditional view. It may be due to the formation of a halo or a change in nuclear interaction in asymmetric environment. Theoretical studies are now in progress. It is extremely important to understand why magic numbers change. In addition, it is not only important in nuclear structure physics but also for nucleosynthesis in the universe.

2.2.3 Nucleosynthesis in the Universe

All elements around us were produced along with the evolution of the universe. Light elements up to Li were synthesized right after the big bang. Heavier elements are then produced in and around stars as stars evolve. Then elements up to uranium were produced in explosive events such as supernovae or collision of neutron stars. This explosion also strews elements to the universe. The earth and solar system were produced from those scattered elements. Figure 4 shows the pathways of nucleosynthesis on the nuclear chart. It is important to see from the figure that the most of the processes goes through region of unstable nuclei. Detailed look shows clearly that not only the decay properties but also the reaction of unstable nuclei are essential for the synthesis. Studies with RI beams are important for understanding the origin of elements.

The nuclear structure the magic numbers are also extremely important for synthesis of heavy elements. Solar abundance peaks are known to be due to the magic numbers in both slow process (S -process) and rapid process (R -process). In particular in R -process, magic numbers in neutron-rich regions play an important role. A change of magic numbers in neutron-rich nuclei are thus important information we have to gain using RI beams.

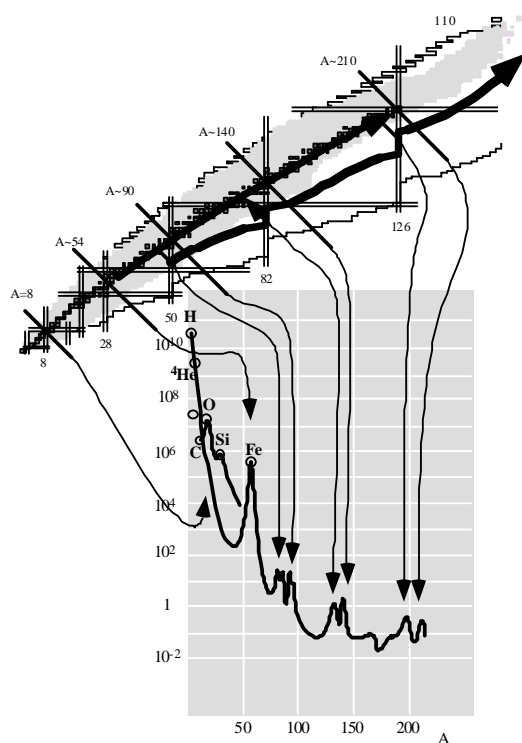


Figure 4. Paths of nucleosynthesis and solar abundance of elements. Unstable nuclei play an important role when heavier nuclides are synthesized.

3 TO THE FUTURE

As described in this paper, RI beams are now indispensable tools for nuclear science. New structures have been discovered and recent studies with RI beams are calling a leap in understanding of nuclei. We have come to the era when we will be able to answer, by experiments in laboratories, how all elements are produced in the universe.

Heavy radioactive elements such as Uranium and Radium left on earth have provided us the entrance to nuclear physics. However, we have not understood how those nuclei have been synthesized yet. It is the time for scientists to understand how U is here on earth in return of kindness of Mother Nature. RI beams are one of the tools that are essential to such studies.

We wish to have RI beams of wide range of energy for wide variety of science. RI beams have to be considered as general accelerated beams, not as beams just for specific use. They are just like heavy-ion beams in wider range of nuclei. They add the freedom to experimentalists.

Cyclotrons are one of the best accelerators to provide the high-intensity beams of heavy-ions and light particles. It is therefore good driver for production of RI beams. For an in-flight production of RI beams high-intensity beams of several hundred MeV to a few GeV per nucleon heavy ions are most appropriate. A large increase of heavy ions is always waited since increase of the intensity is the presently known only method to increase the number of available nuclei. Further development in ion source and cyclotrons are awaited.

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