§28. Feasibility Study on Nuclear Transmutation by Bound State β-decay of Highly Charged Ions

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Nuclear transmutation can be induced in nuclear reactions by neutron bombardments. This is the primary method for treatment of long-lived radioactive fission products, e.g. minor actinides. However, knowledge on the nuclear transmutation is still limited. Basic research is necessary, and it is important also for understanding stellar nucleosynthesis and nucleocosmochronology.

Since it is predicted that efficiencies of the nuclear transmutation via electron capture and β-decay of some heavy elements are sensitive to its charge states, theoretical and experimental investigations have been performed. As an example, neutral ^{163}Dy (Z=66) never transmute to ^{163}Ho (67) via normal β-decay. However, it has been discovered experimentally that bound-state β-decay of bare $^{163}Dy^{66+}$ ions to hydrogen-like $^{163}Ho^{66+}$ ions is allowed [1].

To observe the bound-state β-decay in laboratory plasmas, key issue is sustainability of high-temperature and high-density plasmas. The Large Helical Device (LHD) is disruption free. It has been demonstrated that high peak electron temperatures in the LHD plasma are sustained by neutral beam injection heating after heavy impurity pellet injection, e.g. Fe, W. It is also know that energies of the runaway tail electrons produced with electron cyclotron heating become 100 keV or higher.

In this work, a feasibility study for applying the bound-state β-decay of highly charged ions in helical magnetically confined plasmas to the nuclear transmutation is performed. Also, a novel neutron source using ion cyclotron resonance heating is proposed.

In the bound-state β-decay of highly charged ions with inner-shell holes, an emitted electron via neutron decay in the nucleus is bound in the inner-shell, i.e. the inverse process of the electron capture,

$$n \rightarrow p + e_b^- + \overline{\nu}_e \,.$$

The decay rate is in proportion to squared its decay energy (Q value) which is written in terms of the rest energies of the parent and daughter nuclide as,

$$Q = {}_{Z-1}^{A}Mc^2 - \left({}_{Z}^{A}Mc^2 - Z^2/2\right),$$

where the first term is the rest energy of the parent nuclide, and the second term sum of the rest energy of the daughter nuclide and the orbital energy of the bond electron. The decay is allowed only in cases that the Q values are positive. If the rest energies of the parent and daughter nuclide are close to each other, the Q value becomes sensitive to the binding energy of the electron. For example, ^{163}Dy (parent nuclide) has a little smaller rest energy than that of ^{163}Ho (daughter nuclide) so that normal β-decay is strictly forbidden. However, the bound-state β-decay is allowed, because its Q value becomes positive due to the large binding energy of an electron in $^{163}Ho^{66+}$ ions.

By consulting the old theoretical works by Takahashi et al. [2], experimental decay rates of neutrals and predicted decay rates of its bare ions are compared for a variety of elements. Bare ions of ^{66}Ni, ^{191}Os, ^{228}Ra, and ^{241}Pu are predicted to have relatively larger decay rates of order of 10^{-6} /sec. However, mostly theoretical predictions based on conventional knowledge on isotopes data are available. More experimental investigations are necessary.

In 1966, neutron emission by ion cyclotron heating has been demonstrated at the C-Stellarator in Princeton. 10^6 neutrons per discharge were emitted from the plasma whose radius is 5 cm, H_2:D_2 = 9:1, electron density 4×10^{18} /m^3 [3]. The discharge last about 1 msec. Suppose 1/1000 solid angle for neutron detection in the Princeton experiment, 10^{12} /sec neutron from deuteron nuclear fusion are anticipated in CW operations. This amount is compared to spallation neutron production with a compact proton accelerator, while a scale of the facility is much smaller than that of the proton accelerator. A novel neutron source is based on a helical device equipped with ion cyclotron resonance heating to breed runaway ions (see Fig. 1). Neutrons are produced by bombarding the runaway ions to plasma targets in the helical device.

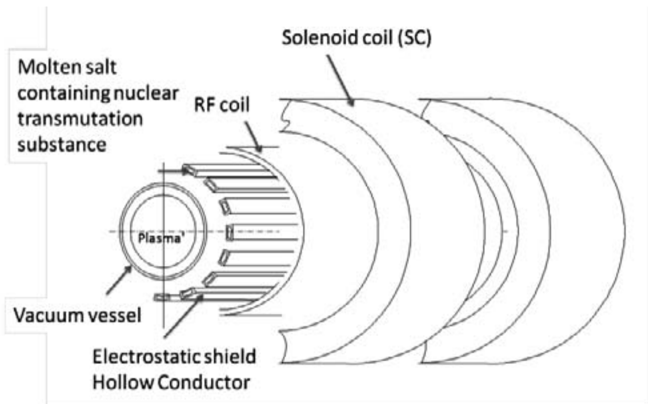

Fig. 1. A conceptual design of a neutron source by ion cyclotron resonance heating.

1) Jung, M. et al.: Phys. Rev. Lett. **69** (1992) 2164.
2) Takahashi, K. et al.: Phys. Rev. C **36** (1987) 1522.
3) Iiyoshi, A. et al.: Phys. Fluids **10(4)** (1967) 749.