Proposal of novel delayed-neutron branching ratio measurements using MRTOF

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The astrophysical r-process plays important roles in synthesis of heavy elements in the universe[1]. The r-process pathway is dominantly determined by the neutron separation energies of neutron-rich nuclei and the abundance of the elements strongly depends on the half-life of the nuclei in the pathway. In addition to these two dominant nuclear properties, the delayed neutron emission probabilities (P_n) and the neutron capture cross sections (σ_n) contribute partially to the element abundance. The cross section does not contribute during equilibrium, but strongly affects the freeze-out stage. However, direct neutron capture cross sections of very neutron rich nuclei is so far very difficult to determine experimentally[2]. During freeze-out, the β-decay path towards stability is defined by P_n. Although almost all nuclei in the r-process pathway have non-negligibly finite P_n, only a limited number of them are experimentally determined.

So far the experimental P_n values have been determined by a limited variety of methods: direct detection of delayed-neutron by ^{3}He gas counters, detection of recoil ions in an ion trap[3], and radiochemical identification of daughter nuclei. We propose a novel method using a gas catcher cell and a multi-reflection time-of-flight mass spectrograph (MRTOF-MS). The principle is the same as the radiochemical method. All daughter nuclides are identified and the yields are compared to determine P_n. In the radiochemical method, characteristic γ-rays and their branching ratios are needed to obtain the yields, however, they are often unknown in such very neutron rich nuclei. In the new method, we identify the daughters and remaining precursor ions by the MRTOF-MS. Figure 1 shows a schematic drawing of the experimental setup. The injected precursor nuclear ions are first thermalized in the gas catcher and decay in the cell. The decay products are also thermalized in the cell and then extracted from the cell using an rf-carpet and transport to the MRTOF-MS. The recoil products are identified by the mass spectrograph. Figure 2 shows a schematic mass spectrum for the case of ^{94}Br. Note that remaining precursor and β decay recoil, single neutron decay recoil, two neutron decay recoil and their daughters (grand daughters of the precursor) are all identified in a single spectrum. It is especially important that the isobaric pair of the precursor and the β-decay product (without neutron emission) can be clearly separated. Such simultaneous detection of multiple atomic mass numbers along with separation of isobaric ions is a unique feature of MRTOF-MS[4]. It is difficult to achieve such capabil-
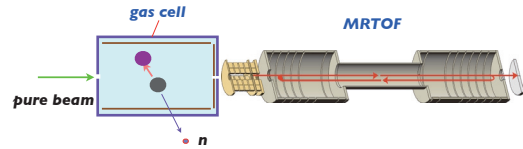

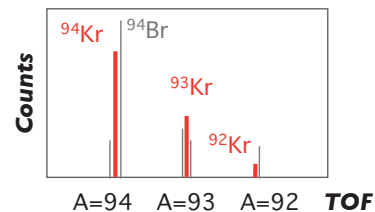Fig. 1. Sketch of setup for P_n measurement with MRTOF

Fig. 2. Schematic time of flight spectrum showing the precursor ^{94}Br, β-decay daughter ^{94}Kr, delayed single neutron decay recoil ^{93}Kr, delayed two neutron decay recoil ^{92}Kr and their daughters.

ities in any other type of separator. The β-delayed neutron decay probabilities can be obtained:

$$P_n = N(A-1)/N_0, \tag{1}$$
$$P_{2n} = N(A-2)/N_0, \tag{2}$$
$$N_0 = N^\star(A) + N(A-1) + N(A-2), \tag{3}$$

where $N(A-x)$ is the sum of x-neutron branch, $N^\star(A)$ is β-decay recoil and daughters excluding the remaining precursor, and N_0 corresponds to the total β-decay number.

Thus obtained P_{xn} have ambiguities due to mixing of the daughter's P_{xn}. However, this can be corrected by an independent measurement using the daughter as a precursor. Moreover, for astrophysical applications, the final mass distribution from a single precursor is the required data. Another possible uncertainty can be attributed to the decay in MRTOF, however, this fraction can be evaluated if the lifetimes are known. In case a cocktail RI beam is provided, one can still determine P_n by solving a linear algebra of the final distributions of isotopes in a few different but known distributions of the cocktail beams.

References
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