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Equivalent determination of tritium production in liquid blanket of fusion reactor using lithium isotopic abundance analysis

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HIGHLIGHTS

- An equivalent method is proposed for measuring the tritium production in the liquid blanket of fusion reactors.
- The theoretical analysis indicates the feasibility of the proposed method.
- A chemical precipitation process is recommended for the sample pretreatment.

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ABSTRACT

Determination of tritium production in the liquid blanket of fusion reactor is necessary for the nuclear material accounting system. In this paper, an equivalent measurement method is proposed, which is based on measuring the isotope abundance of lithium before and after irradiation. Theoretical analysis of the feasibility of the method is carried out, including complex nuclear reactions of neutron and lithium, the influence of the lead matrix, and the influence of gradient of the lithium isotope abundance before and after irradiation.

1. Introduction

Deuterium (D)–Tritium (T) fusion is a key subject of fusion research [1,2]. D-T fusion reactor consumes a large amount of tritium which is very rare in the natural world, and the tritium self-sufficiency in fusion reactors depends on ^{6}Li proliferation in the blanket. In China, both tritium and enriched ^{6}Li are nuclear materials. In accordance with the nuclear safeguard technology and nuclear material control requirements, building a nuclear material accounting system is obligatory to use or produce nuclear materials. Thus, it is essential to measure the accumulated tritium in the blanket of fusion reactors.

The liquid lead-lithium alloy is one of the prominent breeder materials for the blanket of fusion reactor [3–7]. Direct measurement of tritium in the liquid lead-lithium alloy is adopted by most of the current methods and tritium should be extracted from the liquid lead-lithium alloy in these methods [8,9]. But tritium proliferated by ^{6}Li is tightly bound by the liquid lead-lithium alloy, and it is difficult to be extracted [8–12]. Plasma tritium in the core of a fusion reactor may also penetrate into the blanket. Therefore, it is difficult to directly measure the tritium production of the liquid lead-lithium alloy blanket [12]. In addition, tritium has a high diffusion rate for the stainless steel material, and tritium proliferated by ^{6}Li will penetrate into the first wall through the gas solid interface reaction. Calculation of the typical DFLL-TBM model [13–20] showed that there was about 5% of total tritium resident in the blanket system. Meanwhile, there was about 12% resident in the structural material and about 84% resident in the space of system [21]. The penetration and resident of tritium in the blanket system cannot be quantitatively analyzed due to the difficulty of sampling.

In this paper, an indirect measurement method is proposed, which is based on measuring the isotopes of lithium before and after irradiation. The principle of the method is simple, the quantity of sampling is small, and the accuracy of the method is high. So it is suitable for measuring the tritium production in the liquid blanket of fusion reactors.

2. Methods

Based on the reaction of $^6\mathrm{Li} + \mathrm{n} \rightarrow {}^3\mathrm{H} + {}^4\mathrm{He} + 4.79\mathrm{MeV}$, generating a tritium atom must consume a ^{6}Li atom at the same time. By

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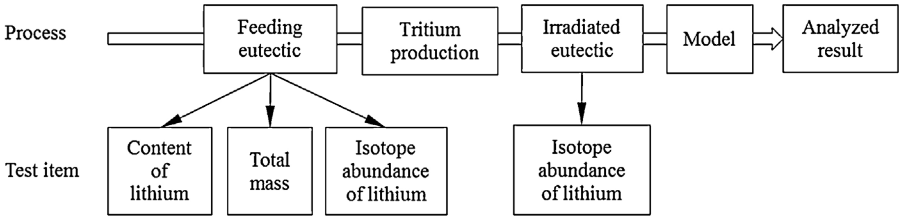

Fig. 1. Measurement process of the method.

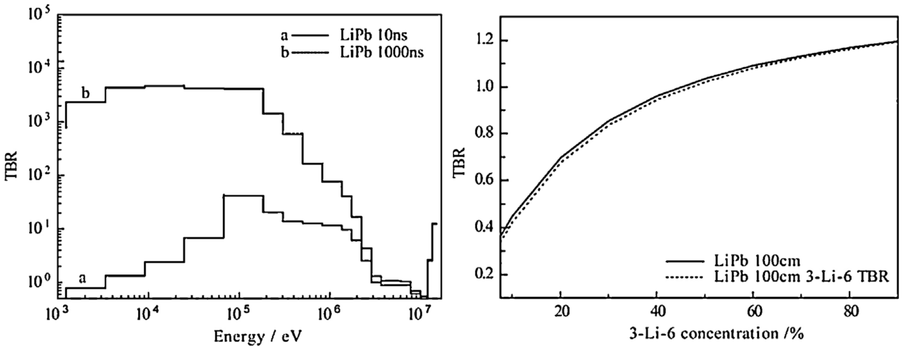

Fig. 2. TBR versus energy and TBR versus ^{6}Li concentration calculated by Yi Weiwei [23].

measuring the total mass and the content of lithium in the liquid lead-lithium alloy, and measuring the lithium isotope abundance before and after irradiation by Thermal surface Ionization Mass Spectrometry (TIMS), the tritium proliferated in the liquid blanket can be calculated eventually. The measurement procedure of the method is shown in Fig. 1.

3. Feasibility analysis of the method

3.1. Key factors evaluation

The reaction between neutron and lithium atoms is very complex, including both elastic and inelastic scattering, and various neutron capture reactions. The main nuclear reaction and cross sections of neutron and lithium atoms are listed in Table 1 [22]. In the liquid blanket, the content of lead is much higher than that of lithium, and the neutron cross sections of lead is large. Yi Weiwei's research shows that the high energy neutrons will be slowed down rapidly in lead-lithium alloy below threshold of the tritium production with ^{7}Li [23]. Therefore, the cross section of reactions in the blanket is much closer to the fission spectrum in Table 1. From Table 1, ^{7}Li (n, n't) and ^{6}Li (n, p) are the main reactions that may have important effect on measuring tritium production by the indirect method.

The method is based on mass spectrometry, and the tritium production is calculated by the lithium isotope abundance before and after irradiation. The interference of lead and the gradient of lithium isotope abundance before and after irradiation will play an important role in the feasibility of the method. In particular, the gradient of lithium isotope abundance before and after irradiation should be effectively identified by the mass spectrometry measurement.

3.2. The effect of ^{7}Li(n, n't) and ^{6}Li (n, p)

In Table 1, excepting for cross sections of scattering and ^{6}Li (n, t), the cross section of ^{7}Li (n, n't) is the largest which mostly impact the measure method.

^{7}Li and ^{6}Li produce tritium from different reaction channels. Tritium produced by ^{7}Li is the result of high-energy-neutrons reaction, and the threshold energy is close to 3MeV. Tritium produced by ^{6}Li is mainly the result of low-energy-neutrons reaction, and the section of tritium production follows the $1/\nu$ law. The cross section of the tritium production of low-energy-neutrons is much larger than that of high-energy neutrons. With the slowing down of neutrons, the neutron energy spectrum is softer and ^{6}Li is more likely to produce tritium [23].

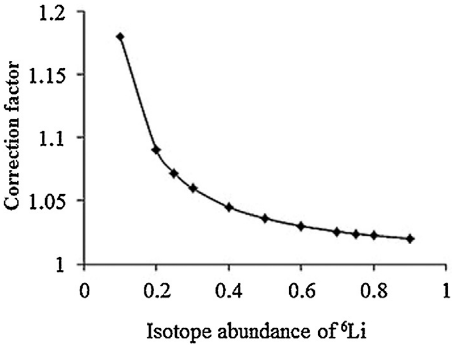

Fig. 3. Correction factor of ^{6}Li/^{7}Li contributed by ^{7}Li (n, n't).

The theoretical calculation results carried out by Yi Weiwei [23] indicated that after the first 10 ns, ^{7}Li was no longer participating in producing tritium. ^{6}Li could sustainably produce tritium for a long time. With the same particle density of ^{6}Li and ^{7}Li, only 1.75% of total tritium was produced by ^{7}Li in the lead-lithium alloy, as shown in Fig. 2 [23]. If the flow channel plug and the first wall tile are present, the neutron in the blanket will be further slowed down and the share of total tritium produced by ^{7}Li will be further reduced. Once the high enrichment ^{6}Li is used in the liquid blanket, tritium produced by ^{7}Li can even be ignored.

The result of mass spectrometry is in a form of ^{6}Li/^{7}Li and the reaction of ^{7}Li (n, n't) has a direct impact on the value of ^{6}Li/^{7}Li. This impact is mainly determined by the abundance of ^{6}Li before irradiation, and it can be eliminated through correction. Theoretical value of the correction factor under different initial abundance of ^{6}Li is shown in Fig. 3. It can be seen that the correction factor