New detector system to measure (n,γ) reaction cross section precisely in China

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Abstract Based on the urgent requirement of the (n,γ) reaction cross-section in the energy range of keV∼MeV, 4π gamma total absorption facility (GTAF) is being constructed at China Institute of Atomic Energy (CIAE). In this paper, firstly the review of historic experimental facilities over the world is presented, and then measurement method of GTAF is described. Finally, the structure requirement for GTAF is presented. Neutron capture reactions are the key process of nucleosynthesis in astrophysics beyond iron element. The application of such facility will improve the experimental condition for the research of (n,γ) reaction.

Key words neutron capture reaction, BaF_2 crystal, 4π γ total absorption facility (GTAF), time of flight technology (TOF technology)

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1 Introduction

Nuclear astrophysics is one of the most active research fields over the world. New method of measurement is the impetus of development. There are two aspects in nuclear physics for astrophysics research. One is direct test of the astrophysics models which have been built. Neutrino plays an very important role because of its really small react rate with other material. The other is to provide the important input parameters for astro-physics models, which are nuclear reaction rate, decay rate, related nuclear structure information and so on. Building and completing the reaction chain is one of the key research work. The reaction processes are H_2 burning, He burning, C-N-O process and s, r, p processes. Among them, the nucleosynthesis beyond iron comes from s, r process(slow neutron capture process and rapid neutron capture process). After the reactions, $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$, they start. The high stellar temperature is about 10^8 k, Thus the interesting energy range is about 1—500 keV. To measure the nuclear capture cross-section, using the acti-method has been performed for a long time in China. The advantages of this method is that the experimental setup is simple and high precise data can be deduced. But the disadvantage is that the half life of the compound nuclei has to be suitable for off-line measurement, which blocks the measurement of a lot of interesting nucleus capture cross section. Therefore a new method is needed for the measurement of neutron capture cross section.

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2 Review of the historic experimental facilities over the world

Since 1950s, various (n,γ) on-line measurement facilities have been built, which are large liquid scintillator, Moxon & Rae detector, C6D6 detector and 4π BaF_2 detector. The first three facilities and the advantage and disadvantage of them will be introduced.

Figure 1 shows the experimental arrangement for large liquid scintillator which consists of neutron source, collimator, scintillator and some of the shielding. The sample is located in the center of the liquid scintillator detectors and the direction of the neutron beam. The γ rays from (n,γ) reaction will be detected by the liquid scintillation detectors. With the time of flight (TOF) technology, the cross section of (n,γ) for different neutron energy can be measured[1, 2]. However, one of the disadvantage of this detector system is that the γ ray from (n,γ) of the sample and from H(n,γ) can not be distinguished clearly because of the bad energy resolution. The other disadvantage is that due to the low detection efficiency gamma multiplicities affects the measurement result. The uncertainty of result could not be better than 10%, which is not satisfied by the requirement.

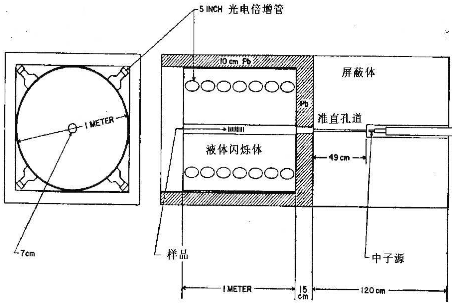

Fig. 1. Experimental arrangement for large liquid scintillator.

Some years later, Moxon and Rae built the new method[3], and the detector is very simple. The experimental arrangement is showed in Fig. 2, and the γ ray is detected by the system which composed of graphite, plastic-scintillation and Photomultiplier Tube (PMT). Its absolute efficiency which is increased with the energy of γ ray is small. To be more specific, an expression for $\varepsilon_{\text{capt}}$ can be written as:

$$\varepsilon_{\text{capt}} = \sum \varepsilon(E_\gamma) = \sum kE_\gamma = kE_{\gamma,\text{tot}} \ . \qquad (1)$$

From the Eq. (1), the detection efficiency is only related with the sum-energy of the cascade γ-rays, and independent of the single γ-ray energy. The main advantage of Moxon & Rae method is that the efficiency of detection is independent of the multiplicity of cascade γ-ray. However the limit of this method is that the efficiency is only about 1% for 1 MeV γ-ray. The efficiency is too small to get the cross section value with the uncertainty better than 10%.

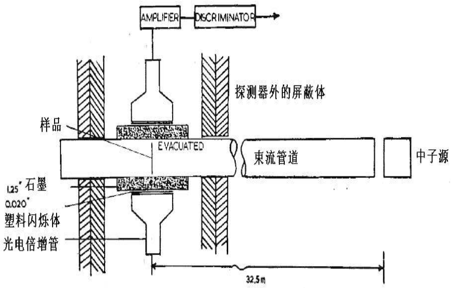

Fig. 2. Schematic of Moxon & Rae detector system coupled with TOF technology.

Figure 3 shows a schematic view of the experiment with C6D6 detector[4, 5]. The detector efficiency for such a system can reach to about 20% and it has very low sensitivity to neutron. The detection efficiency can be deduced from the weighting function, which not only related with the γ-ray energy but also with the structure of the detector geometry and the materials of environment. Unfortunately, it is very difficult to get the precise weighting function to decide the detector efficiency[6]. Therefore, it is not so believable to get data with the uncertainty of better than 5% by the C6D6 detectors.

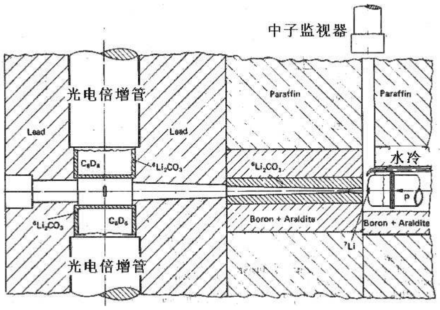

Fig. 3. Schematic setup for the system of C6D6.

In order to get the high precise (n,γ) cross section, the excellent detector system with higher efficiency, better resolution, lower background and faster time response is needed, besides of the good neutron source.

Muradyan et.al had tried to build 4π detector system to measure the cross section of (n,γ) with the good energy resolution and high detection-efficiency. However, because of the bad time resolution of NaI detector, they can not get the precise cross section with precise neutron energy. Development of BaF_2 crystal with good time resolution gives us the chance to build a detector system with good performance. Professor F. Kaeppeler has developed such a system[7—9]. From some papers, high precise results, whose uncertainty is about 2%—3%, has been published. The scintillation light from BaF_2 crystal has two components, one is slow component with a decay time about 620 ns and $\lambda = 325$ nm, another is fast part with a decay time about 0.6 ns and $\lambda = 225$ nm. The decay time of its fast component is the shortest among the inorganic scintillation crystals[10]. The advantages of BaF_2 are high γ detection efficiency, good time resolution, low neutron sensitivity and easy handling etc. To measure the (n,γ) cross section precisely, the 4π gamma total absorption facility (GTAF) with more than 95% event detection efficiency is being built at China Institute of Atomic Energy.

3 Measurement method of GTAF

Neutron capture event is characterized by a cascade of prompt γ-rays. The multiplicity and the energies of the individual gamma quanta are determined by the transition probabilities to a great variety of accessible nuclear levels. The only fixed quantity is the sum energy of the cascade that corresponds to the binding energy of the captured neutron plus the kinetic energy of the captured neutron. It is indicated schematically in Fig. 4 and we have $E_{\mathrm{sum}}=S_{\mathrm{n}}(A+1)+E_{\mathrm{n}}$. $S_{\mathrm{n}}(A+1)$ is the neutron separate energy of the compound nuclei, it's usually about 6—8 MeV. Based on such method, the detector system have the performances of good energy resolution, high detection efficiency, low neutron sensitivity and excellent time resolution, and it can give the information of gamma multiplicity. Using such a detector system combined with the TOF technique, the (n,γ) cross section depending on the neutron energy can be measured accurately.

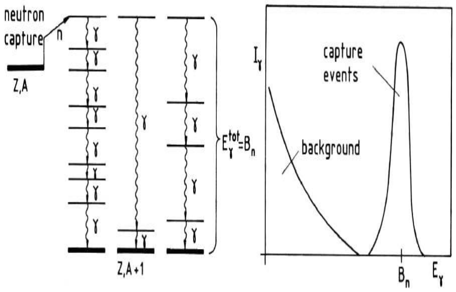

Fig. 4. Left: The excited states in the compound nucleus that are populated by neutron capture can decay via many different gamma ray cascades; Right: Sum energy spectrum of all cascade gamma.

4 The structure requirements for GTAF detector

The essential structure requirements for the detector system for (n,γ) cross section precise measurement are the following:

1) The (n,γ) event detection efficiency reach to 95%, which requires our detector should almost cover the 4π solid angle and the thickness of crystal is not less than 15 cm.

2) Usually, the efficiency is increased with the volume of crystal. However, the cost of crystal and α background from the crystal itself will go up linearly. So, the detector efficiency is high enough for our experiment, while the volume of crystal is as small as possible.

3) Enough Distance from target to crystals is also required to lower the background from the scattered neutrons of target using the TOF technology.

4) Easy construction and minimum cross talk between detector modules. The problem of subdividing a spherical shell into individual crystals has previously been studied[9, 11, 12]. It has shown that the class of optimum polyhedra always has 12 pentagons and a varying number of hexagons. This yields new polyhedra with discrete "magic" number of elements ie 32, 42, 72, 92, 122, 136, 162 etc. Detection ability of detector for strong radiation increased with more granules. However, it will be difficult to afford the cost of system. Usually, the peak of multiplicity is less than 6. An array of 32 elements would be sufficient in this respect, however, because of the limited size of the available BaF_2 crystals, the array of 42 element would be our choose. Also, for the array of 42 granularity covers almost the same solid angle which

is good for the multiplicity measurement. The final shape of the two types of BaF_2 crystals we have chosen is shown in Fig. 5.

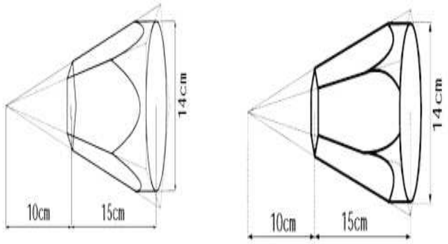

Fig. 5. Shape of the hexagonal and pentagonal BaF_2 crystals for the GTAF. the left is pentagonal crystal and the right is hexagonal crystal.

Each crystal is cut from a cylinder of 14 cm diameter and 15 cm thickness. The detector structure is shown in Fig. 6. The expected key performances are that neutron capture event detection efficiency is more than 95% and time resolution is less than 1 ns. So far, the test for 40 single BaF_2 modules has been done. The test results are that the energy resolution is 14%±2%, and time resolution is 675±47 ps.

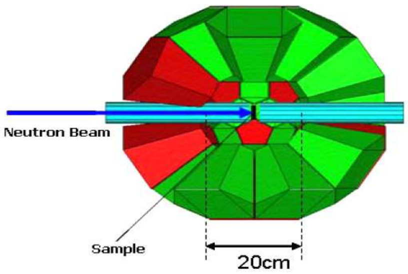

Fig. 6. Scheme of GTAF structure.

5 Conclusions

In this paper, we have given the review of some facilities which are used for the on-line measurement of (n,γ) cross section in the energy range of keV∼MeV over the world. And the introduction of GTAF system which is being built in China Institute of Atomic Energy is presented.

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