Measurement of the neutron spectrum of a Pu-C source with a liquid scintillator

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Abstract The neutron response function for a BC501A liquid scintillator (LS) has been measured using a series of monoenergetic neutrons produced by the p-T reaction. The proton energies were chosen such as to produce neutrons in the energy range of 1 to 20 MeV. The principles of the technique of unfolding a neutron energy spectrum by using the measured neutron response function and the measured Pulse Height (PH) spectrum is briefly described. The PH spectrum of neutrons from the Pu-C source, which will be used for the calibration of the reactor antineutrino detectors for the Daya Bay neutrino experiment, was measured and analyzed to get the neutron energy spectrum. Simultaneously the neutron energy spectrum of an Am-Be source was measured and compared with other measurements as a check of the result for the Pu-C source. Finally, an error analysis and a discussion of the results are given.

Key words neutron response function, the SAND-Ⅱ iterative method, the neutron spectrum of a Pu-C source

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1 Introduction

Pu-C neutron sources are widely used in many nuclear experiments; for example, the neutron radiation effect research of electronics, instruments and various materials, research on the radiation biological effect, and so on. A Pu-C source is also often used for the calibration of gamma and neutron detectors. The 6.13 MeV gammas produced by a Pu-C source represent a very good high energy gamma source for energy and efficiency calibration. For the Daya Bay neutrino experiment, a Pu-C source has been proposed to calibrate the neutrino detectors with its 6.13 MeV gammas and neutrons. There are two key energy points in the Daya Bay neutrino experiment. One is 1.022 MeV, which is the prompt positron signal from the neutrino events. The other is 6 MeV that corresponds to the detection threshold of the delayed neutron signal from the neutrino events. Therefore, the 6.13 MeV gammas from a Pu-C source are very good candidates for energy calibration of the neutrino detectors. The neutrons from a Pu-C source can also simulate the neutron capture signals in the neutrino detectors. In addition, the Pu-C source can also provide other five energy points in the energy region of 1—8 MeV: 1.02 MeV from an electron pair effect, 2.2 MeV from γ ray emission of the ^{1}H(n,γ) reaction; 4.43 MeV γ from the ^{12}C(n,n')^{12}C* reaction; 4.95 MeV from γ ray emission of the ^{12}C(n,γ) reaction and ~8 MeV from the Gd(n,γ) reaction. This is very good for the study of the nonlinearity, energy resolution and stability of the neutrino detectors. The neutron energy spectrum of the source should be known in order to analyze the calibration data with detailed Monte Carlo simulations. However, there are very few neutron energy spectrum measurements for a Pu-C

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source that have been reported in the literature[1], and the neutron energy spectra from different Pu-C sources are different due to the differences in the manufacturing procedure, sealing geometry and sealing materials. Therefore it is necessary to measure the neutron energy spectrum of our own Pu-C source to facilitate the calibration requirements of the Daya Bay neutrino experiment.

This work contains two parts. First, a series of monoenergetic neutron energies from 1—20 MeV produced by the p-T reaction at the HI-13 tandem accelerator at the China Institute of Atomic Energy (CIAE) were used to determine the response function and response matrix of a BC501A liquid scintillation neutron detector. Second, the PH spectrum of neutrons from the Pu-C source was measured using the calibrated BC501A neutron detector, and then the measured PH spectrum was unfolded by the SAND-II unfolding method using the known neutron response matrix, to get the neutron energy spectrum of the Pu-C source.

2 The neutron response function and matrix measurement of the BC501A neutron detector

2.1 Experimental principles and arrangement

The experiment was performed at the HI-13 tandem accelerator at CIAE. The T(p,n) reaction was chosen to produce neutron energies from 1—20 MeV, and a tritium gas target was used to produce good monoenergetic neutrons. The source was shielded and collimated at zero degrees to eliminate accidental background. The neutron detector was placed at the end of the collimator at a distance of 6 m from the source. The neutron detector is a BC501A liquid scintillator (with a size of $\phi 2'' \times 2''$) coupled with a XP-2020 photoelectron multiplier tube with a base of ORTEC-269. The time-of-flight (TOF) technique was applied to suppress the influence of the breakup neutrons from the source in the 8—20 MeV region and the pulse-shape-discrimination (PSD) technique was used to eliminate the gamma background.

First, gamma calibration was performed before the experiment to obtain the relation between the ADC channels and electron-equivalent energy. Compton scattering is the most possible process when γ rays enter into the LS. Thus, if the Compton edge can be accurately determined, then the gamma calibration can be done well. Table 1 shows the γ ray energy and the corresponding maximal Compton scattering electron energy used in the calibration in this work.

Table 1. The γ ray source used in the gamma calibration experiment.

γ ray source	E_γ/keV	E_{emax}/keV
^{137}Cs	661	477
^{54}Mn	834.8	639
^{22}Na	511	341
^{22}Na	1274.5	1061
^{65}Zn	1115.5	907

After the gamma calibration, the LS was irradiated by monoenergetic neutrons with different energies from 1—20 MeV. Three parameters for every event including the pulse height (PH), the PSD for n/γ discrimination and the neutron TOF were recorded by the DAQ system during data taking.

2.2 Data analysis

The basic principle of the data analysis for gamma calibration is the following.

(1) Using the half maximum of Compton edges, a rough gamma calibration result was obtained[2].

(2) The PH spectra of the LS for different gamma sources were simulated by the GRESP code.

(3) The simulated spectra were folded with an energy dependent resolution function and the energy scale was adjusted according to the first calibration result from step (1).

(4) The simulated spectra (after folding and energy scale adjustment) were fitted to the measured ones at the Compton edge region to determine the measured Compton edge. Then a new calibration result could be obtained and step (3) and step (4) could be done iteratively to improve the result. Convergence is reached if the deviations between the results of two consecutive steps are within the uncertainties. Fig. 1(a) shows the simulated spectrum of a ^{54}Mn source compared with the measured spectrum.

For the neutron data, the data analysis was similar to that of the gamma calibration. First, the PH spectra for different neutron energies were simulated by the NRESP[3] code using a default light output function as input. Then the simulated spectra were folded and the energy scale adjusted according to the result of the gamma calibration. After this, the simulated PH spectra were fitted to the measured ones at the edge region to determine the recoil proton edge. From this a new light output function was determined and improved iteratively and finally fixed. Fig. 1(b) shows the simulated PH spectrum compared with the

measured one at $E_{\rm n}=2.04$ MeV. The simulated spectrum agrees very well with the measured one. With this new light output function (Fig. 2), the neutron response matrix could be obtained with the NRESP code.

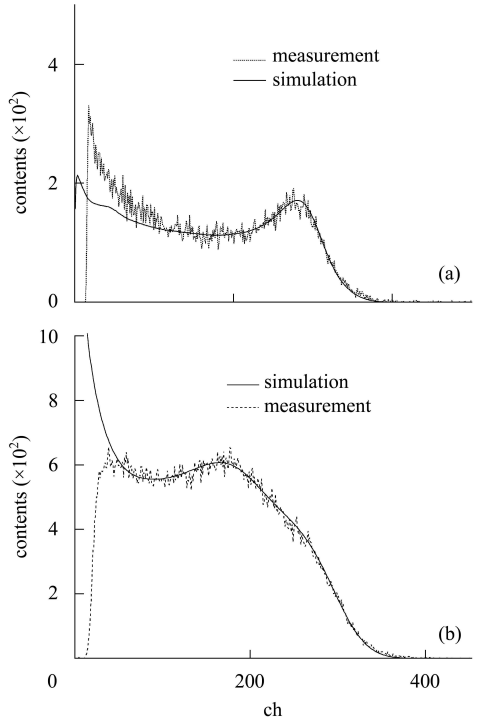

Fig. 1. Comparison of the simulated PH spectrum with the measured one: (a) ^{54}Mn γ ray source, (b) $E_{\rm n}=2.04$ MeV.

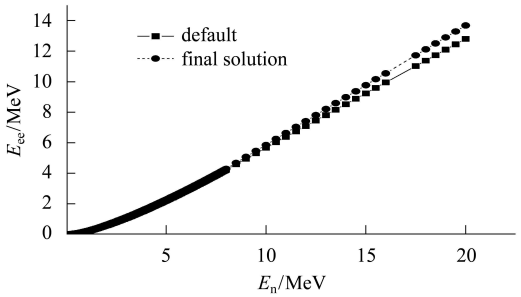

Fig. 2. The light output function of the BC501A detector determined in this work compared with the default light output function of the NRESP code.

3 Unfolding the neutron spectrum of the Pu-C source

3.1 The principle of unfolding

For an LS the measured PH spectrum is related to the incident neutron energy spectrum as follows[4]:

$$N_k(E)=\int R_k(E,E')\Phi(E')\mathrm{d}E',\quad k=1,2,\cdots,K, \quad (1)$$

where K is the number of energy bins of the measured PH spectrum and we label with the index k: $N_k(E)$ is the measured counts in the $k^{\rm th}$ energy bin, $R_k(E,E')$ is the neutron response matrix of the LS and $\Phi(E)$ is the incident neutron fluence spectrum. The procedure of determining an unknown neutron fluence spectrum by solving the set of Eq. (1) is called unfolding the spectrum. There are many methods of unfolding while the iterative method is better in many aspects than other methods and therefore it is widely used. A typical and most widely used method is the SAND-II method. The basic principle of SAND-II for unfolding is the following[5—7]. First, the requested neutron energy region is divided into I energy bins that we label with the index i for the purpose of discretization of Eq. (1). Under this condition Eq. (1) can be written as:

$$N_k(E)=\sum_{i=1}^{I}R_{ki}(E,E')\Phi_i(E')\Delta E'_i,\quad k=1,2,\cdots,K, \quad (2)$$

where $\Delta E'_i$ is the width of the $i^{\rm th}$ energy bin, $R_{ki}(E,E')$ is the neutron response function for the $k^{\rm th}$ energy bin of the measured PH spectrum, $\Phi_i(E')$ is the neutron fluence in the $i^{\rm th}$ energy bin and is also the solution spectrum. Second, one selects an initial approximate input spectrum Φ_i^0 that contains the prior information for the first interaction, then the iteration proceeds according to Eq. (3) and Eq. (4), until the convergence criteria are fulfilled.

$$\Phi_i^{j+1}=\Phi_i^j\exp\left(\frac{\sum\limits_{k=1}^{K}W_{ik}^j\ln\left(\dfrac{N_k}{\sum\limits_{i=1}^{I}R_{ki}\Phi_i^j\Delta E_i}\right)}{\sum\limits_{k=1}^{K}W_{ik}^j}\right),$$
$$j=1,2,\cdots,J, \quad (3)$$

$$W_{ik}^j=\frac{R_{ki}\Phi_i^j}{\sum\limits_{i=1}^{I}R_{ki}\Phi_i^j}\frac{N_k^2}{\sigma_k^2}, \quad (4)$$

where J is the maximum number of iterations, σ_k is the estimated measurement error.

The iteration process terminates if either the value of the standard deviation between the measured PH spectrum and the calculated PH spectrum becomes smaller than a predefined value or if the maximum number of iterations is reached.

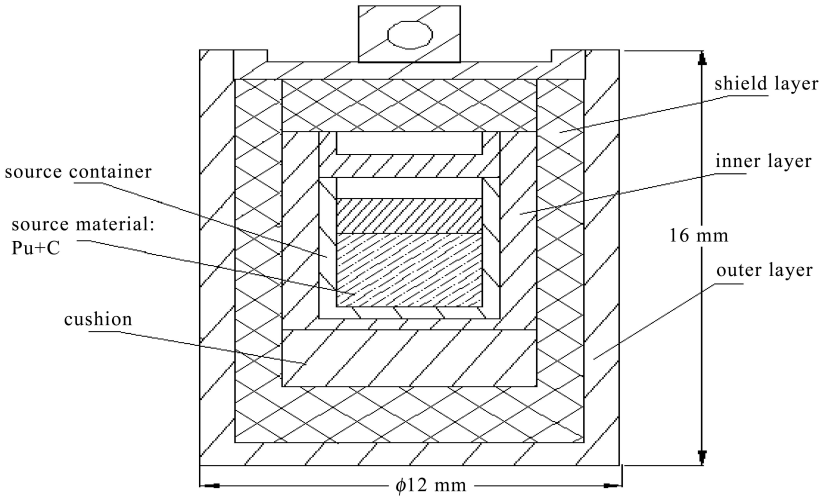

Fig. 3. The structure of the Pu-C neutron source used in this experiment.

Table 2. Size parameters and material of the Pu-C source (in: mm).

name of layers	radius		thickness			height	material
	outer	inner	wall	bottom	top		
source material	6					~3.5	^{13}C, ^{238}Pu
source container	6.6	6	0.3	0.5	0.5	6	Al
inner layer*	8.3	6.7	0.8	0.5	1.5	8	SS
shield layer	10.4	8.4	1	2	2	14	SS
outer layer*	12	10.5	0.75	0.5	1.5	16	SS
cushion	8.2					2	SS

*: Sealed by welding, SS: stainless steel.

3.2 The experiment and results

Before the experiment gamma calibration has to be performed to calibrate the ADC channels as a function of electron-equivalent energy. Then the PH spectrum of neutrons from the Pu-C source can be measured. In this measurement the PSD technique must be used to suppress the gammas from the Pu-C source. The distance between the LS and the source is 10 cm. The structure of the Pu-C source is shown in Fig. 3 and the corresponding parameters are listed in Table 2.

Three input files were needed to unfold the measured PH spectrum using the SAND-II method, namely the measured PH spectrum including the statistical uncertainty, the neutron response matrix and the initial incident neutron energy spectrum. The neutron response matrix was obtained by the NRESP code using the new determined light output function. The neutron energies were chosen according to the energy dependent resolution function of the LS, which was determined from the experimental data of the neutron response function. A uniformly distributed spectrum was used as the initial spectrum since little information on the neutron energy spectrum of the Pu-C source was available. The neutron energy spectrum of the Pu-C source derived with the SAND-II unfolding method is shown in Fig. 4(a). Fig. 4(b) shows the reconstructed PH spectrum according to Eq. (2) using the neutron energy spectrum of Fig. 4(a) in comparison with the measured one. One can see that good agreement has been obtained.

4 Uncertainties and discussion of the results

4.1 Uncertainties

The uncertainty of the results come mainly from the statistical errors of the measured PH spectrum (~2%), the neutron response function of the LS (~2%), the n/γ discrimination (~2%), the gamma calibration (1.5%) and the error propagation in the unfolding procedure (<5%). The total uncertainty of the derived spectrum of the Pu-C source is estimated to be about 6.5%—8.5%.

4.2 Discussion

The ^{13}C(α,n)^{16}O reaction has three neutron groups corresponding to the ground, and 6.049 and

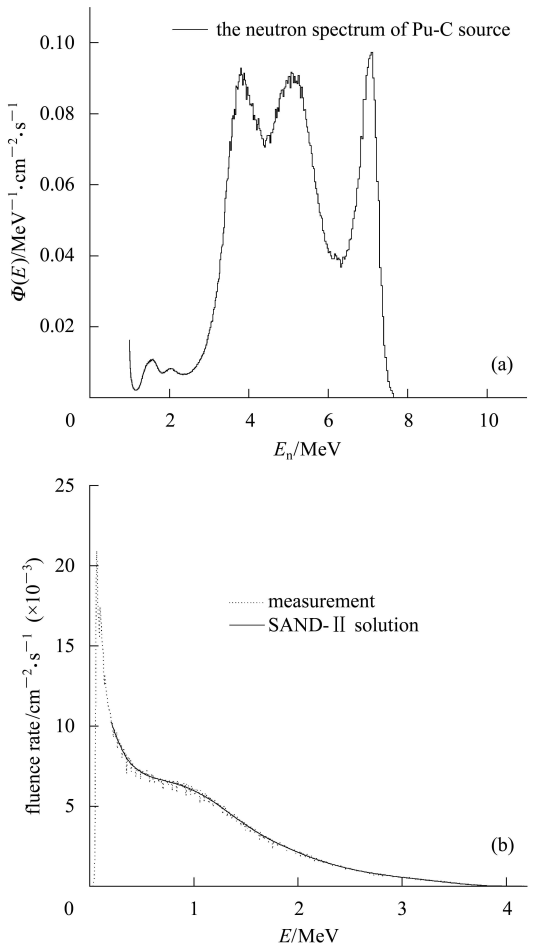

Fig. 4. The neutron spectrum of the Pu-C source derived with the SAND-II unfolding method (a); comparison of reconstructed PH with the measured one (b).

6.13 MeV excited states of ^{16}O. The thresholds of the ^{13}C(α,n)^{16}O reaction for the 6.049 and 6.13 MeV states of ^{16}O are 5.01 and 5.12 MeV, respectively. The maximum alpha energy of ^{238}Pu is 5.5 MeV. Therefore we can conclude that most of the neutrons detected by the LS come from the ^{13}C(α,n)^{16}O (^{16}O at ground state) reaction. From the excitation function we know that the ^{13}C(α,n)^{16}O reaction has many resonances in the 2—5.5 MeV region. Three wide resonances are located at 2.0—2.4 MeV, 3—3.3 MeV and 5—5.5 MeV, respectively. In addition there are many other narrow resonances. If the neutron emission occurs mainly at forward angles[1], the neutron groups will appear at 4.1—4.6, 5.3 and 7.1 MeV and the maximum energy is about 7.5 MeV. From Fig. 4(a) one can see that the neutron peaks at 5.3 and 7.1 MeV agree well with our prediction, while the peak at 3.8—3.9 MeV is slightly lower than the prediction. This may come from other unknown effects such as the lack of precise knowledge of the reaction cross sections and the differential cross sections, the energy loss of alpha particles in the source powder, etc.

In order to verify our result, the neutron spectrum of an Am-Be source (Fig. 5(a)) was also measured using the same method, and the neutron spectrum was compared with other works (Fig. 5(b)). The agreement is reasonable since the three sources are almost the same. To some extent this comparison proves the credibility of our measured neutron spectrum of the Pu-C source.

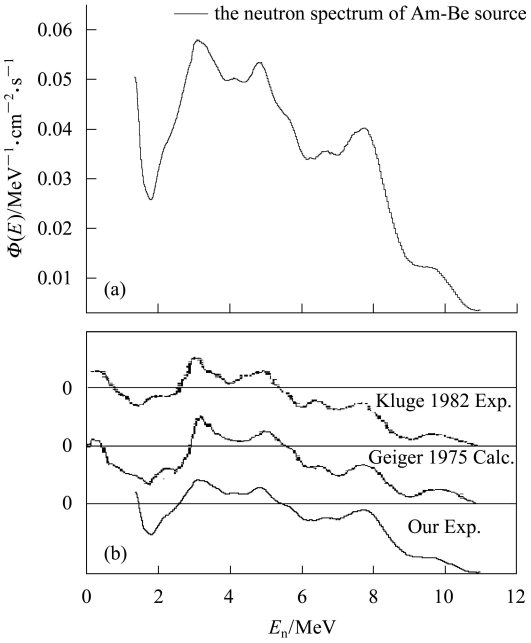

Fig. 5. The neutron spectrum of an Am-Be source measured with the same method as for the Pu-C source. (a) The measured neutron spectrum of the Am-Be source; (b) comparison of the present work with others.

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