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Energy calibration of a BC501A liquid scintillator using a γ-γ coincidence technique

YAN Jie(言杰)[1,2;1)] LIU Rong(刘荣)[2] LI Cheng(李澄)[1]
JIANG Li(蒋励)[2] LU Xin-Xin(鹿心鑫)[2] ZHU Tong-Hua(朱通华)[2]

[1] Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China
[2] Institute of Nuclear Physics and Chemistry, Chinese Academy of Engineering Physics, Mianyang 621900, China

Abstract An accurate energy calibration of a BC501A liquid scintillator by means of Compton scattering of γ-rays is described. The energy resolution and the position of the Compton edge have been precisely determined using a γ-γ coincidence technique and fitting the coincidence spectrum with a Gaussian function superimposed on a quadratic polynomial for the background. The position of the Compton edge relative to the position of the maximum and the half height of the distribution in dependence on the relevant energy resolution is discussed in detail. The results indicate that the maximum energy of the recoil Compton electron does not occur at the half height distribution but at 0.90±0.05 of the maximum height in the energy range considered. The energy resolution varies from 15.6% to 8.02% for electrons in the energy region from 0.5 MeV to 3 MeV.

Key words BC501A liquid scintillator, energy calibration, γ-γ coincidence

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1 Introduction

Organic liquid scintillation detectors of type BC501A (equivalent to NE213) are widely used in fast neutron spectroscopy, neutron time-of-flight measurements and neutron monitoring for its high detection efficiencies and excellent n-γ pulse shape discrimination properties. The accuracy of the determination and setting of the bias level which is mainly attributed to the energy calibration is important in neutron spectroscopy in determining the absolute efficiency and neutron response function measurements for a liquid scintillation detector [1]. Moreover, since the properties of a liquid scintillation detector, such as the energy resolution, are strongly dependent upon the detecting composition (e.g. materials of the scintillator), the geometry of the construction of the detector such as the shape and size of the scintillator, and the type of the photomultiplier (PMT). The energy calibration is very important not only for nuclear physics research and the application of nuclear technology, but also for the study of the scintillator's luminescence mechanism. Therefore the energy calibration is an indispensable procedure before any experiment.

There are two methods for carrying out the calibration procedure by means of "monoenergetic" γ-rays in the preparatory experiments. The first method, viz. the Monte Carlo method, is described by the ICARUS Collaboration [2] and Huang Hanxiong [3]. The Monte Carlo Compton electron spectrum $N^{\rm MC}(E)$ is generated by means of a three-dimensional photon transport code GRESP [4] without considering the resolution smearing of the detector. In order to get the detector energy resolution and the real Compton edge, the experimental Compton electron spectrum is fitted by making use of the "realistic" Monte Carlo spectrum $N^{\rm RE}(H)$ which is obtained from the convolution of the Monte Carlo spectrum with the energy dependent resolution function $R(H,E)$ of the detector system:

$$N^{\rm RE}(H)=\int R(H,E)N^{\rm MC}(E){\rm d}E, \qquad (1)$$

where H is the discrete ADC counts scale and E is the electron energy. The energy dependent resolution function is based on the assumption that for a

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1) E-mail: yanjie@mail.ustc.edu.cn

fixed energy the response function of the detector is a Gaussian whose FWHM describes the energy resolution of the detector system. The second method, viz. the γ-γ coincidence method, is described by D. L. Smith [5] and H. H. Knox [6]. In this method a small gamma ray source is usually placed between the tested detector and a monitor detector. By using the γ-γ coincidence technique, only the photons from the gamma ray source resulting in head-on collisions in the tested detector with subsequent back reflection to the monitor detector define the maximum energy that the Compton electrons can acquire. All events corresponding to other scattering angles are therefore suppressed. The resulting spectrum is a Gaussian, whose centroid value and FWHM represent the maximum Compton electron energy, namely the Compton edge, and the energy resolution of the detector system, respectively.

The precision of the result from the Monte Carlo method depends on the method of modeling and the uncertainty of the reaction cross section in the Monte Carlo code. Inevitably, some approximations are introduced into the calculation. For example, it is assumed that the electrons deposit all their energy inside the scintillator as long as the distance of the interaction to the boundary is greater than the mean range, energy losses due to bremsstrahlung are neglected and so on. In contrast, the γ-γ coincidence method is only affected by the solid angle between the tested and the monitor detectors and by the spread in energy resolution due to the coincidence electronic circuit. The results from this experimental method are much more significant for the application of the detector than the Monte Carlo method.

For this reason, in the present paper, the γ-γ coincidence method is adopted to do the energy calibration of a BC501A liquid scintillation detector by using the channels corresponding to the centroid of the γ-γ coincidence peak. The energy resolution is obtained for electrons in the energy region from 0.5 to 3 MeV. The location of the peak of the Compton distribution is found to be much closer to the Compton edge than to the energy corresponding to the half height of the distribution.

2 Experimental setup

Two BC501A liquid scintillation detectors were set up opposite to each other with a separating distance of 80 mm. The tested scintillation detector consists of a commercial cylindrical detector cell filled with BC501A liquid scintillator. The inner length and diameter of the cell is 2″ (5.08 cm). The cell is coupled to the photocathode of a 9807B photomultiplier tube with silicone oil. In order to reduce the influence of the solid angle between the two detectors, a 1″ BC501A liquid scintillation detector was used as the monitor detector to record the 180° backscattered gamma rays. The gamma ray source was placed at the centre of the surface of the monitor detector. The schematic diagram of the γ-γ coincidence electronic circuit is shown in Fig. 1.

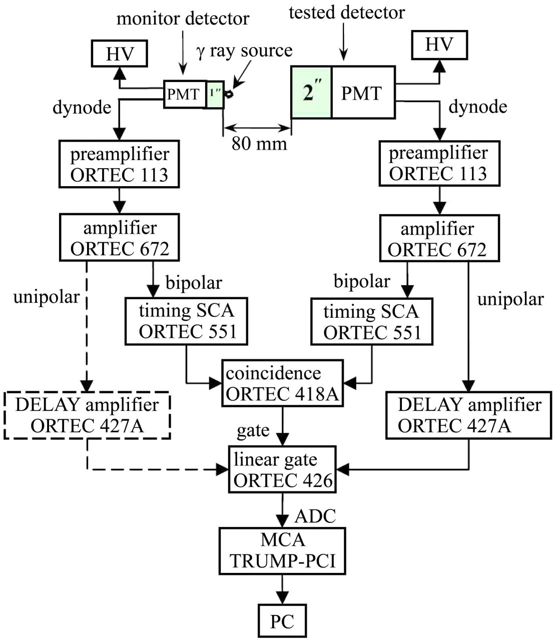

Fig. 1. Schematic diagram of the γ-γ coincidence electronic circuit.

3 γ-γ coincidence measurement

The γ-γ coincidence measurement proceeds as follows [7]. First, the energy windows of both Timing Single-Channel Analyzers (TSCAs) were set to the minimum Lower Level Discriminating (LLD) and the maximum Upper Level Discriminating (ULD) to measure the direct Compton electron spectrum for the two detectors without coincidence, respectively. The location of the half height of the Compton electron spectrum was approximately regarded as the Compton edge whose position represents the maximum energy of the Compton recoil electrons and is given by:

$$E_{\rm c} = \frac{2E_{\gamma}^2}{0.511+2E_{\gamma}}, \tag{2}$$

where E_{γ} is the energy of the incident γ-rays in MeV. The positions corresponding to the maximum energy of Compton electrons (E_{c}) due to incident γ-rays, measured by the tested detector, and the maximum energy of Compton electrons ($E_{\mathrm{c}}^{'}$) due to 180° backscattered γ-rays, measured by the monitor detector, were determined through calculations and are listed in Table 1. Secondly, by adjusting the values of LLD and ULD of the two TSCAs, a wide energy window for the tested detector was set to cover the maximum energy of the Compton electrons, while a narrow energy window corresponding to the energy of the Compton electrons induced by 180° backscattered gamma rays was set for the monitor detector. As shown in Table 1, the maximum energy of the Compton electrons ($E_{\mathrm{c}}^{'}$) due to 180° backscattered gamma rays does not vary much with the incident gamma ray energy. The TSCA window for the monitor detector can be fixed to be the same. Therefore, only if the detector pulse height is acquired in coincidence with the selected signal from the monitor can the signal be recorded.

Measurements were carried out for "monoenergetic" gamma ray sources from ^{137}Cs, ^{54}Mn, ^{24}Na and ^{88}Y. The data of the gamma ray sources used for calibration are also shown in Table 1. The direct Compton electron spectrum and the γ-γ coincidence spectrum were acquired for each source. The typical results for the two spectra of ^{137}Cs and ^{24}Na are shown as circles and crosses in Fig. 2(a) and Fig. 2(b), respectively. From the coincidence spectrum, the centroid and FWHM of the distribution were calculated by using a fit function consisting of a Gaussian function superimposed on a quadratic polynomial for the background. The fitting results are shown as smooth lines in Fig. 2(a) and Fig. 2(b).

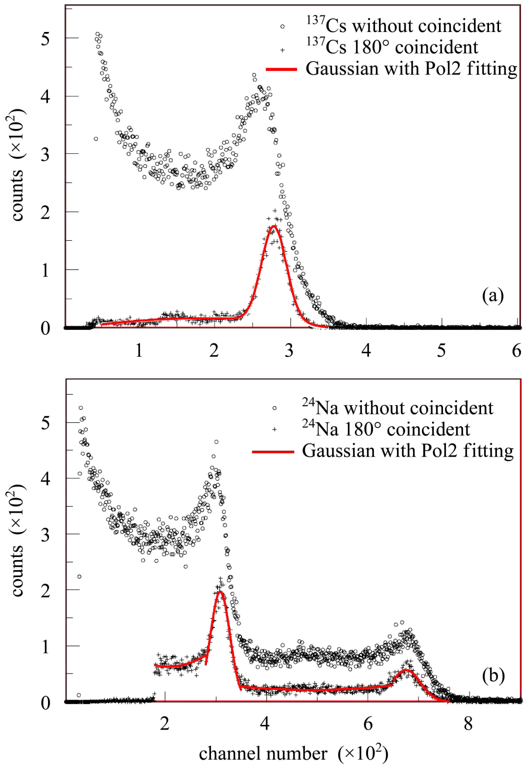

Fig. 2. The typical direct Compton electron spectrum (∘) superimposed on the γ-γ coincidence spectrum (+) for ^{137}Cs (a) and ^{24}Na (b). The smooth lines are the fitting results.

Table 1. Data of the γ-ray sources used for calibration (MeV).

γ-ray source	half life	E_γ	E_{c}	$E_\gamma^{'}$ (backscattered γ-ray)	$E_{\mathrm{c}}^{'}$
^{137}Cs	30 y	0.662	0.477	0.185	0.078
^{54}Mn	312.5 d	0.835	0.639	0.196	0.085
^{88}Y	106.6 d	0.898	0.699	0.199	0.087
^{24}Na	15 h	1.369	1.154	0.215	0.098
^{88}Y	106.6 d	1.836	1.612	0.224	0.105
^{24}Na	15 h	2.754	2.520	0.234	0.112

4 Results

4.1 Energy resolution function

According to Refs. [7, 8], an empirical fit was made to the energy resolution data as a function of the electron energy using the below relation:

$$\frac{\Delta E_{\mathrm{c}}}{E_{\mathrm{c}}}=\sqrt{\alpha^2+\frac{\beta^2}{E_{\mathrm{c}}}+\frac{\gamma^2}{E_{\mathrm{c}}^2}}. \tag{3}$$

It includes three independent contributions:

(a) A constant term α due to the locus-dependent light transmission from the scintillator to the photocathode. It limits the resolution of the detector system at high energy;

(b) A stochastic term β due to the statistical behavior of the light production and attenuation in the liquid, and of the photon-electron conversion and electron amplification in the PMT;

(c) A noise term γ due to the photo-multiplier (dark current) and electronic amplifiers, which can usually be neglected.

All these parameters depend upon the properties of the detector components as well as on constructive details. In our case the contribution from the noise term is expected to be negligible compared to the other two terms. From the FWHM information of the coincidence spectrum fit results described above in detail, the energy resolution data were best fitted by the empirical function with the parameters α=4.92±0.46%, β=10.30±0.23% as shown in Fig. 3. The coefficient β is very sensitive to the scintillator light output and mainly determines the energy resolution of the scintillator. It agrees very well with the previous calculation results (10.0%, G. Dietze, 1982, Ref. [8]; 10.2%–10.8%, ICARUS Collaboration, 1998, Ref. [2]; 10.5±0.5%, A. Öhrn et al, 2008, Ref. [9]; 10.6%, Huang Hanxiong, 2009, Ref. [3]).

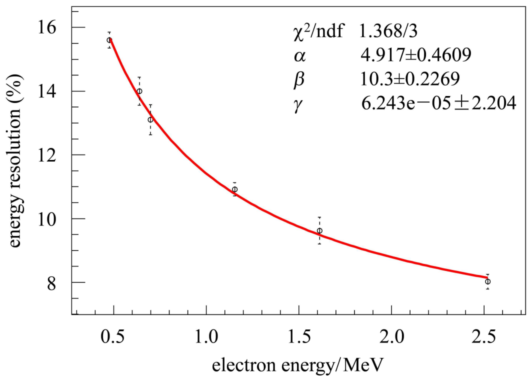

Fig. 3. Pulse height dependent resolution $\Delta E_c/E_c$ for the 2″ BC501A liquid scintillator.

4.2 Position of the Compton edge

Previously published works obtained different results of the position of the Compton edge for the scintillator with different size or different material. Prescott [10] and Beghian [11] found that two-thirds of the maximum height coincides with the maximum Compton electron while Dietze [8] used 0.7 and Knox's result [6] was about 0.89. Besides these, many authors using the Monte Carlo method for the energy calibration did not point out the exact position of the Compton edge. Conventionally the location of the half height distribution is used as a measure of the maximum energy of the Compton electrons in the energy calibration scheme. In the case of the γ-γ coincidence spectrum, because only the gamma rays with 180° backscatter which transfer the maximum energy to the Compton electron, can be recorded, the centroid location of the coincidence distribution represents the accurate position of the Compton edge. Comparing the direct Compton electron spectrum with the γ-γ coincidence spectrum as shown in Fig. 2(a) and Fig. 2(b), it is clear that the Compton edge is neither at the position of the peak of the Compton distribution, nor at the position corresponding to the half height of the distribution. Three deviation parameters defined as $(L_{\max}-L_c)/L_c$, $(L_{1/2}-L_c)/L_c$, $(L_{1/2}-L_{\max})/L_{1/2}$ were used to describe the influence of the finite energy resolution on the position of the Compton edge, where $L_{\max}$, $L_{1/2}$ and L_c represents the position of the peak, the position of the half height of the Compton distribution and the position of the real Compton edge, respectively. The relations for these three deviation parameters as a function of the energy resolution of the detector are shown in Fig. 4. In our experiment we obtained as a result that the maximum recoil energy of the Compton electrons occurs at 0.90±0.05 which agrees very well with H. H. Knox's result.

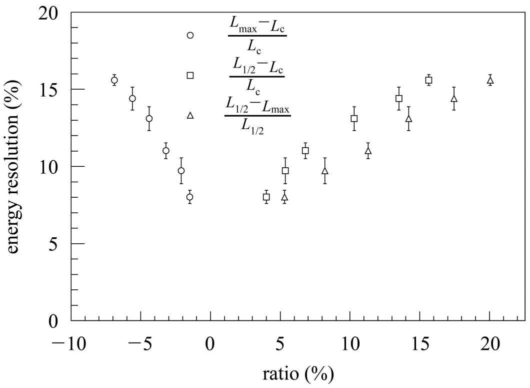

Fig. 4. The positions of the peak $L_{\max}$ and the half height $L_{1/2}$ in a Compton electron spectrum relative to the position of the Compton edge L_c as a function of the relative resolution of the scintillation detector for various energies.

4.3 Linear dependence of the pulse height on the energy of the incident particle

The energy calibration is usually carried out by the linear relationship between the pulse height and the corresponding energy of the incident particle. In conventional energy calibration, taking into account the finite resolution of the detector, one often uses the half height of the Compton distribution as the Compton edge. However, as described above in this paper, the centroid of the coincidence spectrum should be regarded as the real position of the Compton edge. The linear fit of the Compton recoil electron energy and pulse height values from various gamma ray sources is shown in Fig. 5. From the statistical analysis of the linear fit results, the position of the maximum distribution yielded the smallest variance to the real Compton edge.

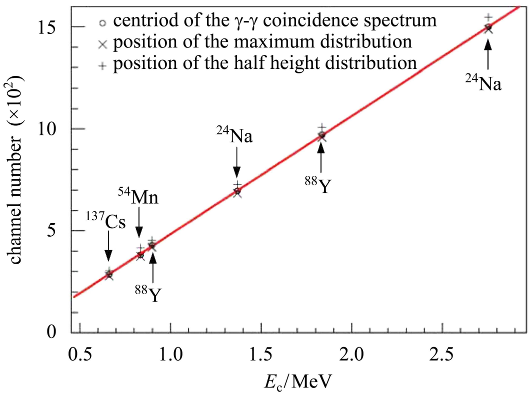

Fig. 5. Linear fit of the electron light output and pulse height values from various gamma ray sources.

5 Discussion and conclusion

The distribution of Compton electrons with the maximum energy was obtained for a 2″ BC501A liquid scintillation detector by using the γ-γ coincidence technique. By fitting the coincidence spectrum with a Gaussian function, superimposed on a quadratic polynomial for background, the energy resolution for electrons in the energy region from 0.5 MeV to 3 MeV and the position of the Compton edge were accurately determined. An empirical energy resolution function was used to fit the relations of the energy resolution with the incident photon energy in terms of Compton electron energy. The fitting results show a good agreement with previous calculations. The maximum energy of the recoil Compton electron occurs closer to 0.90±0.05 of the position of the maximum height. It agrees very well with Knox's results.

In neutron energy spectrum measurements, complex neutron energy spectra can be extracted by unfolding the pulse height spectra on the basis of reference spectra measured with monoenergetic neutrons. The detector response function is an important parameter in the unfolding calculation. The energy calibration results in our experiment can be used to obtain the detector response function by combining it with the charged particle response, as described in Refs. [12, 13]. In the time of flight (TOF) method, the measured spectrum is the neutron time of flight spectrum, which needs to be converted to an energy spectrum. The detection efficiency, which is essentialy relative to the setting of bias levels, is one of the important converting factors. The γ-γ coincidence technique is useful for reducing the uncertainty in determining and setting the bias levels through the energy calibration by using the precise position of the Compton edge. Furthermore, to calculate the neutron detection efficiency, the resolution parameters of the energy resolution function have to be used in the NEFF [14] and SCINFUL [15] Monte Carlo codes.

From the discussion of the relations for the position of the peak and the half height of the Compton distribution with the position of the Compton edge, it is concluded that the conventional assumption that the Compton maximum recoil electron energy occurs at the half height of the Compton distribution is inadequate for this 2″ BC501A liquid scintillation detector. For convenience, it is better to use the location of the maximum of the distribution instead of the position of the half height distribution as the Compton edge in order to perform the energy calibration for this 2″ BC501A detector.

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