A NOVEL METHOD FOR MEASURING THE ENERGY SPECTRUM OF AN INVERSE COMPTON SCATTERING SOURCE BASED ON NUCLEAR RESONANCE FLUORESCENCE

J. Lin[*], H. Ding, Y. Du, J. Sun, C. Tang, H. Zhang, Z. Zhang
Tsinghua University, Beijing, China

Abstract

We proposed a novel method of using nuclear resonance fluorescence (NRF) as a probe for spectrum measurements. By utilizing the continuous tunability of an ICS source, NRF photons can be excited at different points across the spectrum. The shape of the energy spectrum can then be effectively scanned and reconstructed by recording the relative NRF yields at different energy points. The feasibility of the proposed method was validated by Geant4 simulations of measuring NRF photon emission from ^{56}Fe irradiated by an ICS source. The simulation results showed high precision for quasi-monochromatic gamma ray spectrum measurements, with a normalized root mean square error (NRMSE) of less than 5 %. To maintain a sufficient signal-to-noise ratio (SNR) during the measurement, the energy resolution of detectors is suggested to be less than 1 % of the energy being measured. Given an energy tuning precision of ΔE, the minimum measurable width of the energy spectrum, in terms of standard deviation, can reach $0.85 \cdot \Delta E$.

INTRODUCTION

ICS sources have emerged as an advanced light source for generating high-energy gamma rays by colliding relativistic electrons with a laser beam, during which the electrons transfer energy to the photons. The characteristics of the gamma ray pulses generated by ICS sources are quasi-monochromatic, continuously tunable over a wide energy range and ultrashort, allowing a broad range of applications. Before employing an ICS source in gamma ray applications, measuring its energy spectrum is crucial for both produced beam analysis and subsequent experimental use. Traditional direct energy spectrum measurement methods, which rely on energy-sensitive detectors, are highly susceptible to severe pulse pile-up problems due to the short pulses and high brightness of ICS sources. Indirect measurement methods include the Compton scattering method [1], the Bragg crystal diffraction method [2] and the transmission method [3]. The Compton scattering method required placing collimators in front of detectors to achieve higher accuracy, which substantially reduced detection efficiency. The Bragg crystal diffraction method faced challenges in measuring an scattering angle of less than 0.01 degree when the energy reach the MeV level. The reconstruction of the energy spectrum from transmission data was a highly ill-conditioned problem for energy above 100 keV because the attenuation coefficient exhibited an increasingly smooth variation. In summary, current energy spectrum measurement methods face challenges in achieving high-precision and efficient measurements of high-energy and quasi-monochromatic ICS spectra. In this work, we proposed a novel method to measure the spectrum of an ICS gamma ray source based on NRF. By leveraging the continuous energy tunability of the ICS source, the NRF process can be excited at distinct energy points across the spectrum. The spectral shape can then be reconstructed by scanning the energy range and recording the relative NRF yields at different energy points. Simulation work was performed to validate the feasibility of the proposed method using Geant4.

THEORY AND METHOD

^{56}Fe was chosen as the target in this work. The abundance of ^{56}Fe is 91.75 % in nature with less isotopic interference. ^{56}Fe has two nuclear levels at approximately 845 keV and 3449 keV, which provide a larger measurable energy range. The NRF cross section of ^{56}Fe is also relatively higher. Geant4 was used to simulate the measurements of NRF photons from ^{56}Fe. The layout of the simulation was depicted in Fig.1. The gamma ray source was a cone beam with an energy spectrum following a Gaussian distribution or a segmented Gaussian distribution. Incident gamma rays propagated along the Z axis, and the linear polarization was along the X axis. Four HPGe detectors were positioned around the target at an angle of 135 degrees (α in Fig.1) relative to the direction of incident photons. The total number of incident gamma ray events was 10^{11}.

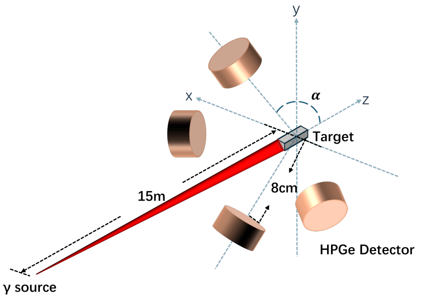

Figure 1: The schematic diagram of the layout.

The normalized root mean squared deviation (NRMSE) was employed to evaluate the accuracy of energy spectrum measurements, which was defined as:

$$NRMSE = \frac{\sqrt{\sum_{i=1}^{M} (S_{m,i} - S_{t,i})^2 / M}}{max(S_t) - min(S_t)}. \tag{1}$$

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[*] linj21@mails.tsinghua.edu.cn

where M was the number of measured points across the spectrum, S_m was the measured spectrum, and S_t was the true spectrum.

RESULTS

A Gaussian Spectrum at 845 keV

A Gaussian spectrum with a standard deviation of 1 % at 845 keV was first used as the incident spectrum. We shifted peak energy with a step size of 2 keV and measured the corresponding NRF yield at each step. For one specific measurement, the energy spectrum detected over the full energy range was shown in Fig.2. Another peak adjacent to the NRF peak with a comparable energy was observed, which came from Rayleigh scattering. The narrow NRF peak enabled background estimation via linear interpolation between two adjacent points, reducing interference from Compton and Rayleigh scattering. The net NRF count was then obtained by subtracting this background from the total peak area.

The signal-to-noise ratio (SNR) was defined in Eq.(2) to evaluate the confidence level of the net NRF count,

$$SNR = \frac{N_{total} - N_{noise}}{N_{noise}}. \quad (2)$$

Assuming that the detection of at least 100 NRF photons is required for data points with intensities above 10 % of the peak intensity, the required SNR is at least 0.5.

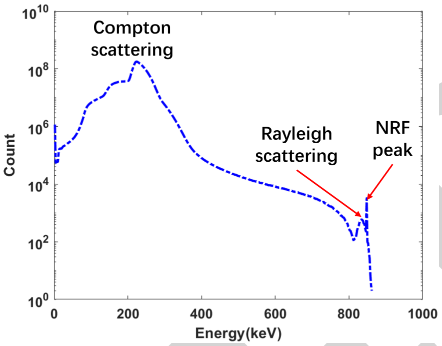

Figure 2: The energy spectrum directly read out by detectors over the full energy range at 845 keV.

As this method required detecting NRF photon counts at different energies, its accuracy was related to the energy resolution of the detectors. Figure3 present the energy spectrum measurement results under different detector energy resolutions. The NRMSE between the measured spectrum and the true spectrum, as well as the SNR for the point at 10 % of the peak intensity under different energy resolutions were shown in Fig.4. When the energy resolution was better than 10 keV, the NRMSE between the measured and the true energy spectra was less than 5 %, indicating good agreement. To meet the requirement of at least 0.5 SNR for data points with intensities above 10 % of the peak intensity, the energy resolution was required to be at least 8 keV.

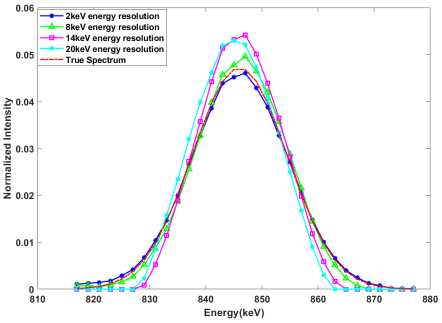

Figure 3: Energy spectrum measurement results under different detector energy resolutions at 845 keV.

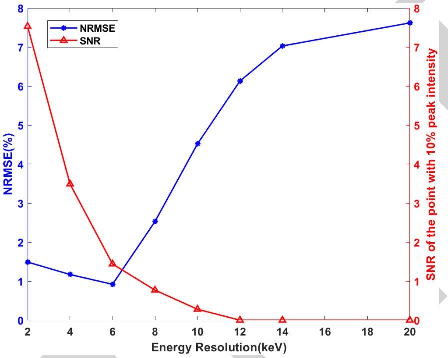

Figure 4: The variation of NRMSE and SNR with different detector energy resolutions at 845 keV.

A Segmented Gaussian Spectrum at 3449 keV

In addition to the energy range below 1 MeV, we also simulated the energy spectrum above 1 MeV using the 3449 keV NRF photons of ^{56}Fe. The spectrum detected over the full energy range in a single measurement was shown in Fig.5. In this energy range, another peak at 3370 keV was observed. These photons originated from inelastic scattering between protons and the ^{56}Fe nuclei, the $(p, p'\gamma)$ reaction. According to the Rayleigh criterion, an energy resolution of at least 40 keV is required to distinguish the 3370 keV peak from the 3449 keV NRF peak.

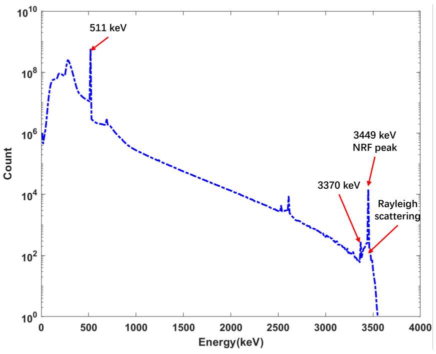

Figure 5: The energy spectrum directly read out by detectors over the full energy range at 3449 keV.

A segmented Gaussian spectrum with a standard deviation of 2.5 % below the peak energy and 1.8 % above it was simulated. Figure6 present the energy spectrum measurement results under different detector energy resolutions. The

NRMSE between the measured spectrum and the true spectrum, as well as the SNR for the point at 10 % of the peak intensity under different detector energy resolutions, were shown in Fig.7. The NRMSE remained below 5 %. The minimum NRMSE was 1.11 % when the energy resolution was 40 keV. The SNR decreased with the detector energy resolution. To ensure an SNR of at least 0.5, the detector resolution can be less than 70 keV. To obtain better measurement results, an energy resolution better than 40 keV was recommended.

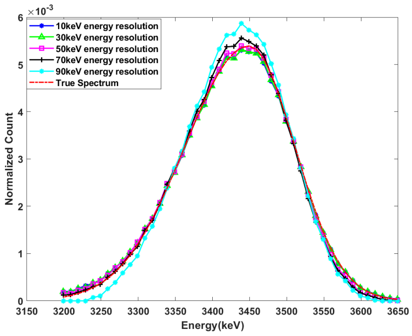

Figure 6: Energy spectrum measurement results under different detector energy resolutions at 3449 keV.

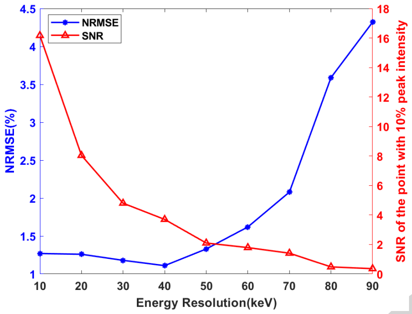

Figure 7: The variation of NRMSE and SNR with different detector energy resolutions at 3449 keV.

DISCUSSIONS

The spectral measurement capability of this method is predominantly limited by the energy level width of NRF, the step size for tuning the mean gamma ray energy, and the energy resolution of the detectors. In practice, within this range, the width of typical energy spectra far exceeds the intrinsic width of NRF, satisfying the key requirement for measurement. The step size for tuning the mean gamma ray energy determines the number of sampling points in the energy spectrum measurement. According to the Shannon sampling theorem, given an energy tuning precision of ΔE, the minimum measurable width of the energy spectrum is approximately $0.85 \cdot \Delta E$ in terms of standard deviation. Figure8 showed that the FWHM remained nearly constant with variations in the step size. Therefore, for quasi-monochromatic spectrum measurement, satisfying the Shannon sampling theorem is sufficient. To maintain a sufficient SNR and obtain a better spectrum measurement result, the energy resolution of the detectors is suggested to reach about 1 % of the energy being measured. The flux of the incident gamma ray beam also plays a significant role. For the setup and material used in this work, given an ICS quasi-monochromatic gamma ray flux of 10^7 photons per second, the measurement time per energy point is approximately 17 minutes.

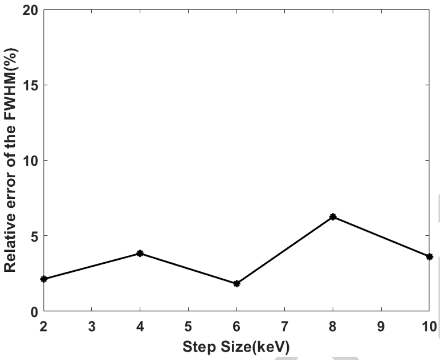

Figure 8: The variation of the relative errors of the FWHM between the reconstructed spectrum and the theoretical value with respect to the step size.

This method also has some limitations. One limitation is that it can only measure the spectrum at energies near the nuclear energy levels of the material. Besides, for real experiments, fluctuations in the total number of incident photons also affect the results of energy spectrum measurements. An additional detector can be placed behind the target to monitor the number of incident photons. Other sources of noise, including environmental background noise and electronic noise, were not taken into consideration in this work.

CONCLUSIONS

We have proposed a novel energy spectrum measurement method of leveraging the continuous energy tunability of an ICS source to excite NRF at different points across the spectrum and reconstructing the spectral shape by scanning the energy range. Given an energy tuning precision of ΔE, the minimum measurable width is $0.85 \cdot \Delta E$. The energy resolution of detectors is preferably less than 1% of the energy being measured. Simulation results demonstrated the precise measurement capability of this method for quasi-monochromatic gamma ray spectra. Further experiments are needed to confirm the practical feasibility of this energy spectrum measurement method.

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