Efficiency calibration of neutron detector array for β decay of exotic nuclei*

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Abstract The research of the in-beam efficiency calibration of Neutron Detector Array of Peking University using ^{17}N and ^{16}C beams was introduced in this paper. The efficiency of neutron wall and ball are comparable to the foreign similar devices and neutrons can be detected from low to high energies in high efficiency.

Key words neutron detector array, efficiency calibration, ^{17}N, ^{16}C

PACS 23.40.-s, 29.40.Mc, 27.20.+n

1 Introduction

β decay of exotic nuclei provides one of primary tools for the investigation of nuclear structure as well as of weak interaction. The large β-decay energy for such nuclei often leads to the population of particle-unbound states in the daughter nuclei. As a result, β-delayed particle emission is frequently the dominant decay mode. For neutron-rich nuclei, most of the emitted particles are neutrons. In order to study the β-delayed neutron decay, the Neutron Detector Array was built in Peking University[1, 2]. Using this Neutron Detector Array, the β-decay of ^{21}N experiment was carried-out in Lanzhou[3]. The result of the in-beam efficiency calibration of the Neutron Detector Array in this experiment was introduced in this paper.

2 Experimental setup

The present experiment was performed at the Institute of Modern Physics(IMP), Lanzhou, China. The primary beam of ^{26}Mg at 68.8 MeV/nucleon was provided by the Heavy Ion Research Facility in

Received 8 July 2008

* Supported by National Basic Research Program (973 Program) of China (2007CB815000, 2005CB724800) and National Natural Science Foundation of China (10775003, 10475004, 10405001, 10221003)

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Lanzhou (HIRFL) and impinged on a ^{9}Be primary target. The produced fragments were separated, purified, and collected by the Radioactive Ion Beam Line in Lanzhou (RIBLL)[4].

The experimental setup is shown in Fig. 1 and Fig. 2. The ^{17}N/^{16}C beam passed through a thin Kapton window which separated the vacuum of the beam line from the air. Before the ^{17}N/^{16}C beam was finally stopped in a thin plastic scintillation detector, referred to as the implantation detector, it also passed a silicon surface-barrier ΔE detector which was used for on-Line monitoring of the purity of the ^{17}N/^{16}C beam in combination with the time of flight measurement and an energy degrader(whose thickness was adjustable). The ΔE detector also allowed us to determine the exact number of ^{17}N/^{16}C ions deposited in the implantation detector. To verify that the ^{17}N/^{16}C ions were indeed stopped in the implantation detector, a silicon surface-barrier veto detector was placed behind the implantation detector. During the experiment, the purities of ^{17}N and ^{16}C were 59% and 46.5% respectively. The main impurity was ^{18}O and ^{20}F for ^{17}N beam and ^{19}O for ^{16}C beam.

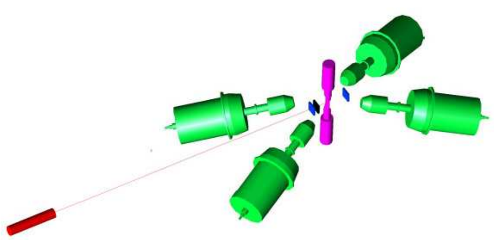

Fig. 1. the Implantation detection system and clovers.

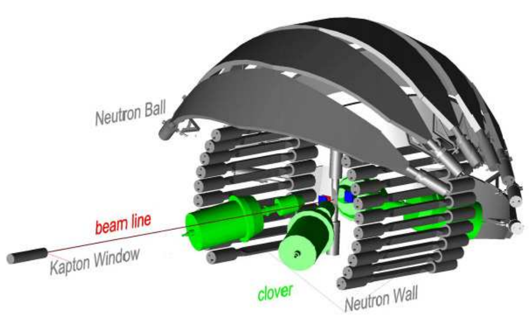

Fig. 2. Neutron Detector Array: neutron wall and neutron ball.

The β-delayed neutrons were measured by Neutron Detector Array, which includes two sections, neutron wall and neutron ball shown in Fig. 2. The neutron ball is composed of 8 pieces of plastic scintillator (BC408) and every piece is a wedge-shaped with a length of 157 cm and curved to a radius of 100 cm in order to keep the same distance for neutron TOF measurement at all directions. The thickness of the scintillator is 2.5 cm and the width is 40 cm at the middle and reduced to 20 cm at both ends. The ball can cover a total solid angle of up to 30% of 4π. Because of higher neutron detection threshold, it is used for the detection of neutrons between 1 MeV and 10 MeV. The neutron wall consists of 20 paddles shaped as 40 cm×4.5 cm×2.5 cm which is also made of plastic scintillator BC408. The distance from the center of neutron wall's each bar to that of implantation detector is about 62 cm. It has the lower energy threshold for neutrons and mainly built for the observation of neutrons with low energies(<1 MeV).

Four high-purity germanium 4-fold segmented clovers were used to detect γ-rays in this experiment. The distance between the center of each clover detector to that of the beta detector is about 12 cm.

3 Experimental method

In this experiment, the beam was pulsed at regular intervals so that the ^{17}N/^{16}C ions were implanted while the beam was on and decays were detected while the beam was off. This provided clean conditions for the observation of the β-delayed neutron decay, free from interference from the direct beam. The beam was turn on and off by using a module Chopper. During the experiment, the durations of beam-on and beam-off periods were chosen to be 9.25 s/10.75 s (on/off) for ^{17}N and 2 s/2 s for ^{16}C.

Both ^{17}N and ^{16}C beams were used to calibrate neutron detection efficiency in this experiment. These nuclei produce neutrons with well-known energies/branching ratio of 382.8±0.9 keV/(38.0±1.3)%, 1170.9±0.8 keV/(50.1±1.3)%, 1700.3±1.7 keV/(6.9±0.5)% from ^{17}N decay and 810±5 keV/(84.4±1.7)%, 1714±5 keV/(15.6±1.7)%, 3290±30 keV/(1.0±0.2)% from ^{16}C decay[5, 6]. The calibration function is:

$$\varepsilon_{\mathrm{int}}(E_i) = \frac{N(E_{\mathrm{i}})_{\mathrm{obs}}}{N_{\beta} \times \varepsilon_{\mathrm{l.t.}} \times B.R.(E_{\mathrm{i}}) \times \varepsilon_{\mathrm{geom}}} ,$$

where E_{i} is the energy of the delayed neutron group emitted from the unbound state i; $N(E_{\mathrm{i}})_{\mathrm{obs}}$ is the observed number of the delayed neutrons; N_{β} is the counts of β particles recorded during the beam-off period; $\varepsilon_{\mathrm{l.t.}}$ is used to correct the dead time; $B.R.(E_{\mathrm{i}})$

is the branching ratio for this neutron group; $\varepsilon_{\rm geom}$ is the geometrical efficiency of neutron detector.

4 Analysis and results

4.1 β decay of ^{17}N/^{16}C

The total number of beta events detected by the implantation detector throughout the beam off period was recorded by the scaler. In this experiment, the beta decay curves were measured by choosing a pulse as the master trigger whose period was set to make the dead time disappear exactly. The individual contributions to the decay from each implanted nuclide are shown in Fig. 3 and Fig. 4 by fitting the decay curves. The half-lives of ^{17}N, ^{20}F (impurity for ^{17}N) and ^{16}C, ^{19}O (impurity for ^{16}C) were fixed since they were known from previous work. Only the number of implanted nuclides at the beginning of beam-off were kept as variables through the fitting procedure. Then the contribution of each component to the total beta events was defined, 93.6% for ^{17}N and 42.1% for ^{16}C.

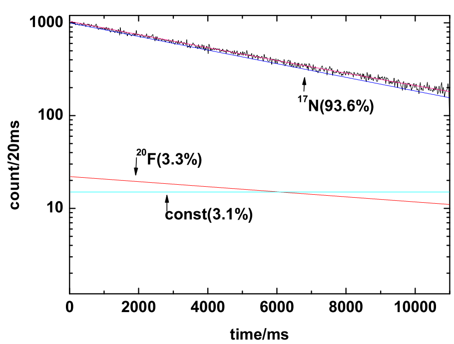

Fig. 3. β-decay curve of ^{17}N.

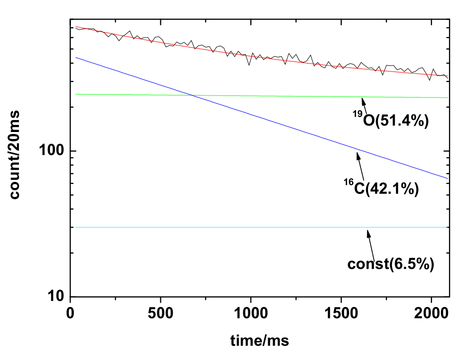

Fig. 4. β-decay curve of ^{16}C.

In the experiment, we also detect the β-delayed γ. Because the efficiency of the γ detectors have been calibrated, the γ branching ratios were well-known and the numbers of the γ for every γ-peak have been recorded, the contribution extracted above by fitting the decay curves can be checked by their γ-rays data. The result indicates that they agree with each other within 5% uncertainties.

4.2 Analysis of the neutron time-of-flight data

The neutron time-of-flight spectra measured by the neutron wall and neutron ball are shown in Fig. 5 and Fig. 6. Time zero was deduced from the position of a prompt peak which was produced by relativistic electrons. Three delayed neutron groups emitted from the β-decay of ^{17}N can be seen clearly. These neutron peaks observed were fitted simultaneously with hypergaussian function and polynomial background plus exponential tail on the long time-of-flight (low energy) side to account for scattered neutrons, using the program PEAKFITS.

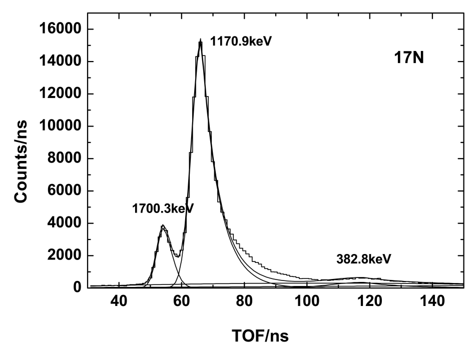

Fig. 5. β-delayed neutron time-of-flight spectrum of ^{17}N decay from the neutron ball.

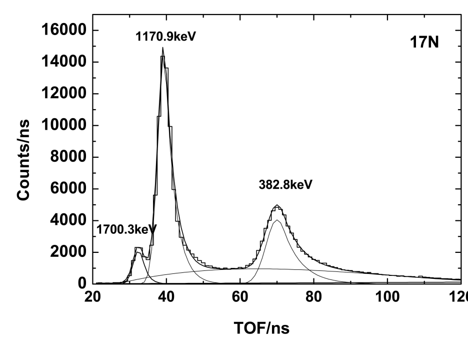

Fig. 6. β-delayed neutron time-of-flight spectrum of ^{17}N decay from the neutron wall.

5 Results and discussion

The efficiency for the array was calibrated using peak areas from the total neutron energy spectra from ^{17}N and ^{16}C decays and known emission probabilities corresponding to each transition . Six data points were obtained for ball/wall and the uncertainities were about 10%. To extend the efficiency curve to higher energy, Monte Carlo calculations using the KSUEFF program[7] have been made. Fig. 7 and Fig. 8 show the efficiency curve for the entire neutron ball and wall, respectively. For the neutron ball, the intrinsic detection efficiency is about 25% at 1.5—2.5 MeV, and decreases quickly below 1.5 MeV. For the neutron wall, the intrinsic detection efficiency is about 40% at 1 MeV and still high at low energy region, 30% at 0.383 MeV.

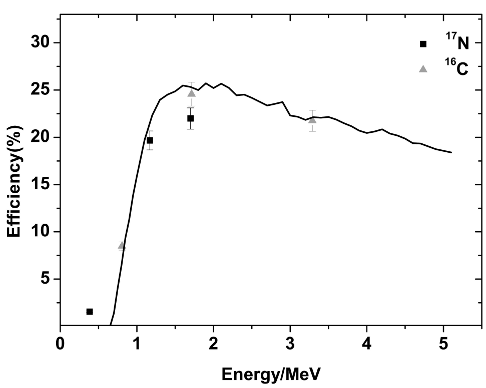

Fig. 7. Neutron efficiency as a function of neutron energy for the neutron ball. The solid line represents the Monte Carlo calculations using the KSUEFF program.

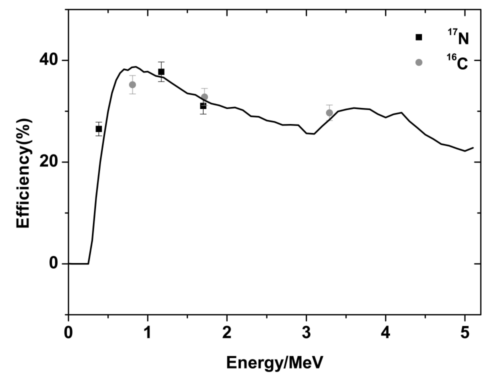

Fig. 8. Neutron efficiency as a function of neutron energy for the neutron wall. The solid line represents the Monte Carlo calculations using the KSUEFF program.

The efficiency of the ball is comparable to the similar device in the world such as neutron sphere of MSU[8], whose thickness is 2.5 cm and length is 157 cm. The intrinsic detection efficiency of the sphere of MSU is about 20% at 1—2 MeV. The neutron wall of Peking University has low detection threshold that can make the whole neutron detection array have low detection threshold. So the neutron detection from low energy to high can be realized using the neutron detection array of Peking University.

We would like to acknowledge the staffs of HIRFL for providing the ^{26}Mg primary beam and the staffs of RIBLL for all kinds of assistance.

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