# Probing neutron unbound states of $^{10}$Be populated in $^{9}$Be+$^{9}$Be collisions

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## I. INTRODUCTION

Nuclear reactions involving weakly bound stable nuclei ($^{6,7}$Li,$^{9}$Be) have been of considerable interest in recent years due to their pronounced breakup channels and cluster structures. Among them, $^{9}$Be is particularly important because of its Borromean nature, which is key for the probe of three body forces in the nuclear domain. However, $^{10}$Be is a long-lived radioactive isotope with half-life $\sim$ 1.39 Myr, often used in geochronology and cosmogenic studies. $^{10}$Be also exhibits interesting cluster structure and halo-like features in excited states [1, 2]. The study of unbound and resonant states in $^{10}$Be provides valuable information on the interplay between clustering, continuum coupling, and shell evolution in light neutron-rich systems. In the present work, we have investigated neutron-unbound states of $^{10}$Be populated via the $^{9}$Be($^{9}$Be, $^{10}$Be) $^{8}$Be reaction, with the aim of exploring the decay mechanisms and resonance structures of $^{10}$Be above the neutron separation threshold.

## II. EXPERIMENTAL DETAILS

The experiment was performed at the BARC–TIFR Pelletron -linac Facility, Mumbai, using a pulsed $^{9}$Be beam incident on a self-supporting $^{9}$Be target of thickness $\sim$1 mg/cm$^2$. Charged particles were detected with four silicon strip detector telescopes in a $\Delta E$–$E$ configuration. Each telescope consisted of a thin $\Delta E$ detector (T1–T3: 30 $\mu$m; T4: 40 $\mu$m) and a thick $E$ detector (T1–T3: 1.5 mm; T4: 1.0 mm), positioned 13.4 cm from the target and cov-

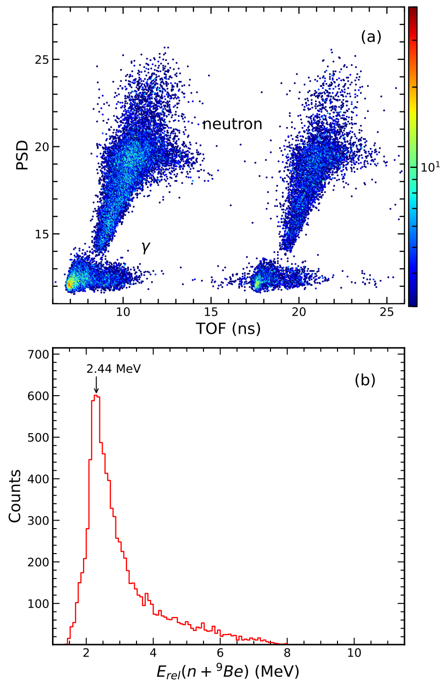


FIG. 1: (a) Typical pulse-shape discrimination (PSD) versus time-of-flight (TOF) spectrum for the $^{9}$Be+$^{9}$Be system at $\theta$ = 58°. (b) Reconstructed relative energy distribution of the $^{9}$Be and neutron measured in coincidence.

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ering laboratory angles from 20°-70°. Neutrons were detected using an array of 15 liquid organic scintillator (EJ-301) detectors [3], placed at laboratory angles between 25° and 65°, with their centers located 72 cm from the target. Neutron–$\gamma$ ray discrimination was performed using the standard pulse-shape discrimination (PSD) technique. Data were collected in an event-by-event mode with a VME-based acquisition system. Time calibration was carried out using a precision time calibrator. Neutron energies were extracted from their TOF relative to the pulsed beam is shown in Fig. 1(a) and used for subsequent analysis. The silicon detectors were calibrated using the known energies of $\alpha$ particles from a $^{229}$Th source.

## III. ANALYSIS AND RESULTS

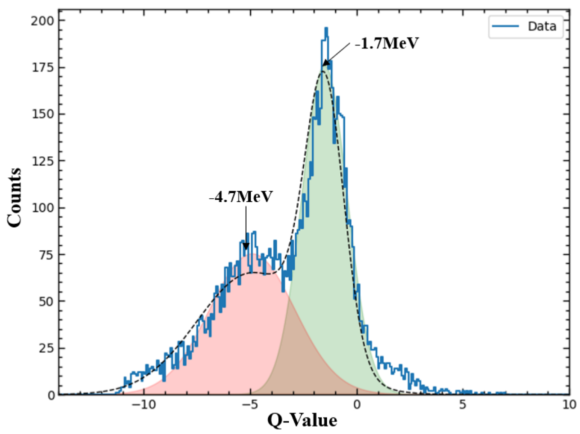


FIG. 2: The reconstructed $Q$-value distribution for the $^9$Be($^9$Be, $n\,^9$Be)$^8$Be reaction from coincidence events of $^9$Be and neutron.

Particle identification was performed using the $\Delta E$–$E$ technique based on energy-loss measurements. Events corresponding to $^9$Be and $n$ detected in coincidence were used to extract the scattering angles, kinetic energies, and excitation energies of $^{10}$Be prior to breakup. The measured energies ($E_n$, $E_{^9\mathrm{Be}}$) and relative angles ($\theta_n$, $\phi_n$; $\theta_{^9\mathrm{Be}}$, $\phi_{^9\mathrm{Be}}$) were then used to reconstruct the kinetic energy ($E_{^{10}\mathrm{Be}}$), emission angle ($\theta_{^{10}\mathrm{Be}}$), and relative energy $E_{\mathrm{rel}}$ of the scattered $^{10}$Be prior to breakup. The relative energy between the neutron and $^9$Be fragments was calculated using:

$$E_{\mathrm{rel}} = \frac{m_{^9\mathrm{Be}}E_n + m_n E_{^9\mathrm{Be}} - 2\sqrt{m_n m_{^9\mathrm{Be}} E_n E_{^9\mathrm{Be}}}\cos\theta_{n,^9\mathrm{Be}}}{m_n + m_{^9\mathrm{Be}}}$$

where $m_n$ and $m_{^9\mathrm{Be}}$ are the masses, $E_n$ and $E_{^9\mathrm{Be}}$ are the kinetic energies, and $\theta_{n,^9\mathrm{Be}}$ is the opening angle between the neutron and $^9$Be. The resulting relative energy spectrum is shown in Fig. 1(b). A distinct peak is observed at $E_{\mathrm{rel}} \approx 2.44$ MeV, corresponding to the decay of the 9.27 MeV ($4^-$) state of $^{10}$Be.

For the one-neutron transfer channel in the $^9$Be+$^9$Be system, the $Q$ value is +5.14 MeV, while the neutron separation energy of $^{10}$Be is $S_n$ = 6.81 MeV. The $Q$-value spectrum of the one-neutron transfer to 9.27 MeV ($4^-$) state in $^{10}$Be, obtained by gating on $E_{\mathrm{rel}} \approx 2.46$ MeV, is shown in Fig. 2. Two distinct peaks at −1.7 MeV and −4.7 MeV correspond to excitation of the complementary fragment $^8$Be in its ground state ($0^+$) and first excited state ($2^+$ at 3.03 MeV). The detailed investigation will be presented.


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