Direct observation of $4^+$ to $2^+$ gamma transition in $^8$Be

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The low lying states in $^8$Be are believed to have a two-alpha cluster structure and hence a large intrinsic quadrupole deformation. An earlier calculation showed a large collective enhancement in gamma transition probability between the low lying states leading to a $4^+$ to $2^+$ gamma branch of $\sim 10^{-7}$ and a resonant radiative cross section of 134 nb for the $\alpha + \alpha$ entrance channel. We report here the first experimental evidence for this transition through a $\gamma - \alpha - \alpha$ coincidence measurement in the reaction $^4$He($\alpha, \alpha \gamma$)$^8$He using a gas target. The measured cross sections on and off the $4^+$ resonance are $165 \pm 41$ (stat) $\pm 35$ (sys) nb and $39 \pm 25$ (stat) $\pm 7$ (sys) nb, respectively.

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The $^8$Be nucleus is believed to be the simplest composite $\alpha$-cluster system. The ground state is 92 keV above the $\alpha - \alpha$ threshold and is a narrow resonance while the first and second excited states are much broader resonances$^1$ as shown in Fig. 1. These were identified through the phase shift analysis of $\alpha - \alpha$ elastic scattering data and have been assigned as members of the ground state rotational band$^2$. This assignment is primarily based on their energies and spins calculated using an $\alpha$-cluster model$^3$$^4$.$^5$. A crucial observable in support of this assignment is the enhanced $E2$ transition probability between the successive band members arising from the very large intrinsic deformation predicted by the cluster model. To date there does not exist any direct measurement of the electromagnetic transition rate between the low lying states of $^8$Be. Such a measurement, though difficult because of the small gamma branching ratio, would also be of interest in the context of the study of alpha linear chain configurations (LCC) in heavier nuclei such as $^{12}$C, $^{16}$O, $^{20}$Ne and $^{24}$Mg$^6$.

There are two measurements in $^8$Be, which is the simplest $\alpha$ LCC, searching for $\alpha - \alpha$ bremsstrahlung at $E_{\alpha} = 9.4$ MeV$^7$ and at $\geq 12 - 19$ MeV$^8$ by only detecting the charged particles. Coincident $\alpha$ particles were measured at fixed angles of $\pm 27.5^\circ$ and $\pm 35^\circ$, respectively, with respect to the beam. Frois et al.$^9$ did not find evidence for gamma emission and placed an upper limit of $\sim 3 \mu b/\text{sr}^2$ at 67% confidence level while Peyer et al.$^{10}$ found that the measured cross section is higher than that calculated including only external bremsstrahlung. The results of Ref.$^7$ suggested the presence of an additional internal bremsstrahlung amplitude due to the enhanced $4^+$ to $2^+$ $E2$ transition$^8$. It should be mentioned that these measurements were not aimed at measuring, even if only indirectly, the resonant radiative cross section since the beam energies were not optimal for either of the $2^+$ or $4^+$ $\alpha - \alpha$ resonances. A substantial improvement over these measurements would be to detect the gamma ray in coincidence with the two alpha particles emitted subsequently from the final state. Further, the measurements should be made at beam energies corresponding to on and off resonance.

It may be worthwhile at this point to summarize the relevant properties of the low lying states of $^8$Be. The experimental energies and widths of the lowest $0^+$, $2^+$ and $4^+$ states can be reproduced reasonably by the $\alpha$-cluster model$^2$$^4$. The widths arise primarily from the $\alpha$-decay channel since the proton and neutron decay are not energetically possible. Using this model the $E2$ gamma decay widths for the first two excited states of $^8$Be have been calculated$^4$,$^{11}$ to be 8.3 meV and 0.46 eV corresponding to the $B(E2)$ values of $\sim 75$ W.u. and $\sim 19$ W.u.$^{11}$, respectively, indicating a substantial collective enhancement. However, the calculated gamma branching ratios for the two transitions are still very small viz. $5.9 \times 10^{-9}$ and $1.2 \times 10^{-7}$, respectively. The resonances in the reaction $^4$He($\alpha, \gamma$)$^8$Be are predicted at excitation energies of 2.8 MeV and 10.7 MeV, which are lower than the energies shown in Fig. 1, with the corresponding peak cross sections of 14 nb and 134 nb. Considering the relatively larger cross section we have chosen to measure the gamma decay of the $4^+$ resonance. In this letter

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FIG. 1: Level scheme of $^8$Be showing the spin and parity ($J^\pi$), excitation energy (E$_x$) and width ($\Gamma$) of the ground and first two excited states.

E$_x$ = 9.4 MeV$^7$ and at E$_\alpha$ = 12 - 19 MeV$^8$ by only detecting the charged particles. Coincident $\alpha$ particles were measured at fixed angles of $\pm 27.5^\circ$ and $\pm 35^\circ$, respectively, with respect to the beam. Frois et al.$^9$ did not find evidence for gamma emission and placed an upper limit of $\sim 3 \mu b/\text{sr}^2$ at 67% confidence level while Peyer et al.$^{10}$ found that the measured cross section is higher than that calculated including only external bremsstrahlung. The results of Ref.$^7$ suggested the presence of an additional internal bremsstrahlung amplitude due to the enhanced $4^+$ to $2^+$ $E2$ transition$^8$. It should be mentioned that these measurements were not aimed at measuring, even if only indirectly, the resonant radiative cross section since the beam energies were not optimal for either of the $2^+$ or $4^+$ $\alpha - \alpha$ resonances. A substantial improvement over these measurements would be to detect the gamma ray in coincidence with the two alpha particles emitted subsequently from the final state. Further, the measurements should be made at beam energies corresponding to on and off resonance.

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we present the first direct experimental evidence for this electromagnetic decay branch.

The $^8\text{Be}$ nucleus was populated through the $\alpha+\alpha$ channel, using a gas target, at two beam energies of 22.4 MeV and 26.5 MeV. These correspond to on and off the $4^+$ resonance, respectively, in the reaction zone after accounting for the energy loss in the intervening material. Gamma rays were measured in coincidence with the two $\alpha$ particles from the breakup of the final state. The alpha detectors were placed in the forward direction so as to optimise the detection efficiency for the coincident $\alpha$ particles which emerge from the target region within $\sim 30^\circ$ of the beam. The $4^+$ to $2^+$ radiative transition in $^8\text{Be}$ has been detected in the present experiment. The measured cross sections are $165 \pm 41$ (stat) $\pm 35$ (sys) and $39 \pm 25$ (stat) $\pm 7$ (sys) nb, for on and off resonance, respectively. The measurements agree reasonably with the cluster model calculation of Ref. [10].

The experiment was done using alpha beams from the 14UD Pelletron at Mumbai with a beam current of $\sim 1$ pnA. The reaction chamber was designed for use of a gas target and housed a charged particle detector array at forward angle. It allowed the placement of gamma detectors in a compact geometry leading to a high combined detection efficiency. Bi and C foil targets could be inserted in the beam path for calibration of the charged particle detectors by measuring the elastic and inelastic scattering of the alpha beam. A schematic diagram of the set up is shown in Fig. 2. A helium gas target of purity $> 99.9\%$ was used at 0.8 bar pressure and the target chamber was isolated from the beam line vacuum by 1.8 mg/cm$^2$ thick Kapton foils at the entry and exit. The target chamber was evacuated through a liquid nitrogen trap (LNT) and flushed with helium passing through another LNT. This cycle of evacuation and flushing was repeated a few times before filling the chamber with helium at the above mentioned pressure. Gamma rays were detected in two arrays, each having seven close packed hexagonal bismuth germanate (BGO) scintillation detectors placed $\sim 3$ cm above and below the target. The upper BGO detectors had a thickness of 76 mm and a face to face width of 56 mm while the corresponding numbers for the lower set were 64 mm and 56 mm. The two $\alpha$ particles resulting from the decay of the $2^+$ resonance, subsequent to the $4^+ \rightarrow 2^+ \gamma$ transition, were detected in an array of six silicon (Si) PIN diodes (9 mm $\times$ 9 mm $\times$ 500 $\mu$m). These were placed at forward angles in a close packed configuration (see Fig. 2). A suitably placed 8 mm aperture in the beam path blocked elastically scattered alpha particles from the Kapton window. The downstream snout reduced the coincident elastically scattered $\alpha$ particles. A Monte Carlo simulation was used to optimise the efficiency and decide the aperture and Si detector geometry. The simulations indicated an effective target length of about 12 mm centered around the aperture and the angles covered by the forward Si detectors to be between $\sim 15^\circ$ to $35^\circ$. A 300 $\mu$m thick Si detector was placed at $\sim 110^\circ$ with respect to the beam and the spectra were recorded separately to monitor the impurities (mainly air) in the helium gas via their corresponding elastic peaks. In order to estimate the contribution of the residual air background, measurements were also made with air at 0.1 bar at both beam energies. This pressure results in a similar energy loss for the incoming and outgoing alpha particles as with the helium gas target.

The energy resolution of the Si detectors for 5.5 MeV alpha particles from an $^{241}\text{Am-}^{239}\text{Pu}$ source was $\sim 50$ keV. The BGO arrays were calibrated for high energy gamma rays using $^{241}\text{Am-Be}$ (4.44 MeV) and $^{238}\text{Pu-}^{13}\text{C}$ (6.13 MeV) sources. The energy resolution for 4.44 MeV.
Gamma rays in each array was \( \sim 7.5\% \). The gamma ray response of the arrays was simulated using the code GEANT\(^{12}\), taking into account the attenuation due to the stainless steel lids of the target chamber. The simulation, after background addition, agrees with the measured source spectrum in shape and magnitude (within \( \pm 15\% \)).

The anode signal from each BGO detector in an array was sent to a two way passive splitter and the two outputs were sent to two separate fast amplifiers. One amplifier was set to a higher gain and was used to generate a fast logic timing signal. The output of the other was summed and sent to a charge sensitive analog to digital converter (with a 1 \( \mu \text{s} \) wide gate) to generate the total energy signal. The signal from the charge sensitive preamplifier for each Si detector was processed to give an analog energy signal and a fast timing signal. Data were collected in the event by event mode, in a computer based data acquisition system \(^{13}\), requiring at least two Si detectors and one of the BGO arrays in fast coincidence. The parameters recorded were 1) the energies of the Si detectors, 2) the sum energies of the upper and lower BGO arrays and 3) the timing between the BGO arrays and each Si detector. The on and off resonance data have been acquired for beam charges of 112 \( \mu \text{C} \) and 69 \( \mu \text{C} \), respectively.

The data was sorted by selecting the diagonally opposite (1-6, 2-5 or 3-4, see Fig. 2) Si detectors in coincidence with each other and with one of the BGO arrays. Typical one dimensional projections of the BGO–Si time spectra and Si–Si time spectra are shown in Fig. 3. Two dimensional (2D) \( E_\gamma - (E_{\text{Si1}} + E_{\text{Si2}}) \) spectra, where \( E_\gamma \) is the energy deposited in one of the gamma detector arrays. The random contribution was estimated from the 2D spectra created by putting appropriate prompt and random gates in the Si–Si and Si–BGO coincidence gates. A peak can be seen in the \( E_{\text{Si1}} + E_{\text{Si2}} + E_\gamma \) sum energy spectrum at the lower (on resonance) beam energy. This clearly corresponds to the \( 4^+ \rightarrow 2^+ \) radiative transition in \(^8\text{Be}\). The peak energy is lower than the beam energy at the target zone because of the energy loss of \( \alpha \) particles, following the radiative transition, in the intervening gas region before they reach the Si detectors. At the higher (off resonance) beam energy there is a small excess of counts above background but with a larger fractional error. Similar sum spectra have also been generated for non diagonal pairs (1-5, 2-6 and 3-5) of Si detectors in coincidence with the gamma detectors. The on resonance spectra do not show such a peak. This is as expected because the two alpha particles and the beam have to lie in the same plane since the recoil effect due to the radiative transition is negligible. This observation also shows that there is no significant contribution from events corresponding to a sequential \( \alpha \) emission from the excitation of the target impurities accompanied by pileup in the BGO array leading to a peak in the energy region of interest.

In order to extract the cross section for the radiative transition in the present reaction, a Monte Carlo program was used to simulate the experiment and generate \( \gamma - \alpha - \alpha \) events. The angular distribution of the alpha particles emitted following E2 gamma decay was included in the simulation. The measured alpha singles spectral shapes were compared with the Monte Carlo simulations to constrain the possible transverse position offsets of the beam. These were found to be \( < 1 \text{ mm} \) and result in a change in the triple coincidence efficiency of less than \( \pm 5\% \). The gamma ray response for the two BGO arrays were simulated using the code GEANT, taking into account the angular distribution of the E2 gamma rays. Typical values of the photopeak efficiency (defined for a deposited energy of upto 1 MeV lower than the full energy
peak) are about 12.5% and 11.5% for gamma ray energies of 8 and 10 MeV, respectively for each of the BGO arrays. This response was used in the simulation program to generate a data file from which the $E_{\text{Si1}} + E_{\text{Si2}} + E_{\gamma}$ spectra were projected. These were scaled and added to a linear background to fit the data. After accounting for the efficiency loss due to the dead time of the acquisition system and the gates used in the data analysis, this scaling factor was used to obtain the best fit cross section. The best fits to the data, on and off the resonance, are shown in Fig. 4. The extracted gamma cross sections at the two beam energies of 22.4 and 26.5 MeV are 165 ± 41 (stat) + 35 (sys) and 39 ± 25 (stat) ± 7 (sys) nb, respectively. The systematic error includes the error due to the uncertainty in beam position, the choice of the fitting procedure and the subtracted air background. The measured on and off resonance gamma cross sections compare favorably with the 134 nb and ~12 nb calculated in Ref. [10] within experimental errors. This corresponds to a B(E2) of 24 ± 6 (stat) ± 5 (sys) $e^2$ fm$^4$ assuming a Breit-Wigner shape for the resonance as in Ref. [10]. This also agrees, within errors, with the B(E2) of 18.2 ± 0.4 $e^2$ fm$^4$ calculated by the ab initio quantum Monte Carlo method [14].

The natural extension to the present work would be to scan the 4$^+$ resonance and to search for the 2$^+$ to 0$^+$ gamma transition in $^8$Be. A more precise measurement than the one described above would require higher segmentation of the alpha detectors in order to handle higher beam currents. This will also give information on the angular correlation of the emitted $\alpha$ particles after the radiative transition.

In summary we have made the first direct observation of the 4$^+$ to 2$^+$ gamma transition in $^8$Be through a $\gamma - \alpha - \alpha$ triple coincidence measurement. The derived on and off resonance gamma cross sections agree reasonably with an earlier cluster model calculation. The present experiment demonstrates the feasibility of gamma ray measurements to confirm the $\alpha$ LCC in heavier nuclei.

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[11] With a radius parameter of 1.2 fm the quoted E2 widths correspond to B(E2) values of 49 and 21 W.u. for the 2$^+$ to 0$^+$ and 4$^+$ to 2$^+$ $\gamma$ transitions, respectively.