Positive-parity linear-chain molecular band in $^{16}$C

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An inelastic excitation and cluster-decay experiment $^2$H($^{16}$C, $^4$He + $^{12}$Be or $^6$He + $^{10}$Be)$^7$H was carried out to investigate the linear-chain clustering structure in neutron-rich $^{16}$C. For the first time, decay-paths from the $^{16}$C resonances to various states of the final nuclei were determined, thanks to the well-resolved Q-value spectra obtained from the three-fold coincident measurement. The close-threshold resonance at 16.5 MeV is assigned as the $J^p = 0^+$ band head of the predicted positive-parity linear-chain molecular band with $(3/2^-)^2(1/2^-)^2$ configuration, according to the associated angular correlation and decay analysis. Other members of this band were found at 17.3, 19.4, and 21.6 MeV based on their selective decay properties, being consistent with the theoretical predictions. Another intriguing high-lying state was observed at 27.2 MeV which decays almost exclusively to $^4$He + $^{10}$Be($\sim$ 6 MeV) final channel, corresponding well to another predicted linear-chain structure with the pure $\sigma$-bond configuration.

Clustering is a general phenomenon appearing at every hierarchical layer of the matter universe, including the largest star systems [1] and the smallest hadron systems [2]. In light nuclei, cluster formation has been widely adopted to interpret some peculiar occurrences of quantum states together with their particular population and decay properties [3–8]. In recent years, clustering phenomenon has attracted further attention in the study of unstable nuclei in which the extra valence nucleons may act as covalent bonds to stabilize the whole system [9], analogous to those in atomic molecules [5–8]. In these studies, cluster-decay measurement has played an essential role. It provides the high sensitivity to the clustering states having much lower level-density, the advantage to determine spin of the resonance from model-independent angular correlation analysis [10], and the possibility to connect the unknown structures of the mother nucleus to the known structures of the detected daughter fragments [11].

For neutron-rich beryllium isotopes, molecular structures built on the dual-$\alpha$ cores have been extensively studied by configuring the valence neutrons into $\pi$-type or $\sigma$-type covalent bonds [5–7]. Similar studies have been naturally extended to the triple-$\alpha$ systems, the carbon isotopes, where the triangle and linear-chain configurations are anticipated [5, 12]. In recent years, substantial works have been devoted to investigating the linear-chain configurations in $^{13–14}$C and some evidences have been reported in the literature [11, 13–19]. Latest antisymmetrized molecular dynamics (AMD) calculations, without using the predefined cluster degrees of freedom, have also predicted several linear-chain molecular bands in $^{16}$C [20, 21]. Most importantly, the calculations have proposed a characteristic decay pattern which collects the members of the positive-parity linear-chain band to the $^4$He + $^{12}$Be and $^6$He + $^{10}$Be final channels, with the Be fragments at various low-lying states. However, observation of this pattern requires precise measurements allowing to discriminate states in the final nuclei. This relies quite often on the resolution of the reaction Q-value. Unfortunately, so far the experiments aiming at $^{16}$C-clustering have not been able to achieve this requirement due basically to the limited beam quality, detection system performances and statistics [22–25].

In this letter, we report on a new inelastic scattering and cluster-decay experiment for $^{16}$C, in which all final particles were coincidentally detected with high efficiency. This kind of full particle-detection method has been applied previously to suppress the reaction background in the experiment using the stable nucleus beam [26]. In our case, this method is essential to deal with the large energy-spread problem resulted from the secondary radioactive ion beam. The beam energy can actually be deduced, event by event, from the three final particles according to the energy-momentum conservation. As a result, the obtained Q-value resolution does not rely on the original beam energy spread and allows to reconstruct $^{16}$C excitation spectra based on their decay paths. The predicted positive-parity linear-chain molecular band has been systematically analyzed.
and confirmed. Another exotic state at 27.2 MeV was also found to decay primarily into $^{10}$Be ($\sim$ 6 MeV), in line with the property of the predicted pure $\sigma$-bond linear-chain band at even higher energies.

The experiment was performed at the Radioactive Ion Beam Line at the Heavy Ion Research Facility in Lanzhou (HIRFL-RIBLL) [27]. A 23.5 MeV/nucleon $^{16}$C secondary beam, with an intensity of about 1.5 × 10⁴ particles per second and a purity of about 90%, was produced from a 59.6 MeV/nucleon $^{18}$O primary beam impinging on a 4.5 mm thick $^{9}$Be target. Three $x$-$y$ position-sensitive parallel plate avalanche chambers were employed to track the $^{16}$C beam onto a 9.53 mg/cm² ($\text{CD}_2$)ₙ target foils. The deuterium target was chosen owing to its easiness to be detected as a recoil particle and its power to excite the projectile.

A schematic layout of the detection system is given in Fig. 1. The decaying helium and beryllium fragments, from the $^2\text{H}(^{16}\text{C}, ^4\text{He}+^{12}\text{Be})^2\text{H}$ and $^2\text{H}(^{16}\text{C}, ^6\text{He}+^{10}\text{Be})^2\text{H}$ reactions, were coincidentally detected by a zero-degree Si-CsI telescope ($T_0$), while the recoil $^2\text{H}$ was measured by the annular double-sided silicon strip detectors (ADSSD) and four other Si-CsI telescopes ($T_{1x}$ and $T_{2x}$). The $T_0$ telescope was composed of three double-sided silicon strip detectors (DSSD), three single-sided silicon detectors (SSD), and a $2 \times 2$ CsI(Tl) scintillator array. Each DSSD has a nominal thickness of 1000 µm and an active area of 64 × 64 mm² with 32 strips on each side of the silicon layer. Each SSD has the same active size as the DSSD while its nominal thickness is 1500 µm. The first layer of the $T_0$ array was placed at 156 mm from the target, accepting almost 100% of the decaying fragments because of the inverse kinematics [28, 29]. The $T_{1x}$ and $T_{2x}$ telescopes were centered at 35° and 69° with respect to the beam direction, and at distances of 178.7 mm and 156.6 mm from the target, respectively. Each of them was composed of a thin DSSD (60 or 300 µm), a thick SSD (1500 µm) and a $2 \times 2$ CsI(Tl) scintillator array. Four sectors of ADSSD (150 or 400 µm thick) were installed around $T_0$ telescope at a distance of 123 mm from the target.

Energy calibration of the detectors was accomplished by using $\alpha$-particle sources and the procedures described in Refs. [30, 31]. Timing information obtained from the DSSD strips was applied to assure the real coincidence among the recorded signals. This is particularly important for $T_0$ telescope which was directly exposed to the beam. Particles produced from the reactions on the detector layers, instead of those on the target, were excluded by employing the tracking method. Fake-coincident signals resulted from the inter-strip gap-hitting were also discriminated by matching the tracks and energies in neighboring detector layers. Thanks to the excellent energy, timing and position resolutions of the silicon detectors, isotopes from hydrogen to carbon were unambiguously identified based on the standard energy loss versus residual energy ($\Delta E$-$E$) technique [32]. The detection and calibration were validated by using the two- and three-$\alpha$ coincident events to reconstruct the known $^8$Be and $^{12}$C resonances, respectively [4, 25, 33].

As aforementioned, $Q$-value resolution is of essential importance to differentiate various decay-paths in the present experiment. The reaction $Q$-value is defined as:

$$Q = E_{^4\text{He}} + E_{^{12}\text{Be}} + E_{\text{beam}}$$

where $^4\text{He}$ and $^{12}\text{Be}$ denote $^{4}\text{He} + ^{12}\text{Be}$ or $^{6}\text{He} + ^{10}\text{Be}$ decay pairs, and $E_{\text{beam}}$ the beam energy. In most cases, only two outgoing particles are detected while the third one is deduced by using the energy and momentum of the projectile [11, 19, 25]. Due to the relatively large energy spread of the radioactive beam produced by projectile fragmentation (PF) type facility, the extracted $Q$-value spectra could hardly reach the required resolution [19, 22, 24, 25]. To overcome this difficulty we directly measured all of the three final particles and deduced the beam energy event by event according to the energy-momentum conservation [11]. Hence, the $Q$-value resolution lies solely on the performances of the detection system, but not on the beam energy uncertainty. Presently obtained $Q$-value spectra are shown in Figs. 2(c) and 2(g) for the two final channels, respectively. For the first time, in PF-type experiments, $Q$-value peaks corresponding to the ground and low-lying excited states in the final fragments are clearly discriminated. For $^4$He decay channel (Fig. 2(c)), the peak at about $-13.8$ MeV is for all three final particles in their ground states (ggg). Another peak at about $-15.9$ MeV is mainly associated with $^{12}$Be in its $2^{+}_1$ (2.109 MeV) state. The decay to the $0^+_1$ (2.251 MeV) state can not be resolved from this $Q$-value peak but would have much lower probability based on the analysis below. The decay to another nearby $1^+_1$ (2.715 MeV) state is less likely because it should stand at the far edge of the actual $Q$-value peak.

![FIG. 1. A schematic view of the experimental setup. x in $T_{1x}$ and $T_{2x}$ stands for up and down.](Image 338x559 to 541x740)
but apparently no structure appears there. For $^6$He decay channel (Fig. 2(g)), the highest peak at about $-16.5$ MeV is for the $Q_{tot}$ state, and another two at about $-19.8$ MeV and $-22.5$ MeV are associated with $^{10}$Be in its first excited state ($2^+_1$, $3.368$ MeV) and the four adjacent states around $\sim 6$ MeV ($2^+_2$, $1^-_2$, $0^+_2$, $2^-_2$) [11], respectively.

The relative energies of $^{16}$C resonances can be derived from two breakup fragments using the standard invariant mass method [11, 28]. The excitation energy spectrum can be plotted simultaneously by gating on a certain $Q$ fragment, the excitation energy spectrum can be plotted to guide the eyes for the corresponding states. The relative energy and the cluster separation threshold $Q$ are related to the states of the final fragments and the detection efficiencies as a function of $Q$. The vertical black-dotted lines are used to indicate the detection efficiencies, as demonstrated in Fig. 3. The extracted resonances are listed in Table I.

The excitation spectra in Fig. 2 are fitted simultaneously by several resonant peaks (Breit-Wigner functions [34, 35]), modified by detection efficiencies and convoluted with gaussian functions representing energy resolutions. The standard event-mixing background [36] has been evaluated but found to have negligible contributions to the spectra, possibly attributed to the rigorous timing matching of events as described above. The extracted resonances are described in the text.

The latest AMD calculations [21] have proposed a positive-parity linear-chain molecular band headed by the $16.81$ MeV $0^+$ state which is close to the presently observed $16.5$ MeV state (Fig. 2(a)). Since little contamination was presented beneath this lowest energy peak, it would be adequate to apply the model-independent angular correlation analysis to determine its spin [25, 28, 37, 38]. For a spin-$J$ composite nucleus decaying into two spin-zero fragments, the projected angular correlation function can be formulated by a Legendre polynomial of order $J$, $|P_J(\cos(\psi + a\theta^*))|^2$. Here $\psi$ is the polar angle of the relative velocity vector between the two fragments and $\theta^*$ the center-of-mass scattering angle of the resonant particle. $a$ is the phase shift correction factor which is not essential for small-angle scattering [37] or $J = 0$ resonances [28]. The presently obtained correlation function for $16.5$ MeV state (gated on $15.0 - 17.0$ MeV) is plotted in Fig. 3 as a function of $|\cos(\psi)|$, which is symmetric about $\cos(\psi) = 0$ [28]. Experimental data are compared with the theoretical distributions assuming various $J$ values and corrected by the detection efficiencies, as demonstrated in Fig. 3. The best fit of the data is achieved with $J^* = 0^+$ whereas other spin assignments can be excluded due basically to the behavior at the minima and also to the much larger reduced $\chi^2$ values. We tried to use various cuts

| Table I. Excitation energies, spin-parities and total decay widths of the resonances in $^{16}$C, in comparison to those from the AMD calculations. Errors for positions and widths of the observed resonances are statistics only. |
|---------------------------------|----------|---------------------------------|
| $E_x$ (MeV) | $J^*$     | $\Gamma_{tot}$ (keV)          | $E_x$ (MeV) | $J^*$     |
| 16.5(1)     | 0$^+$    | 1200(200)                       | 16.81       | 0$^+_2$  |
| 17.3(2)     | 0$^+$    | 400(200)                        | 17.51       | 2$^+_1$  |
| 18.3(1)     | 0$^+$    | 800(100)                        | 18.99       | 4$^+_0$  |
| 19.4(1)     | 0$^+$    | 1500(160)                       | 21.49       | 6$^+_0$  |
| 21.6(2)     | 0$^+$    | 2200(200)                       | 23.5(2)     | 0$^+_2$  |
| 25.5(2)     | 0$^+$    | 1230(200)                       | 27.2(1)     | 1460(200)| 29.30     | 0$^-_1$  |

The relative energy resolution is simultaneously estimated, varying from 100 to 250 keV (FWHM) in the spectrum-covered ranges [11, 28]. The estimated production cross sections are about $3.25 \pm 0.19$ mb and $0.97 \pm 0.10$ mb for $^4$He and $^6$He channels, respectively, which are consistent with the previous reports [24].
around the center of 16.5 MeV peak but no significant changes were found for the shape of the correlation spectra. Consequently, the observed 16.5 MeV state can be considered as the most promising candidate for the 0\(^+\) band head of the positive-parity linear-chain rotational band of \(^{16}\)C. As a cross check, we tried also the standard angular correlation analysis \([25, 32]\) for the observed 19.4 MeV state which is quite isolated in the channel decaying to \(^{10}\)Be(g.s.) (Fig. 2(d)). It is found that, even though the low statistics do not allow a definite spin assignment, it is consistent with a spin-4 distribution. For other observed resonances, the spin determination would be impractical because of their overlaps with closely states or the very low statistics.

As indicated qualitatively in some early works \([5, 6]\) and predicted quantitatively in recent AMD calculations \([17, 20, 21]\), the decay from the mother resonance to certain states of the daughter fragments is closely related to the similarity of their structures. This structural link provides an important tool to probe the exotic structure in the former when a typical configuration has been clearly established in the latter \([11]\). In the case of \(^{16}\)C, a positive-parity linear-chain molecular band, with the \((3/2^+)(1/2^+)\) configuration, was predicted to have members at 16.81 (0\(^+_0\)), 17.51 (2\(^+_1\)), 18.99 (4\(^+_3\)), and 21.49 (6\(^+_5\)) MeV \([21]\). Among them the 6\(^+\) member is predicted to possess peculiar decay features, as illustrated in Fig. 4 (right panel). The large difference in partial decay width between its decays to the \(^{12}\)Be(2\(^+_1\)) and to the \(^{12}\)Be(g.s.) states could partially be accounted for by the difference in penetration factors, but is still strongly related to the correlation between the chain-like structure in \(^{16}\)C(21.6 MeV) and the angular momentum in the daughter nucleus \([6, 21]\). From the experimental side, the observed 21.6 MeV state is close to the predicted 21.49 MeV (0\(^+_3\)) state (Table I). Adopting a spin-parity of 6\(^+\), this state should decay with higher probability to the \(^{12}\)Be(2\(^+_1\)) state than to the \(^{12}\)Be(0\(^+_3\)) state, because of the more than five times larger penetration factor for the former than for the latter. This observed decay is also much stronger than that to the \(^{12}\)Be(g.s.), being well consistent with the prediction. The theoretical calculations also predict small partial decay widths for the ground and first excited states of \(^{16}\)Be, which are also perfectly confirmed by our experimental observations, as displayed in Fig. 2 and plotted quantitatively in Fig. 4 (left panel) for the 21.6 MeV state. As a consequence, the observed 21.6 MeV resonance should be regarded as the 6\(^+\) member of the predicted positive-parity linear-chain molecular band of \(^{16}\)C, despite the lack of direct spin measurement. We also assign the 2\(^+\) and 4\(^+\) members of the band to the observed resonances at 17.3 and 19.4 MeV states, considering their similarities in excitation energies and selective decay properties (Fig. 4). The observed 18.3 MeV state (Fig. 2 and Table I) is also quite close to the proposed 4\(^+\) member but actually not classified into the present positive-parity band due to its primary decay path to \(^{12}\)Be(g.s.) and negligible decay to the \(^{10}\)Be channel, which is contradictory to the prediction. This additional state with a quite large \(\alpha\)-decay probability might belong to other molecular...
configurations [21]. As for the 16.5 MeV state, the above
spin-zero band-head assignment can be further confirmed
by its pure decay to $^{12}\text{Be}(g.s.),$ in agreement with
the theoretical prediction. We note that the systematic error
for these relative decay widths is estimated to be less
than 5%, due basically to uncertainties in simulation and
detection.

It is worth noting that the previously reported peak
at about 20.6 MeV, reconstructed from the $^6\text{He}+^{10}\text{Be}$
channel without $Q$-value selection [25], is not observed in
our measurement. This prior peak might be understood
by erroneously shifting the presently observed 23.5 MeV
peak in Fig. 2(e) and 27.2 MeV peak in Fig. 2(f) into
Fig. 2(d), according to their different $Q$-values.

Another intriguing high-lying state at 27.2 MeV
(Fig. 2(f) and Table I) is found to decay primarily
into the $^{6}\text{He}$ states in $^{10}\text{Be}$. We have made
further investigations with AMD method to explain the
states in $^{16}\text{C}$ at very high excitation energies, where a
novel linear-chain molecular band with $(1/2^-)^2(1/2^+)^2$
configuration appears, which decays predominantly to
the $0^+_2$ (6.179 MeV) state of $^{12}\text{Be}$. The property of
the presently observed 27.2 MeV state in $^{16}\text{C}$ (Fig. 4)
agrees quite well with the predicted band head state
$0^+_1$. Further experimental investigations are certainly
encouraged to clarify the existence of this very high-lying
linear-chain molecular band in $^{16}\text{C}$.

In summary, a new inelastic excitation and cluster-
decay experiment was carried out for $^{16}\text{C}$ and the
triple coincidence detection with quite high efficiency was
realized. For the first time, in PF-type measurements,
good $Q$-value resolution was achieved for both $^4\text{He}+^{12}\text{Be}+^2\text{H}$ and $^6\text{He}+^{10}\text{Be}+^2\text{H}$ final channels, allowing
the reconstruction of $^{16}\text{C}$ resonances according to their
decay paths. The systematic decay-pattern analysis and
the spin determination for the band head fully
support the existence the $(3/2^-)^2(1/2^+)^2$-type linear-
chain molecular band in $^{16}\text{C}$, as predicted by the latest
AMD calculations [20, 21] and by the earlier molecular-orbital
approach [39]. Moreover, an exotic high-lying excited state at 27.2 MeV is found to decay dominantly
to the $^{10}\text{Be}(\sim 6$ MeV) state, in line with the predicted $0^+$
member of $(1/2^-)^2(1/2^+)^2$ linear-chain molecular band
at even higher energies. It would be very interesting
to further investigate the clustering structures in $^{16}\text{C}$ at
even higher excitation domain where the pure $\sigma$-bond
and the high-lying negative-parity molecular bands may
be accommodated.

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