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Experimental investigation of a linear-chain structure in the nucleus ^{14}C

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A B S T R A C T

It is a well-known fact that a cluster of nucleons can be formed in the interior of an atomic nucleus, and such clusters may occupy molecular-like orbitals, showing characteristics similar to normal molecules consisting of atoms. Chemical molecules having a linear alignment are commonly seen in nature, such as carbon dioxide. A similar linear alignment of the nuclear clusters, referred to as linear-chain cluster state (LCCS), has been studied since the 1950s, however, up to now there is no clear experimental evidence demonstrating the existence of such a state. Recently, it was proposed that an excess of neutrons may offer just such a stabilizing mechanism, revitalizing interest in the nuclear LCCS, specifically with predictions for their emergence in neutron-rich carbon isotopes. Here we present the experimental observation of α-cluster states in the radioactive ^{14}C nucleus. Using the $^{10}\text{Be} + \alpha$ resonant scattering method with a radioactive beam, we observed a series of levels which completely agree with theoretically predicted levels having an explicit linear-chain cluster configuration. We regard this as the first strong indication of the linear-chain clustered nucleus.

Atomic nuclei are frequently observed to manifest effects of a clustered substructure within, and the particular importance of α particle clustering was pointed out even in the earliest works of nuclear physics [1,2]. In 1956, Morinaga [3] came up with the novel idea of a particular cluster state: the linear-chain cluster state (LCCS). In that work, it was suggested that the 7.66-MeV state in ^{12}C –which is now known as the Hoyle state– may correspond to a state of three α particles arranged in a row. Similar α-clustering in other 4n-nuclei, which are comprised of multiple α particles, was also discussed in the same work. Later, it was shown by Horiuchi [4] that the Hoyle state could be a molecular-like level of $^{8}\text{Be} + \alpha$, or equivalently three α particles weakly coupled to each other, instead of an LCCS. However, the concept of the LCCS has particularly drawn the attention of nuclear physicists, both experimentally and theoretically. Now the LCCS is commonly considered as extreme and exotic, due to its presumed propensity to exhibit bending configurations. Therefore, its identification would have a strong impact on the research field of quantum many-body systems.

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Despite its pursuit by many scientists for more than half a century, up until now the LCCS has been only hypothetical. There have been LCCS candidates, such as the one in ^{16}O proposed by Chevallier et al. [5] based on the large moment of inertia found for an assumed rotational band. However, the spin-parity assignment of the 19.3-MeV level was questioned in later experiments [6,7], and the interpretation as an LCCS was not supported by recent theoretical works [8–10]. As for the carbon isotopes, Itagaki et al. [11] studied α-cluster states in ^{12,14,16}C using a microscopic model. They investigated breathing and bending motions and concluded that ^{16}C might have a linear-chain structure but at high excitation energies $E_{ex} > 20$ MeV. In the work by Oertzen et al. [12], it was proposed that prolate deformed bands should exist in ^{14}C. Their idea was that those bands might be attributed to an underlying LCCS structure, but the reasoning was merely based on the relatively large momentum of inertia, and the spin and parity J^π were confirmed only for low-lying levels in the bands. The LCCS in ^{13}C have also been studied both experimentally and theoretically [13–17]; however, there is no agreed-upon interpretation that the observed cluster levels may arise from an LCCS. In summary, there is no clear evidence of any LCCS in nuclei at present.

A theoretical prediction of LCCS in ^{14}C was made by Suhara and En'yo [18] with an antisymmetrized molecular dynamics (AMD) calculation, yielding a prolate band ($J^\pi = 0^+, 2^+, 4^+$) that has a configuration of an LCCS at a few MeV or more above the ^{10}Be$+\alpha$ threshold. They showed that the LCCS is stabilized by its orthogonality to lower-lying states. At lower excitation energy in ^{14}C, there are triaxially deformed cluster states, which are constructed by bases with bending configurations. To fulfill the orthogonality condition between different states, higher-excited LCCSes are prohibited from bending. This is in stark contrast with ^{12}C, where no triaxial bands exist, and therefore such an LCCS-stabilizing mechanism does not work. A further investigation [15] showed that the AMD wavefunction has a configuration in which two α particles and two neutrons are located close to each other, while the remaining α particle is relatively further away, as illustrated in Fig. 1. This implied that such an LCCS could be experimentally accessible from the ^{10}Be$+\alpha$ channel in a single step. The emergence of the prolate band as LCCSes had been discussed in the previous pioneering work [12], and two essential new features found in [18] are the absence of the negative-parity band, which appears to be contradictory to the concept of the parity inversion doublets [19], and the higher level energies above the ^{10}Be$+\alpha$ threshold. The former was explained as the result of a stronger mixing of the negative parity LCCS, in which the ^{10}Be core can be rotated easily, with other bending-shaped configurations. The latter can result from the consumption of kinetic energy from the linear-chain alignment.

The excited states in ^{14}C have been studied by various reactions [12,20–27], but only the excitation energies are known for most levels. In the present work we applied the ^{10}Be$+\alpha$ resonant scattering method in inverse kinematics [28] to identify the predicted LCCS band in ^{14}C. Our experimental setup was similar to the previous one in the ^{7}Be$+\alpha$ experiment [29], but we placed an extra silicon detector telescope to cover a broader angular range, instead of the NaI detectors, as shown in Fig. 2. The new setup enabled us to perform a reliable analysis on the angular distribution. An advantage of the present method is that only natural parity levels ($\pi = (-1)^J$) are selectively observed since both particles have $J^\pi = 0^+$. The coverage of the most forward laboratory angle θ_{lab}, corresponding to the center-of-mass angle $\theta_{c.m.} = 180°$, provided us with the clearest identification of the resonances, because the Coulomb potential scattering is at minimum there, and it suffers the least from the uncertainty of the nuclear phase shift.

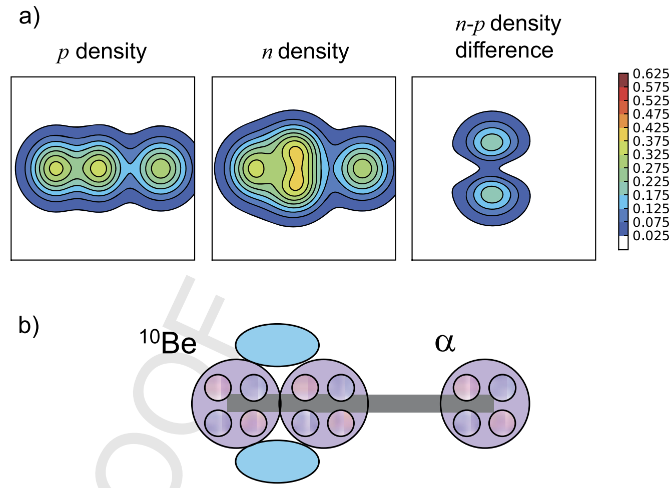

Fig. 1. Wavefunction dominant in the LCCS in ^{14}C calculated by the AMD method [18,15]. a) Proton density ρ_p, neutron density ρ_n and the difference between them. The box size is 10×10 fm^2 for all. b) An intuitive picture of the above wavefunction.

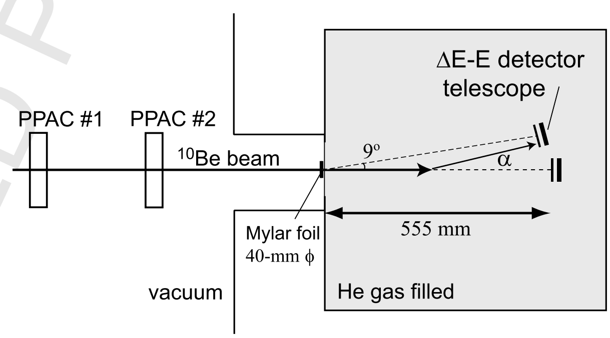

Fig. 2. The experimental setup for the resonant scattering measurement.

Two similar measurements have been independently planned, carried out and published recently. The first work by Freer et al. [30] had a similar setup to ours, but with a more limited angular sensitivity. Another work by Fritsch et al. [31] used an active target setup, but detection was only possible for side scattering angles.

The present measurement was performed at the low-energy radioactive isotope beam separator CRIB [32–34]. The ^{10}Be beam was produced via the ^{11}B(^{2}H, ^{3}He)^{10}Be reaction in inverse kinematics using a 1.2-mg/cm^2-thick deuterium gas target and a ^{11}B beam at 5.0 MeV/u accelerated with an AVF cyclotron. The ^{10}Be beam had a typical intensity of 2×10^4 particles per second, and the beam purity was better than 95%. The beam was counted with two parallel-plate avalanche counters (PPACs), which enabled us to perform an unambiguous event-by-event beam particle identification with the time-of-flight information. The ^{10}Be beam at 25.8 MeV impinged on the gas target, which was a chamber filled with helium gas at 700 Torr (930 mbar) and covered with a 20-μm-thick Mylar film as the beam entrance window. The measured ^{10}Be beam energy at the entrance of the helium gas target, after the Mylar film, was 24.9 ± 0.3 MeV. α particles recoiling to the forward angles were detected by ΔE-E detector telescopes. We used two sets of detector telescopes in the gas-filled chamber, where each telescope consisted of two layers of silicon detectors with the thicknesses of 20 μm and 480 μm. The central telescope was located 555 mm downstream of the beam entrance window exactly on the beam axis, and the other telescope was at an angle of 9° from the beam axis, as viewed from the entrance window position. Each detector in the telescope had an active area of 50×50 mm^2, and 16 strips for one side, making pixels of 3×3 mm^2 altogether. These detec-