PHYSICAL REVIEW C VOLUME 31, NUMBER 4 APRIL 1985

Higher nodal states of alpha + ^{15}N cluster structure in ^{19}F

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(Received 7 September 1984)

The existence of the higher nodal states of the $\alpha+{}^{15}N$ cluster structure in ^{19}F is discussed through the analysis of the backward angle anomaly in alpha-particle scattering from ^{15}N at $E_\alpha = 22$, 24, and 28 MeV.

The essential importance of alpha-cluster structure in light nuclei has been clarified by the comprehensive study of nuclei below ^{24}Mg.[1] The most specific mode peculiar to cluster structure is a relative motion between two clusters in nulcei. The existence of the excited state of the relative motion, i.e., a vibrational cluster state, will further establish the importance of the concept of molecule-like structure in light nuclei. The unique vibrational state hitherto found is the $\alpha+{}^{16}O$ cluster state in ^{20}Ne starting from $E_{ex} = 8.3$ MeV. The reason why such a vibrational cluster state has been barely found in ^{20}Ne may be because the binding ability of intercluster interaction is much weaker than the molecular one.[2] Even in ^{20}Ne the vibrational states 0^+, 2^+, and 4^+ are broad (short lived) and the higher spin states have not been identified as energy levels. It was shown by one of the present authors (S.O.) with Kondo and Nagata[3] that the persistent existence of the 6^+ and 8^+ states in the higher nodal band, which has one more node in the relative motion than the ground band with the $\alpha+{}^{16}O$ cluster, can be traced in the phenomenon of backward angle anomaly (BAA) in alpha-particle scattering from ^{16}O. Recently, a systematic experiment and analysis of α-^{16}O scattering by Michel *et al.*[4] reconfirmed the above finding.

If another example of a higher nodal state in nuclei can be found, the concept of cluster vibrational mode will be further established. In the present Brief Report we show that existence of the higher nodal states of the $\alpha+{}^{15}N$ cluster in ^{19}F can be traced in the phenomenon of backward angle anomaly.

The importance of the $\alpha+{}^{15}N$ cluster structure in ^{19}F has been investigated by many authors with the microscopic model,[5] semimicroscopic model,[6] and phenomenological potential model.[7] It has been shown[5,8] that the $\alpha+{}^{15}N$ cluster structure is well understood as a weak coupling of a $p_{1/2}$ hole with the $\alpha+{}^{16}O$ cluster structure in ^{20}Ne (Fig. 1): According to this weak coupling picture, existence of the higher nodal states is also expected in ^{19}F corresponding to those in ^{20}Ne. Nemoto and Bando[5] obtained the higher nodal states in the bound state approximation with the generator coordinate method; however, it was shown by LeMere and Tang[9] with the resonating group method in the scattering treatment that the corresponding phase shifts never show the resonances. Also in the bound state calculation with the coupled-channel orthogonality condition model,[6] the higher nodal states have not been obtained stably. Experimentally no states corresponding to the higher nodal states in ^{20}Ne have been found.

On the other hand, some attempts[10–12] have been done to understand the BAA in alpha-particle scattering from ^{15}N, which shows anomalous enhancement of cross sections and characteristic oscillations of angular distributions at backward angles. Coelho *et al.*[12] tried to explain the large cross sections by a heavy particle transfer process but not the characteristic oscillations. Oeschler *et al.*[11] explained the characteristic oscillations with a phenomenological Regge-pole model. However, it seems that no systematic and satisfactory explanations have been given. We connect the problem of existence of the higher nodal states with this backward angle anomaly.

We study the higher nodal states of the $\alpha+{}^{15}N$ cluster structure with a deep folding potential model; as an interaction between clusters we adopt the direct potential derived

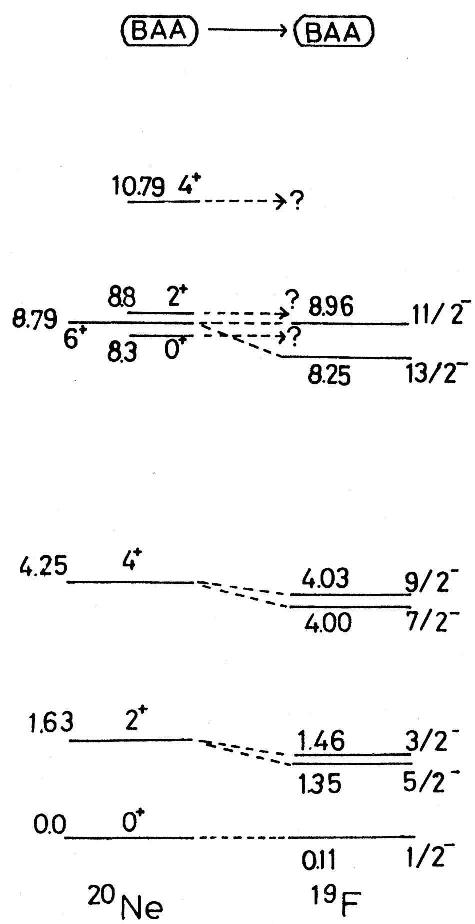

FIG. 1. Weak coupling features of energy levels of ^{19}F with $\alpha+{}^{15}N$ cluster structure and ^{20}Ne with $\alpha+{}^{16}O$ cluster structure is shown.

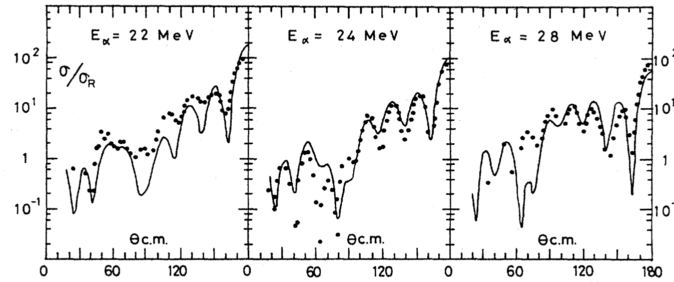

FIG. 2. Angular distributions for α-^{15}N scattering at $E_\alpha = 22$, 24, and 28 MeV. The points and solid lines represent the experimental data and the calculation, respectively. The parameters of the imaginary potential are $W = 9$, 10, 10 MeV for $E_\alpha = 22$, 24, and 28 MeV, respectively, and $r_I = 1.361$ fm and $a_I = 0.30$ fm.

from the effective two-body interaction of HNY[13] with −565 MeV for the triplet even state in the intermediate region which was used in the case of $\alpha + ^{16}$O scattering;[3] spin-orbit interaction is not included. The intrinsic wave functions of alpha and ^{15}N are assumed to be the harmonic oscillator wave functions with a common oscillator parameter $\nu = 0.18$ fm^{-2} ($\nu = m\omega/2\hbar$). Validity of a deep potential for cluster structure study has been shown by the microscopic models[14,15] and the phenomenological analysis.[4]

We analyze the experimental data of alpha scattering from ^{15}N at $E_\alpha = 22$, 24, and 28 MeV measured by Oeschler *et al.*[11] In the analysis an imaginary potential of Woods-Saxon type is introduced phenomenologically and its strength parameter is adjusted to give the magnitude of the experimental cross sections at backward angles. In Fig. 2 the calculated angular distributions are shown in comparison with the experimental data. The characteristic oscillation of BAA is fairly well reproduced.

In order to investigate the mechanism of BAA the scattering amplitude $f(\theta_{\rm c.m.} = 180°)$ at $E_\alpha = 24$ MeV is shown in Fig. 3 as a vector sum of each partial scattering amplitude. It is found that the enhancement of the total scattering amplitude at the backward angle is mainly brought about by the partial waves of $l = 6$ and 8. Similar situation is also seen at $E_\alpha = 22$ and 28 MeV. In Fig. 4 we show the phase shifts calculated by switching off the imaginary potential. The partial waves of $l = 6$ and 8 in Fig. 3 correspond to those of the higher nodal band of the $\alpha + ^{15}$N cluster structure in ^{19}F. Although the $l = 0$, 2, and 4 are not resonances in the sense that the phase shifts do not go through 270°, the $l = 6$ and 8 show broad resonant behavior passing through 270° slowly. Therefore, although the higher nodal states with $l = 0$, 2, and 4 have not been observed, a trace of the states of $l = 6$ and 8 is seen in the phenomenon of backward angle anomaly: The characteristic oscillation at backward angles is nothing but the persistent existence of the higher nodal $l = 6$ and 8. A systematic measurement of angular distributions and excitation functions at backward

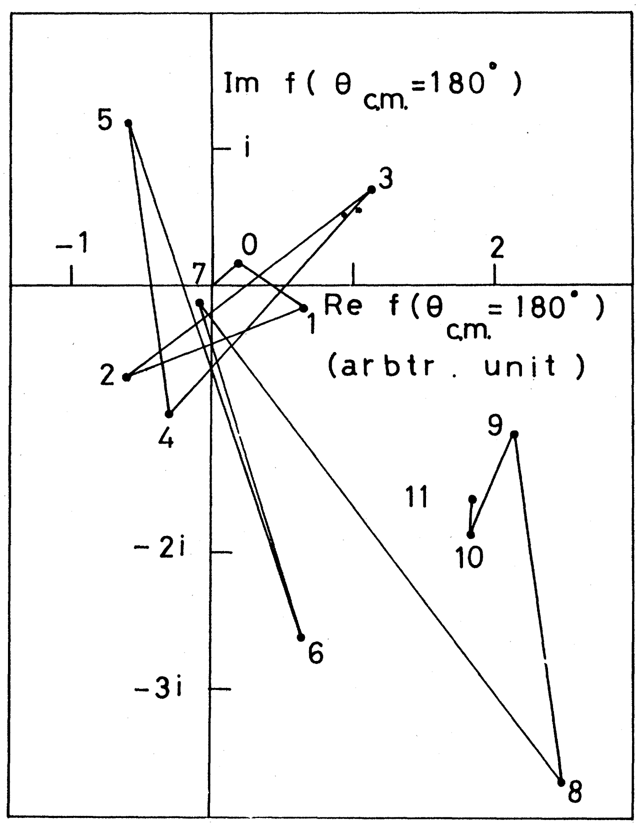

FIG. 3. Scattering amplitudes at $\theta_{\rm c.m.} = 180°$ for α-^{15}N scattering at $E_\alpha = 24$ MeV are shown as a vector sum of the partial scattering amplitudes. Each line represents a partial scattering amplitude and each number indicates the angular momentum.

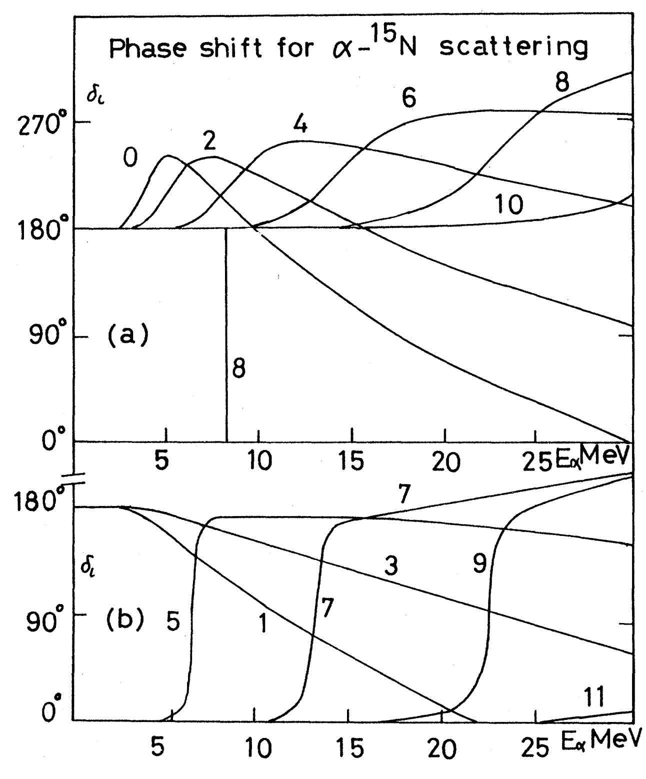

FIG. 4. Phase shifts for the α-^{15}N scattering.

angles of alpha scattering from ^{15}N should further confirm the higher nodal band.

Here we mention the result by Oeschler *et al.* Our real and imaginary potentials are compared with theirs in Fig. 5. These two real potentials have almost the same depth; however, the shapes are considerably different in the outer region: The potential of Oeschler *et al.* gives a broad resonant wave for $l=7$ in the relevant energy region of $E_\alpha = 22$–28 MeV; however, it cannot produce the broad higher nodal resonances of $l=6$ and 8. So if acceptable angular distributions are obtained at backward angles by this potential with a weak imaginary potential, the mechanism of BAA is quite different from our potential. Oeschler *et al.*, in fact, use a strong imaginary potential, which washes out the broad resonance, and introduce a Regge pole of $l=7.1$, 7.3, and 8.4 for $E_\alpha = 22$, 24, and 28 MeV, respectively. These poles should be regarded as simulating the higher nodal resonances of $l=6$ and 8.

How could we find the higher nodal states with low spins? One way of finding an indication of them would be to investigate the $\alpha + {}^{16}_{\Lambda}N$ cluster structure in ${}^{20}_{\Lambda}F$: The Λ particle would be a glue to stabilize[16] the higher nodal states of the $\alpha + {}^{15}N$ cluster structure, which may enable the higher nodal states, particularly the band head, to appear at least as quasibound states. It is very interesting to study the cluster structure of ${}^{20}_{\Lambda}F$ with the $\alpha + {}^{15}N + \Lambda$ cluster model. This is in progress and will be reported elsewhere.

To summarize, we have shown that the vibrational state of alpha-cluster structure—higher nodal states—may be found in ^{19}F in the phenomenon of backward angle anomaly in addition to that in ^{20}Ne. Similarity between the higher nodal states of ^{19}F and ^{20}Ne is found.

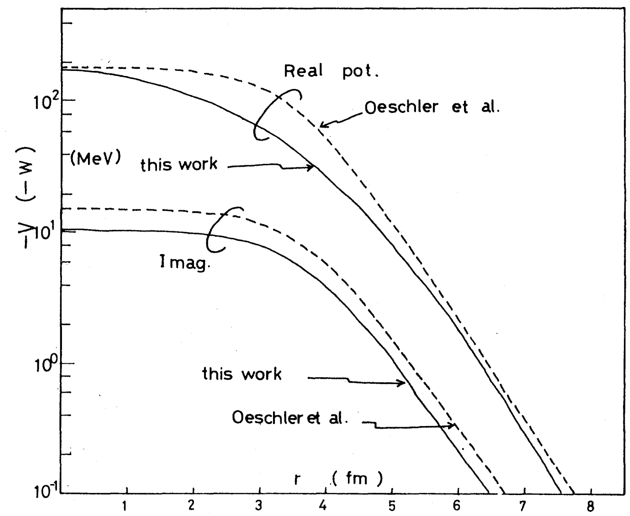

FIG. 5. Comparison of the real and imaginary parts of our potential (solid lines) at $E_\alpha = 24$ MeV with those of Oeschler *et al.* (Ref. 11) (dashed lines).

The numerical calculations were done at the Computer Centers of Kyoto University and Osaka University.

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