Evidence for Alpha-Particle Clustering in the ^{44}Ti Nucleus

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The α-particle cluster structure of ^{44}Ti, which is of considerable interest for investigation of the persistence of α clustering in the region of the *sd*-shell closure, is studied within the frame of a local-potential approach. It is shown that the model leads to specific predictions if continuity with existing unique $\alpha + {}^{40}$Ca optical potentials is insisted upon; in particular, the existence of an as yet experimentally unknown α-cluster negative-parity band, starting just above the $\alpha + {}^{40}$Ca threshold, is strongly suggested.

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The importance for nuclear structure of the α-particle-clustering collective degree of freedom has been recognized for a long time (see, e.g., Bromley[1] and references cited therein). The most thoroughly investigated system from this point of view is ^{20}Ne, where various rotational bands have been described in terms of $\alpha + {}^{16}$O(g.s.) and $\alpha + {}^{16}$O* cluster states.[2] Extension of these concepts in the *fp*-shell region has met with very limited success; in particular, the structure of ^{44}Ti, which is the analog of ^{20}Ne in the *fp*-shell and is thus of considerable interest, is far from being understood.

It is the purpose of this Letter to demonstrate that utilization of the knowledge which has accumulated on the α-^{40}Ca interaction, and very recent advances made in the understanding of the $\alpha + {}^{40}$Ca fusion mechanism, lead to considerable clarification of the problem of α-particle structure in ^{44}Ti.

To date, aside from the members of the ground-state band,[3] which is composed of even-parity states with spins ranging from 0 to 12 and whose structure is reminiscent of that of ^{20}Ne, various α-cluster candidates have been proposed for this system in the literature.[4-6] The states most often quoted are a narrow level with $E_x = 8.54$ MeV, strongly populated in the reaction ^{40}Ca(^{6}Li,*d*), which was tentatively assigned $J^\pi = 0^+$,[4] and a group of broader states with $J^\pi = 0^+$, 1^-, 2^+, and 3^- (with $E_x = 11.2$, 11.7, 12.2, and 12.8 MeV, respectively), seen in a high-resolution ^{40}Ca(α,α) experiment[5,6] and interpreted as members of a mixed-parity rotational band[6] (Fig. 1). On the theoretical side, existing microscopic cluster calculations[7-9] lead to conflicting interpretations of the ^{44}Ti structure; these calculations, which use different effective nucleon-nucleon interactions, disagree essentially on the location of the first α-cluster states with respect to the $\alpha + {}^{40}$Ca threshold.

A more phenomenological but powerful approach to the description of cluster structure in nuclei was initiated some ten years ago by Buck *et al.*,[10] who showed that simple, deep, local intercluster potentials are capa-

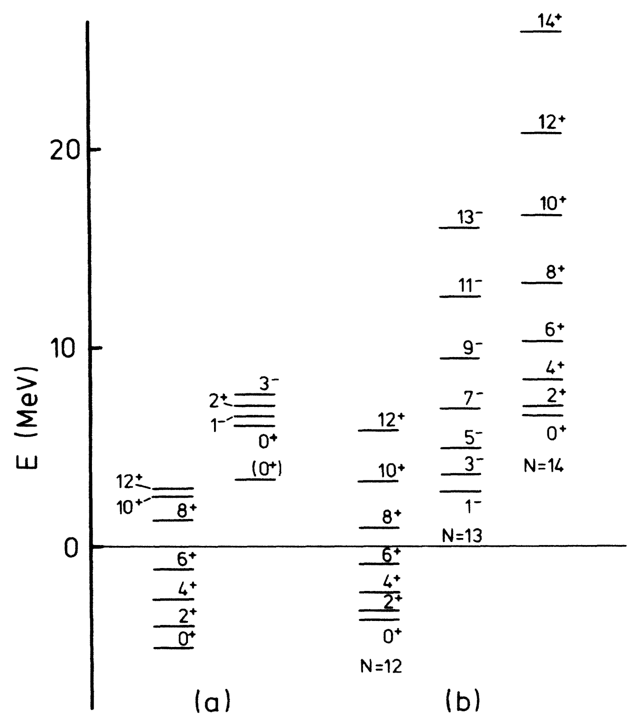

FIG. 1. (a) Experimental ground-state band (Ref. 3) and α-particle cluster-state candidates (Refs. 4–6) in ^{44}Ti; (b) ^{44}Ti $N = 12$, $N = 13$, and $N = 14$ states supported by the local potential (the potential depth is fixed to the average value $U_0 = 180$ MeV). Energies are given with respect to the $\alpha + {}^{40}$Ca threshold.

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ble of reproducing in a natural way many properties of cluster states such as their energy spacings, α-particle widths, and electromagnetic transition probabilities. The construction by Aoki and Horiuchi[11] of local potentials from the resonating-group nonlocal ones has recently given direct support to the use of such deep potentials. The model has been highly successful in accounting for the detailed properties of the $K^{\pi}=0_1^+$ and 0^- α-cluster bands of ^{20}Ne.[10] There have been comparatively few applications of the local-potential model in the *fp*-shell region; to date calculations have been limited to the ^{40}Ca, ^{43}Sc, and ^{44}Ti systems.[12–14]

As a matter of fact, however successful the local-potential–model approach may be when part of the cluster-state spectrum is well established, it is of limited help in disentangling cases like the one investigated here in that it gives no information on the absolute position with respect to the threshold of the various quasirotational bands it predicts. Nevertheless, these local potentials, which can be considered as simple substitutes for the more elaborate nonlocal interactions derived in microscopic approaches, should like the latter be able to describe in a unified way both the negative- and positive-energy properties of the system under investigation. Unfortunately a direct comparison with existing optical potentials is in most cases not meaningful because of the various ambiguities which usually plague optical-model analyses of composite-particle elastic-scattering data. Still there exist two α-nucleus systems, viz. $\alpha+{}^{16}$O (Ref. 15) and $\alpha+{}^{40}$Ca,[16] where an unambiguous determination of the real part of the interaction potential has been achieved. In both cases the absorption found necessary to explain the low-energy data was shown to be exceptionally weak with respect to that needed for most neighboring systems, making the scattering unusually sensitive to the interaction potential in the inside region.[15,16] This low absorption was shown to be responsible for the large-angle enhancement observed in both systems.

The α-^{16}O potential is of particular importance because it can be used as a testing ground in a case where there is general agreement on the cluster spectroscopy of the unified system. In fact it has recently been shown[15] that extrapolation to low energies of the real part of the unique global optical potential fitting the elastic ^{16}O(α,α) data between $E_\alpha \simeq 30$ and 150 MeV provides a consistent description of the $K^{\pi}=0_1^+$, 0^-, and 0_4^+ rotational bands in ^{20}Ne; further calculations have revealed[17] that this potential also gives very satisfactory estimates for the electromagnetic properties and α-particle widths of the members of these bands.

Turning to the $\alpha+{}^{40}$Ca system, we have calculated in the same spirit the properties of the bound and quasibound states associated with the real part of various low-energy ^{40}Ca(α,α) optical potentials belonging to the unique potential family fitting the higher-energy data.[16,18] In this case bound states with $N\equiv 2n_r+l < 12$ have to be discarded on account of the Pauli principle. The remaining states are found[19] to group into quasirotational bands with $N\geqslant 12$.

Quite remarkably, the band head of the $N=12$ band systematically falls below the $\alpha+{}^{40}$Ca threshold, within a few megaelectronvolts from that of the g.s. band of ^{44}Ti; moreover, both bands terminate at $J^{\pi}=12^+$ and qualitatively display the same behavior. In order to test further the merits of the present approach, we next calculated the intraband quadrupole probabilities and rms intercluster separations $\langle R^2\rangle^{1/2}$ for the states of $N=12$ band. Here and in the following, use was made of version *A* of the potential extracted by Delbar *et al.*[16] from an extensive analysis of ^{40}Ca(α,α_0) data extending from $E_\alpha=24$ to 166 MeV. Its depth U_0, which originally is slowly energy dependent, was finely tuned to locate each state at the correct energy with respect to the $\alpha+{}^{40}$Ca threshold; values of $U_0\simeq 180$ MeV were found necessary for that purpose. Values obtained for the $B(E2)$ and rms radii are reported in Table I, together with the potential depth U_0 needed for each state and experimental $B(E2)$ values.[3,20] The calculated transition probabili-

TABLE I. Theoretical and experimental (Refs. 3 and 20) $B(E2)$ values for the $J\rightarrow J-2$ transitions (in $e^2\cdot$fm^4), and intercluster rms radii for the ^{44}Ti $N=12$ and $N=13$ states. The local potential depth given for the $N=12$ states is that reproducing the experimental energies (Ref. 3) with respect to the $\alpha+{}^{40}$Ca threshold; for the $N=13$ states U_0 is fixed to the average value $U_0=180$ MeV.

	$N=12$					$N=13$	
	U_0	$B(E2)$		$\langle R^2\rangle^{1/2}$		$B(E2)$	$\langle R^2\rangle^{1/2}$
J^{π}	(MeV)	Theor.	Expt.	(fm)	J^{π}	Theor.	(fm)
0^+	184.1			4.50	1^-		5.35
2^+	182.5	107.3	120 ± 30	4.51	3^-	264.7	5.28
4^+	181.2	146.4	280 ± 60	4.47	5^-	279.1	5.15
6^+	180.7	140.2	160 ± 20	4.38	7^-	243.6	4.95
8^+	179.0	118.1	>14	4.27	9^-	184.5	4.71
10^+	181.8	74.9	140 ± 30	4.06	11^-	118.1	4.43
12^+	186.8	33.6	40 ± 8	3.83	13^-	54.9	4.14

ties are in very gratifying agreement with experiment, especially if one takes into account that no effective charge has been introduced in the calculation [large effective charges ($\delta e \sim 0.5e$) are needed in $(fp)^4$ shell-model calculations[21] in order to reproduce the $B(E2)$ experimental values]. On the other hand, the rms intercluster distance is seen to decrease from $R=4.50$ fm for the ground state to $R=3.83$ fm for the $J^\pi=12^+$ state (antistretching effect): These values should be compared with the sum of the ^{4}He and ^{40}Ca rms radii,[22] which amounts to 5.16 fm. The overlap between the clusters, which is moderate for the low-spin members of the band, is seen to become severe at high spin; the $N=12$ band has thus, as expected, not a strong cluster character, although—as in the ^{20}Ne case[23]—proper consideration of α clustering seems to be important for a correct reproduction of the intraband transition probabilities.

Our calculation predicts two additional quasirotational bands of opposite parities corresponding to $N=13$ and $N=14$. These states are displayed in Fig. 1 together with those of the ground-state band; calculations reported in that figure were carried out with the average potential depth $U_0=180$ MeV.

The $N=14$ excited positive-parity band is composed of broad states; its head lies about 6.5 MeV above the threshold. Although it is difficult to give a precise definition of an intercluster distance for these states (they are located near the top of their respective barriers), examination of their wave functions shows that the separation between the clusters is considerably larger than in the ground-state band; this band is in fact the analog of the "higher nodal" $K^\pi=0_4^+$ band of ^{20}Ne, and it has a strong α-cluster character. Very recently, we have shown[24] in a calculation using the same real potential as here with $U_0=180$ MeV that the broad oscillations observed in the experimental $\alpha+{}^{40}$Ca fusion excitation function between $E_\alpha=10$ and 27 MeV provide a direct manifestation of states of this band with spins ranging from 6 to 12. This is one of the only examples, along with the well-established case of ^{20}Ne, where an excited vibrational mode of the α-cluster degree of freedom has been observed experimentally. It is very important to recall here that the parity splitting between the even- and odd-N bands predicted by our (deep) potential appears to be an essential ingredient for a correct reproduction of the spacing and peak-to-valley ratio of the fusion oscillations.[24] Therefore, although the lower-spin members of our $N=14$ band have energies and widths comparable to those of the broad experimental positive-parity states with $J^\pi=0^+$ ($E_x=11.2$ MeV) and $J^\pi=2^+$ ($E_x=12.2$ MeV) recently observed by Frekers *et al.*,[6] the $J^\pi=1^-$ and 3^- states (with $E_x=11.7$ and 12.8 MeV, respectively) postulated by these authors to belong to the same (mixed-parity) band are incompatible with the present picture (see Fig. 1). It is to be noted in this respect that the spin determination of the $E_x=11.7$ MeV state seems to be unambiguous, but its interpretation as a simple $\alpha+{}^{40}$Ca(g.s.) cluster state is seriously hampered by the incompatibility between its small width ($\Gamma=40$ keV) and its position with respect to the $l=1$ barrier: Local-potential calculations systematically predict widths of about 1 MeV when this state is located at the correct experimental energy. On the other hand, the spin determination of the $E_x=12.8$ MeV state does not seem very conclusive and awaits an independent confirmation.

Our calculation invariably locates the $N=13$ negative-parity band halfway between the $N=12$ and $N=14$ positive-parity bands, with its bandhead slightly above the $\alpha+{}^{40}$Ca threshold. We have also calculated the $B(E2)$ transition rates and rms radii for the states of this band (using $U_0=180$ MeV) in the bound-state approximation; these are reported in Table I. This band (which is the analog of the "inversion doublet" $K^\pi=0^-$ band[25] of ^{20}Ne) also displays much stronger α-cluster properties than the ground-state band. The states of this band, which are predicted to lie considerably below their respective barriers, are much narrower than those of the $N=14$ band, and thus appear as genuine molecular states, in that their lifetime is much longer than their rotational period; in contrast, these characteristic times are of comparable magnitude for the $N=14$ states, while the states of the $N=12$ band appear to have a transitional character between the shell and cluster phases. Examination of Fig. 1 shows that the $N=13$ band has no known experimental counterpart; however, the very small width expected for these states could make their experimental identification difficult, especially if one takes into account the relatively high level density in ^{44}Ti in this energy region. We note, however, that our $N=13$ bandhead is not far from the $J^\pi=0^+$ ($E_x=8.54$ MeV) experimental level of Strohbusch *et al.*[4]; as the spin assignment of this level was only tentative, one cannot exclude the possibility that this state is in fact one of the first members of our $N=13$ band. Additional states strongly excited in the reaction ^{40}Ca(^{6}Li,d) observed by the same group[4] at higher excitation energy (but lacking spin assignments) can also be considered as possible candidates; mention should also be made of the recent resonance analysis of low-energy ^{40}Ca(α,α) data of Chatterjee *et al.*[26] Clearly additional experimental work is required to clarify the situation. The most powerful tool for that purpose seems to be the measurement of d-α angular correlations in the (^{6}Li,d) transfer reaction, which allows elimination of the direct ^{6}Li breakup events; this technique proved very successful for investigation of the α-cluster structure in the beginning of the sd-shell region up to relatively high excitation energies.[27]

In conclusion, we have shown that extrapolation to low energy of the unique optical potential fitting ^{40}Ca(α,α_0) scattering data above $E_\alpha \sim 25$ MeV gives strong support to an α-cluster interpretation of some of the states of the ^{44}Ti nucleus. Besides the ^{44}Ti ground-state band—which is reproduced qualitatively and found to display limited α-cluster properties—the calculation predicts two excited quasirotational bands with opposite parities and stronger cluster character. States of the positive-parity band have very recently been shown to be responsible for the broad oscillations seen in the $\alpha+{}^{40}$Ca data,[24] and its first members are compatible with some of the states extracted by Frekers *et al.*[6] from their high-resolution ^{40}Ca(α,α) experiment; in contrast, those of the negative-parity band, which we predict to start just above the $\alpha+{}^{40}$Ca threshold, have thus far no conclusive experimental counterparts. We believe that these states should be actively searched for since their experimental detection would definitively settle the present picture and pave the way to an extension of the α-cluster spectroscopy in the *fp*-shell region.

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