Identification of nuclear cluster-molecular states

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Gai *et al.* have proposed that cluster-molecular structure, in which a three- or four-particle cluster is well separated from the core, can be identified by the strong $E1$ transitions connecting cluster states with this structure. We use this signature to determine which cluster states in the $A = 14$–19 region are cluster-molecular states. In addition, we note that such structure can also be recognized by comparing the results of three- and four-particle transfer reactions which populate the nucleus. In a nucleus possessing cluster-molecular structure, the three- and four-particle cluster strength lies in different states. We use this information to support the identification of molecular or nonmolecular structure in several nuclei. The examination of the transfer data also allows us to identify a nucleus, ^{14}N, in which molecular and nonmolecular cluster states may coexist.

In a recent study of the γ-ray spectroscopy of ^{18}O, Gai *et al.* [1] have demonstrated that strong $E1$ transitions [near 10^{-2} Weisskopf units (W.u.)] occur between states which are selectively populated in the α-particle stripping reaction ^{14}C(^{7}Li,t)^{18}O. Gai *et al.* concluded that the large $E1$ matrix elements between these α-particle cluster states occur because the ^{14}C nucleus and α-particle are non-self-conjugate; that is, they have different charge to mass ratios. This difference in charge to mass ratios results in the separation of the center of charge from the center of mass in the nucleus and causes the nucleus to possess an intrinsic electric dipole moment. However, as we show here non-self-conjugate cluster states in some nuclei in this mass region are connected by $E1$ transitions which are *not* strong. Gai *et al.* [1] have proposed that strong $E1$ transitions occur between cluster states *only* when the cluster is well separated from the core. They call these well separated configurations "cluster-molecular" states.

In the present article, we use $E1$ transitions and transfer reaction data to determine which non-self-conjugate cluster states in nuclei in the vicinity of ^{18}O are cluster-molecular states. First, we collect the available data on $E1$ transitions between cluster states in the A=14–19 region, where a considerable amount of information on clustering has been obtained using transfer reactions. Second, we use this information to determine which nuclei possess strong $E1$ transitions between cluster states, making them candidates for cluster-molecular structure. Finally, we examine transfer reaction data for nuclei for which both three- and four-particle cluster states have been located in order to find further information regarding the presence of cluster-molecular structure. The transfer data allow us to confirm the assignments of two nuclei as molecular or nonmolecular. In addition, the transfer data suggest that molecular and nonmolecular cluster states coexist in ^{14}N.

In order to collect information on $E1$ transitions between cluster states, we have referred to the literature to determine which states are non-self-conjugate cluster states, and then searched the tables of electromagnetic transitions in Refs. [2–4] for $E1$ transitions which connect any two of these states. The results of this search are listed in Table I. The 6.45 and 8.91 MeV states in ^{14}N both appear strongly in the ^{11}B(^{6}Li,t)^{14}N study of Clark and Kemper [5]; therefore, they are considered to be ^{3}He cluster states, and the γ-ray connecting them is included in Table I. The 7.16 and 9.83 MeV states of ^{15}N are observed in the ^{12}C(^{7}Li,α)^{15}N triton transfer reaction by Harwood and Kemper [6], so the transition between them is included as well. Two transitions are listed for ^{15}O; the associated states (5.24, 7.28, and 9.49 MeV) are seen in the ^{12}C(^{6}Li,t)^{15}O reaction by Bingham *et al.* [7]. For ^{17}N, the 1.91 and 2.53 MeV states listed with the transition in Table I are seen in the ^{14}C(^{6}Li,^{3}He)^{17}N reaction by Cunsolo *et al.* [8].

The $E1$ transitions between α-particle cluster states in ^{18}O are those listed in Ref. [1]. Finally, the transitions listed for ^{19}F are those between states assigned as cluster states by Buck and Pilt [9]. Only transitions connecting two triton cluster states or two α-particle cluster states are included in the list for this nucleus.

Even a cursory glance at Table I is interesting. First, it is clear that a great deal of work has been done to measure $E1$ strengths in ^{18}O and ^{19}F, and very few $E1$ transitions between cluster states have been measured in other nuclei. Of these other nuclei, ^{15,17}N might be considered particularly interesting because of their *weak* $E1$ transitions between cluster states. Further measurements of $E1$ strengths in these nuclei would clearly be of interest.

An illustration of the distribution of the $E1$ strengths of transitions listed in Table I is shown in Fig. 1(a), where the transitions are placed in a histogram in which the bin sizes are logarithmically equal. For comparison, a corresponding histogram of all $E1$ transitions listed for $A = 14$–19 in Refs. [2–4] is shown in Fig. 1(b). The two histograms demonstrate that the cluster $E1$ transitions are large on the average, but they are not unique in their strength. Furthermore, few cluster $E1$ transitions

TABLE I. $E1$ transitions between non-self-conjugate cluster states in A = 14–19 nuclei.

Nucleus	Cluster [a]	E_i (MeV)	E_f (MeV)	$B(E1)$ (W.u.) [b]
^{14}N	^{3}He	8.91	6.45	(2.0±1.0)x10^{-3}
^{15}N	t	9.83	7.16	(1.2±0.7)x10^{-4}
^{15}O	^{3}He	9.49	5.24	4.8 x 10^{-3}
		9.49	7.28	2.5 x 10^{-2}
^{17}N	t	2.53	1.91	(7.8±0.9)x10^{-5}
^{18}O	α	4.46	3.63	(2.7±0.7)x10^{-2}
		4.46	3.92	(3.5±1.1)x10^{-3}
		5.10	3.92	(2.5±1.1)x10^{-3}
		5.26	4.46	(8.2±0.8)x10^{-3}
		6.20	3.63	(5.5±1.2)x10^{-4}
		6.20	5.26	(1.6±0.3)x10^{-2}
		8.28	5.26	(1.4±0.5)x10^{-2}
^{19}F	α	5.34	0.11	(1.0±0.2)x10^{-2}
		5.34	1.46	(1.2±0.2)x10^{-2}
		5.50	0.11	7.0 x 10^{-3}
		5.50	1.35	9.8 x 10^{-3}
		6.28	1.35	(2.1±0.5)x10^{-3}
		6.28	1.46	(1.2±0.4)x10^{-3}
		6.33	1.35	(5.3±1.3)x10^{-4}
	t	6.09	0.00	(5.1±1.4)x10^{-3}
		6.09	0.20	(3.2±1.0)x10^{-3}
		6.93	0.20	(1.2±0.2)x10^{-2}
		6.93	2.78	(1.7±0.5)x10^{-3}
		9.87	2.78	(3.9±1.2)x10^{-3}

[a]Cluster structure inferred from references listed in the text.
[b]These values are taken from the compilations of Refs. [2–4].

are known in the nuclei in which they seem to be weak (in particular, ^{15,17}N). This lack of data in the odd-A nitrogen nuclei may skew the appearance of the cluster histogram.

In the simple cluster picture, strong $E1$ transitions in a non-self-conjugate cluster configuration are caused by the separation of the center of charge from the center of mass. In the ^{14}C+α cluster configuration in ^{18}O, the charge to mass ratios in the two constituents are somewhat different, so that the centers of charge and mass are separated. However, the three nucleon triton and ^{3}He clusters cause even larger separations, and they would be expected to yield stronger $E1$ transitions. Alhassid, Gai, and Bertsch [10] suggested quantifying this argument with the use of a "molecular Weisskopf unit" (M.W.u.). In this unit, the radius parameter used in the Weisskopf single particle estimate is replaced by the separation of the center of charge from the center of mass in order to yield an estimate for the strength of an $E1$ transition caused by cluster structure. The M.W.u.'s are considerably smaller than the conventional W.u.'s; however, they generally represent strong $E1$ transitions. For example, an α-particle cluster configuration in ^{18}O yields 1 M.W.u. = 1.8 x 10^{-3} W.u, a triton cluster configuration in ^{15}N gives 1 M.W.u. = 7.5 x 10^{-3} W.u., and a ^{3}He cluster in ^{14}N yields 1 M.W.u. = 1.2 x 10^{-2} W.u.

In Fig. 2, we plot the average of the observed $E1$ transitions from Table I against the M.W.u. estimate for $E1$ strength for each cluster configuration. The line for

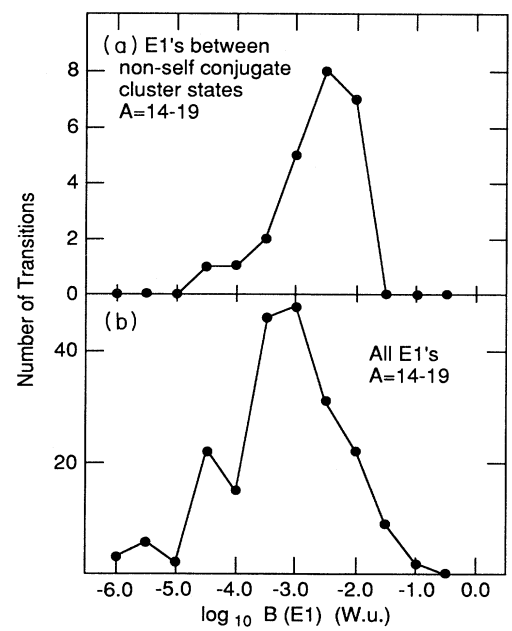

FIG. 1. (a) Distribution of strengths of $E1$ transitions between cluster states in A = 14–19 nuclei as listed in Table I. (b) Distribution of strengths of all $E1$ transitions for A = 14–19 as listed in Refs. [2–4].

which the observed average equals 1 M.W.u. divides the data points into two classes of nuclei in which the $E1$ transitions are strong and weak with respect to the M.W.u. cluster estimate. In the context of the proposal of Gai *et al.* [1] that strong $E1$ transitions identify cluster-molecular structure, the line seems to divide the nuclei into cluster-molecular (above the line—^{15,18}O and ^{19}F) and non-cluster-molecular (below the line—^{14,15,17}N) classes.

Cluster-molecular states may also be recognized from the data on the three- and four-particle transfer reactions which are used to populate cluster states. A configuration in which a four-particle cluster is well separated from the core would have little overlap with a three-particle cluster state. Conversely, a well separated three-particle cluster state would have little overlap with a four-particle cluster configuration. If the three- and four-particle cluster strengths lie in the same states in a nucleus, then the nucleus cannot possess the well separated cluster-molecular structure. However, if the three- and four-particle cluster states are different, then the nucleus does possess cluster-molecular structure. This argument can be used to check the conclusions reached regarding cluster-molecular structure based on $E1$ transition strengths.

Of the nuclei in Fig. 2, experimental information on both three- and four-particle cluster strengths is available for three nuclei, ^{14,15}N and ^{19}F [5, 6, 11]. In ^{19}F, both the α-particle and triton cluster configurations have strong $E1$ transitions connecting them, indicating cluster-molecular structure. Further support for the cluster-molecular interpretation comes from the observation that three- and four-particle cluster strength occurs in different sets of states [11]. In ^{15}N, the $E1$ transition between cluster states is weak, and the three- and four-particle cluster configurations occur in the same states [6]. Therefore, it appears that ^{15}N does not possess cluster-molecular structure.

The single known $E1$ transition in ^{14}N is relatively weak (indicating that cluster-molecular structure does not exist), but the situation in ^{14}N regarding the location of three- and four- particle cluster strength [5] is not well defined as it is for ^{15}N and ^{19}F. Some states are seen strongly in both three- and four-particle transfer reactions, but other states are seen in only one of the reactions. The $E1$ transition listed for ^{14}N in Table I is that between the 8.91 and 6.45 MeV states, which are seen in both the ^{11}B(^{6}Li,t)^{14}N and ^{10}B(^{6}Li,d)^{14}N reactions. Because these states are seen in both reactions, we would identify them as non-cluster-molecular states. The weak $E1$ connecting them also indicates a non-cluster-molecular assignment for these two states. However, we suggest that the states that are seen in only the three-particle reaction or only the four- particle reaction *are* cluster molecular. Our examination of transfer data seems to indicate that cluster states of both molecular and nonmolecular types may coexist in ^{14}N.

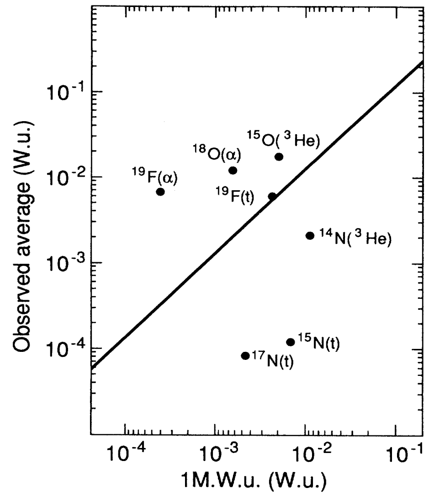

FIG. 2. The averages of strengths of observed $E1$ transitions between cluster states plotted against the cluster $E1$ strength estimate given by the Molecular Weisskopf unit (M.W.u). Each point is labelled with the corresponding nucleus and cluster. The line is given by observed average = 1 M.W.u.

In each of these three cases, the determination of molecular or nonmolecular structure made using the strengths of $E1$ transitions between cluster states is supported by the location of three- and four-particle transfer strength. However, because the conclusions we draw here rely on the very limited γ-ray data presently available for ^{14,15}N, it is important to further investigate $E1$ transitions in these nuclei. In addition, it is important to develop other criteria for distinguishing between cluster-molecular states and other cluster states.

In conclusion, we have examined the strengths of $E1$ transitions connecting cluster states in A = 14–19 nuclei and have found that ^{15,18}O and ^{19}F possess cluster-molecular structure and that ^{14,15,17}N do not. Examination of three- and four-particle transfer reaction data supports the identification of cluster- molecular structure in ^{19}F and nonmolecular structure in ^{15}N. However, transfer reaction data suggest that molecular and nonmolecular cluster states coexist in ^{14}N. Few data are available on $E1$ transitions between cluster states in ^{14,15}N, and new experiments on these nuclei are critical to the understanding of the role of cluster-molecular structure. In general, the strengths of $E1$ transitions between cluster states provide a useful method for distinguishing between cluster-molecular and nonmolecular states.

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