Clustering in non-self-conjugate nuclei

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1. Introduction

Clustering is a well established phenomenon in light N=Z (4N) nuclei. The low excitation energy spectrum of ^{8}Be can be described as a two-center α - α structure[1]. Strong α -cluster quasi-rotational bands (inversion doublets) are known in ^{16}O and ^{20}Ne [2, 3]. The members of these bands have large reduced α widths, comparable to the single particle limit, which is the maximum possible reduced width that a nuclear resonance can have if it has a pure α +core structure. The α -cluster structure of 4N (N = Z) nuclei has been studied extensively, however much less information is available on the α -cluster structure of non-self-conjugate N ≠Z nuclei. Experimental study of clustering in T=1 spectrum of ^{10}B and is reported in this contribution.

2. T=1 states in ^{10}B

The suggestion that the structure of certain states in ^{10}Be can be better described using two center model where "valence" nucleons are added to the system of two α -particles has been made in the early 1970s.[1] A semi-quantitative discussion of this subject can be found in [4] where the two-center molecular states in ^{9}B, ^{9}Be, ^{10}Be, and ^{10}B nuclei were considered in the framework of a two-center shell model. An Antisymmetrized Molecular Dynamics plus Hartree-Fock (AMD+HF) approach was proposed in [5] as a theoretical tool to study the structure of low-lying levels in $^{9,\ 10,\ 11}$Be isotopes. Deformation (distance between the two α for several low-lying states in Be isotopes has been studied. Very large deformation (β=0.852) for the 6.179 MeV 0+ state in ^{10}Be was suggested which corresponds to an interalpha distance of 3.55 fm. This is 1.8 times more than the corresponding value for the ^{10}Be ground state. A similar result was obtained in [6] where the spectrum of ^{10}Be was reasonably well reproduced using a molecular orbit (MO) model. It was shown that the second 0^{+} in ^{10}Be has an enlarged α - α distance and that the highly deformed rotational band with large moment of inertia built on that configuration emerges. The two known states in ^{10}Be, the 0+ at 6.179 MeV and the 2^{+} at 7.542 MeV are believed to be associated with this rotational band. The experimental evidence for the 4+ member of this band is controversial. The state at excitation energy of 10.15 MeV was assigned spin-parity of 3^{-} in [7]. However, in [8, 9] the 4^{+} spin-parity assignment was suggested for this state. It was argued in [9] that the 10.15 MeV state is the next member of the highly deformed K^{π}=0^{+} rotational band built on the 0^{+} state at 6.179 MeV and that the very large moment of inertia of this band indicates (α :2n: α) configuration. If this is the case then an analogous band with (α :np: α) configuration should be found in the spectrum of T=1 states in ^{10}B. Properties of T=1 states in ^{10}B are studied in this contribution.

The experiment was performed at the INFN facility in Catania, Italy. T=1 resonances in ^{10}B were searched for in the excitation functions of ^{1}H(^{9}Be, α)^{6}Li*(T=1, 0^{+}, 3.56 MeV) reaction. While both T=0 and T=1 states can be populated in ^{9}Be+p scattering, only the T=1 states would predominantly decay to the T=1 state in ^{6}Li by α emission due to isospin conservation and the T=0 states would be strongly suppressed in the ^{1}H(^{9}Be, α)^{6}Li*(T=1, 0+, 3.56 MeV) excitation function. Excitation functions of ^{1}H(^{9}Be, α)6Li*(T=1, 0+, 3.56 MeV) were measured by changing the beam energy from 22:3 up to 55:6 MeV with steps ranging between 0.12 and 5.75 MeV (0.012 MeV and 0.575 MeV in c.m.). Both reaction products, α and ^{6}Li, were detected. The ^{1}H(^{9}Be, α)^{6}Li*(T=1, 0^{+}, 3.56 MeV) events were selected using angle-energy correlation of ^{6}Li ions identified using ΔE-E 2-D spectra. The excitation functions for the ^{1}H(9Be, α)^{6}Li*(T=1, 0^{+}, 3.56 MeV) reaction were measured in the c.m. energy range between 2.1 and 5.5 MeV (8.7 - 12.1 MeV excitation in ^{10}B). The excitation function at 55 ± 2.5^{0} in c.m. is shown in Fig. 1. The narrow peak at Ecm = 2.3 MeV corresponds to the doublet of known T=1 states in ^{10}B, the 3^{-} and the 2^{+} at Ex = 8.9 MeV. Spin-parities and widths of these states are known, but the decay branching ratios are not. This data allows for direct measurement of the partial α -widths for these states.

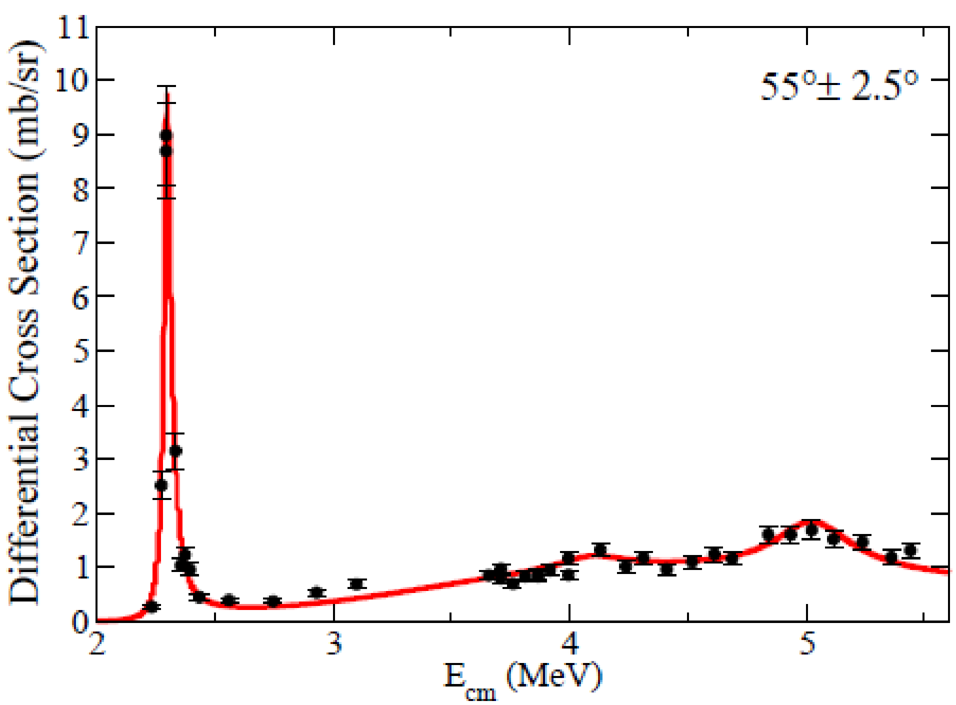

FIG. 1. ^{1}H(^{9}Be, α)6Li*(T=1, 0^{+}, 3.56 MeV) excitation function at 55^{0} in c.m. Solid (red) curve is the best R-Matrix fit.

A multi-channel, multi-level ***R***-matrix analysis of the excitation functions was performed. The reduced width amplitudes were constrained in the ***R***-matrix fit by requiring that corresponding proton and neutron reduced width amplitudes are equal, as determined by the isospin Clebsch-Gordon coefficients for the T=1 states in ^{10}B. The parameters of the resonances are given in Table I. More details on this analysis can be found in [10].

Table I. Resonance parameters from the *R*-matrix fit.

J^π	E_{cm} (MeV)	E_x (MeV)	Γ_{tot} (keV)	Γ_α (keV)	Γ_p (keV)	Γ_n (keV)	θ^2_α
2^+	2.308(2)	8.894(2)	34(4)	18±2.0±2.3	7(4)	2(1)	1.1(2)
3^-	2.312(10)	8.898(10)	80(10)	0.57(5)	75(10)	4(3)	0.42(4)
2^+	4.1(1)	10.7(1)	300±100)	≈8	≈170	≈130	≈0.007
(0^+)	4.4(3)	11.0(3)	3700^{+200}_{-600}	2800^{+200}_{-600}	514(100)	414(100)	$0.97^{+0.06}_{-0.20}$
1^-	5.04(7)	11.63(7)	480(150)	13(6)	260(100)	210(120)	0.004(2)

As it was mentioned above, several theoretical approaches predict a developed α-2n- α structure for $0^+/2^+/4^+$ band with 0^+ bandhead at 6.179 MeV in ^{10}Be. The same should be true for the corresponding analog states in ^{10}B. The most direct experimental observable for the degree of clustering is the partial α width. The excitation energies of the 0^+ states in both ^{10}Be and ^{10}B are below the corresponding α decay thresholds. The partial α widths for the 2^+ states were unknown in both nuclei. The 18±2.0±2.3(sys) keV partial α width for the 2+ state at 8.89 MeV in ^{10}B determined in this experiment corresponds to the α single particle limit. In fact, this width can be well reproduced in the framework of a simple ^{6}Li(T=1)+ α potential model. The Woods-Saxon potential with depth of -119 MeV, radius and charge radius of 2.58 fm and 2.27 fm respectively, and diffuseness of 0.677 fm generates the 0^+ and the 2^+ α -cluster states in excellent agreement with the spectra of ^{10}B and ^{10}Be and predicts the 15 keV width for the purely α – cluster 2^+ state at 8.894 MeV in ^{10}B (0.870 MeV above the ^{6}Li(0^+,3.56 MeV)+ α decay threshold).

The very large partial α width of the 2^+ state at 8.89 MeV measured in this work leaves no doubt about its α -^{6}Li(T=1) molecular type nature. This confirms the assertion made in several theoretical and experimental works [5, 6, 9] that this state (or its analog at Ex=7.542 MeV in ^{10}Be) is a member of a highly clustered rotational band built on the 0+ state at E_x=7.56 MeV in ^{10}B (6.179 MeV in ^{10}Be). The defining feature of this band is its high moment of inertia which is indicative of the large separation between the two α cores [5]. Assuming that the 10.15 MeV state observed in [9] is the 4^+ member of the analogous band in ^{10}Be it can be expected that the excitation energy of the corresponding 4^+ in ^{10}B is ~11.5 MeV. Indeed, if this state has a large dimensionless reduced α width as suggested in [9] for the presumably analogous 10.15 MeV state in ^{10}Be then there is a good chance to see it in the ^{1}H(^{9}Be, α)^{6}Li_(T=1) reaction. The 2^+ resonance at 8.89 MeV that is considered to be a member of the same rotational band as the aforementioned 4^+ is the dominant feature in the measured excitation function (Fig. 1). However, the 4^+ state has not been observed in this work. Besides a trivial reason for not seeing this state because it does not exist or is at higher excitation energy, we can offer another explanation. If this state corresponds to pure α +^{6}Li(T=1) molecular configuration and the admixture of the ^{9}Be(g.s.)+p configuration is too small then the cross section for the (p, α) reaction may be too small making this resonance “invisible" on top of the “background" of other T=1 states in ^{10}B. This may also explain the results of [11] where excited states of ^{10}B were populated in the ^{11}B(^{3}He, α)^{10}B reaction and the 11.5 MeV state was only observed in the ^{6}Li+ α decay channel, and not in the 9Be(g.s.)+p channel. We estimate that the proton dimensionless reduced width for the 4^+ state has to be less than $2x10^{-4}$ to make it unobservable in our measurements. This is 0.6% of the proton dimensionless reduced width of the 2^+ that corresponds to the same rotational band. As shown in Fig. 2 the resonance structure at 11.6 MeV excitation in ^{10}B is evident, but it corresponds to the 1^- state with weak α -cluster component. It is possible that this state is the isobaric analog for the 10.57 MeV state with uncertain (≥ 1) spin-parity assignment in ^{10}Be [12]. The finding of a new broad T=1 0^+ state at ~11 MeV was surprising. Its large partial α width is the direct evidence for the extreme α cluster structure of this state.

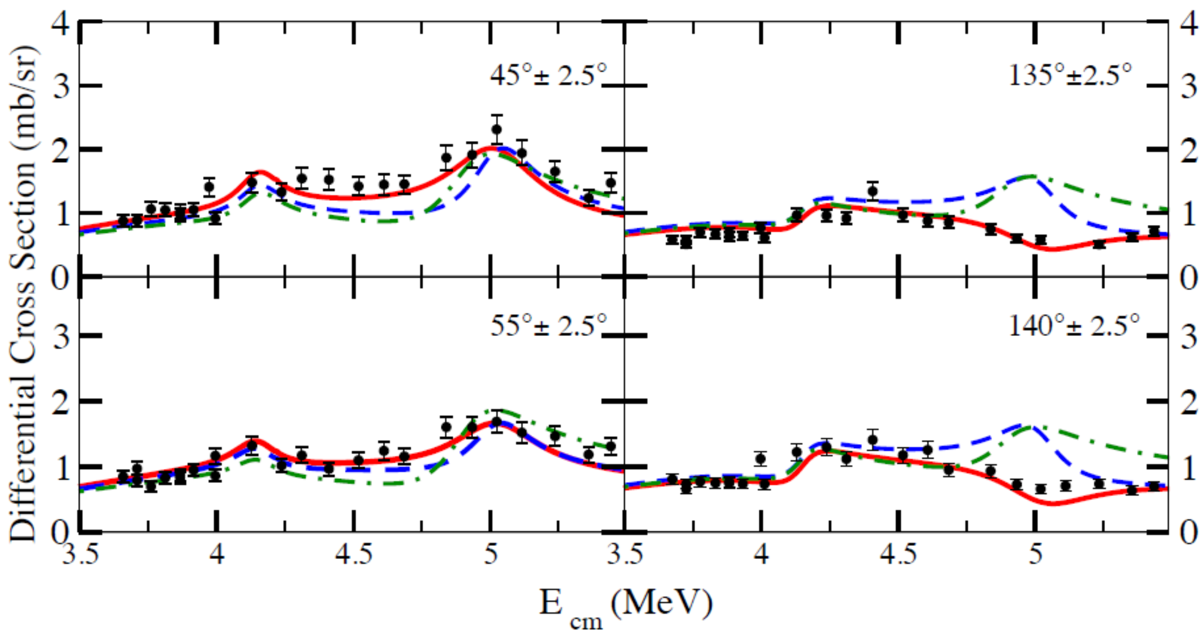

FIG. 2. Excitation functions of ^{9}Be(p, α)^{6}Li(T=1, 0^+, 3.56 MeV) and the R-matrix fits with three different spin-parity assignments for the state at 5 MeV (11.6 MeV excitation energy). The best fit has a 1^- spin-parity assignment, as shown by the solid (red) line, the fit with a 4+ state is shown by the dashed (blue) line, and the fit with a 3^- state is shown by the dot-dash (green) line. All three fits agree with the data relatively well at lower angles, but only the fit with a 1^- state agrees well with higher angle data.

Acknowledgements

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