3^+ and 2^+ states in ^{10}Be and ^{10}B nuclei

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In response to recent papers which suggest that a level around 9.5 MeV in excitation in ^{10}Be nucleus is its first $J^{\pi}T=3^{+}1$ state, the experimental results are presented which undoubtedly prove that it is the fourth $2^{+}1$ state. Recent observations that the state at 7.00 MeV in ^{10}B decays also into $\alpha+{}^{6}$Li*(2.19 MeV) are interpreted as a strong evidence that it is the third $3^{+}0$ state of this nucleus. The structure of these states is discussed.

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Although many theoretical calculations predict a state of ^{10}Be with $J^{\pi}T=3^{+}1$ at excitations close to 10 MeV, there is no firm experimental evidence for its existence. Recent papers by Pieper, Varga, and Wiringa [1], Kanada-En'yo and Horiuchi [2], and Daito *et al.* [3] suggest that the state with excitation energy around 9.4 MeV excited by a Gamow-Teller transition in the ^{10}B$(t,{}^{3}$He$)^{10}$Be reaction [3] may be the $3^{+}1$ state. However, the observed transition together with many other experimental results can be consistently explained in another way. One can start with several recent independent observations [4–9] that the state decays into two zero-spin nuclei, ^{4}He and ^{6}He, a transition not allowed for any unnatural parity state. Mentioned strong Gamow-Teller transition then leaves only 2^{+} and 4^{+} as its possible assignments. Clear $\ell=1$ angular distribution of the ^{11}B$(d,{}^{3}$He$)^{10}$Be reaction involving this state [10] narrows it to 2^{+}. The same assignment is supported by its strong feeding in the ^{10}B$(d,{}^{2}$He) and ^{10}B(π^{-},γ) reactions [11,12], which favor transitions involving spin flip, as well as in the $(^{12}$C, ^{14}O) and other two-proton pickup reactions on ^{12}C [13–16]. The same values of spin and parity resulted from an analysis of measured angular correlations of the ^{6}Li$(^{7}$Li, α^{6}Li$)^{3}$He and ^{7}Li$(^{7}$Li, α^{6}He$)^{4}$He reactions [6], although one may have some reservations on the applicability of this method to the processes involving nonzero-spin nuclei. The authors determined very precisely its excitation energy to be 9.56 MeV. The more direct and final proof comes with its decay into $\alpha+{}^{6}$He*(1.8 Mev, 2^{+}) observed recently [5,7]. This decay would not be observable in these measurements if it were not a 2^{+} state ($\ell=0$ transition), because with the decay energy of only 350 keV any additional centrifugal barrier would strongly suppress it. From all this one can conclude that all the data concerning the 9.56 MeV state can be explained by its $2^{+}1$ assignment. However, one cannot totally exclude the possibility that in its vicinity there is also a $3^{+}1$ state but its existence has yet to be proven.

From the energy differences between other known isobaric analog states in ^{10}B and ^{10}Be nuclei (i.e., 1.7–0.0, 5.2–3.4, 7.5–6.0, 8.9–7.5 MeV, see Fig. 1), the fourth $2^{+}1$ state in ^{10}B can be expected around 11 MeV in excitation. From the results on electron scattering on ^{10}B [17] and their own ^{10}Be(π^{-},γ) data Perroud *et al.* [12] claim that the analog state in ^{10}B is at 11.5 MeV. On the other hand, Yasue *et al.* [18], from their measurement of the excitation functions for the ^{9}Be$(p,\alpha)^{6}$Li reaction leading to different ^{6}Li states, suggest that the assignment of the 10.8 MeV state is $2^{+}1$ while the one at 11.5 MeV is a mixed-isospin state.

Although no $3^{+}1$ state in $A=10$ nuclei has been found yet, now one may claim with certainty that one of its zero-isospin cousins, the third $3^{+}0$ state in ^{10}B, is the level at $E_{\rm exc}=7.00$ MeV. This claim is based upon two recent independent observations [5,20,21] that one of its decay modes is $\alpha+{}^{6}$Li*(2.19 MeV, 3^{+}) with the decay energy of only 360 keV. One may repeat the same argument as in the case of the $2_{4}^{+}1$ state in ^{10}Be: if it were not a 3^{+} state (i.e., $\ell=0$ transition), the decay with so low energy would be strongly suppressed by any additional centrifugal barrier (e.g., the

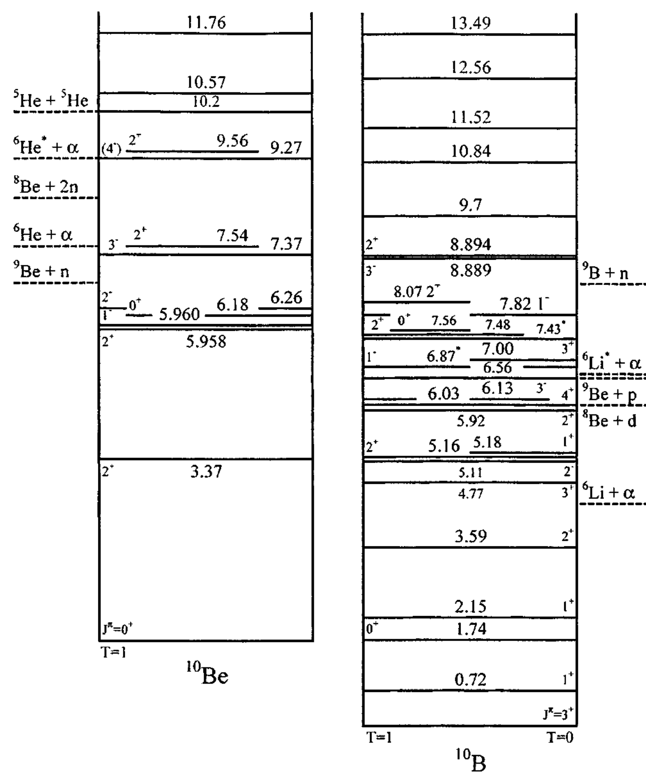

FIG. 1. Energy level diagram for ^{10}Be and ^{10}B nuclei for excitations below 14 MeV adopted with small changes from Ref. [19].

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barrier height for this system and for $\ell=2$ and $R=8$ fm is 830 keV). This state has been observed as a resonance (close to a much stronger one at $E_{exc}=6.88$ MeV) in the (p,α) and (p,d) reactions on ^{9}Be [22–25] [but not in (p,p) and (p,γ)] as well as in the $\alpha+^6$Li elastic scattering [26] [but not in (α,γ)]. From different *R*-matrix analyses of their own data each group gave different preferred assignment, 3^+ [24], 2^+ [26], and 1^+ [25]. From the most recent *R*-matrix analysis [27] of the data from Refs. [22] and [25] as well as of additional lower energy data [28] it is concluded that "the only possibility would seem to be that the 7.00 MeV level is 3^+ rather than 2^+," but "good fits have not been obtained to all the data with such an assumption."

The same assignment was suggested in these two cases: (i) from the similarity of the angular distributions of the $(d,^6$Li) reaction on ^{14}N leading to this state and to the $3^+_2 0$ state at 4.77 MeV [29]; (ii) from the α-α angular correlation measurement of the ^{11}B(^{3}He,$\alpha\alpha$)^{6}Li reaction [30] (although one may have the same reservations on the applicability of this method here like in the similar, previous case concerning the $2^+_4 1$ state in ^{10}Be).

One may add that this state is either not visible or very weakly populated in the proton stripping reactions on ^{9}Be (sometimes not resolved from its close neighbor at 6.88 MeV). Its $\alpha+^6$Li decay was relatively weak with respect to those of other states of ^{10}B lower in excitation observed in the measurements of the relative population of particle-unstable states of intermediate mass fragments in the ^{14}N + Ag and ^{36}Ar + ^{197}Au collisions at $E/A=35$ MeV [31,32].

Concerning the structure of these states it seems that the $2^+_4 1$ state fits well into the 1*p* shell model picture. Not only its energy, 9.16 Versus 9.56 MeV, but also its behavior in one-nucleon transfer reactions is well predicted by the old calculations of 1*p* shell nuclei by Cohen and Kurath [33]. As was pointed out by Schwinn *et al.* [10], the experimental data on the one-nucleon transfer reactions feeding the $2^+_4 1$ state confirm their predictions that it would be strongly excited in the proton pickup reactions but contains no neutron stripping strength. In the same calculation the third 3^+0 state in ^{10}B was predicted at 7.68 MeV. However, in a recent more complex shell model calculation [34] two 3^+0 states have been found in the energy region: the third $0\hbar\omega$ 3^+0 state at 7.82 MeV (7.33 MeV above the 3^+ ground state) and a $2\hbar\omega$ state at 5.61 MeV. The only experimental indication about the fourth 3^+0 state came from the Distorted-Wave Born Approximation analysis of the ^{14}N(d,^{6}Li)^{10}B reaction measurement [29]. Its excitation energy of 8.68 MeV corresponds to the position of a resonant structure observed in the excitation functions of the (p,d) and (p,α) reactions on ^{9}Be [35,36]. Although one may be tempted to suggest that the 7.00 MeV state corresponds to the $2\hbar\omega$ state and the one at 8.66 MeV to the third 3^+0 $0\hbar\omega$ state, more experimental information on both levels is needed for any final conclusion.

Significant challenges will be on one side the experimental determination of higher 3^+0 states in ^{10}B, of the $2^+_4 1$ analogs as well as of any $3^+_1 1$ state in $A=10$ nuclei, and on the other side the computation of all these states by modern theoretical approaches.

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