Reply to “Comment on ‘Three-body properties of low-lying ^{12}Be resonances’ ”E. Garrido,¹ A. S. Jensen,² D. V. Fedorov,² and J. G. Johansen²¹*Instituto de Estructura de la Materia, CSIC, Serrano 123, E-28006 Madrid, Spain*²*Department of Physics and Astronomy, Aarhus University, DK-8000 Aarhus C, Denmark*

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We suggested that the two resonances at 0.89 and 2.03 MeV above the two-neutron separation threshold have spins and parities of 0^+ and 1^- . In the Comment, Fortune claims that these states almost unambiguously must be 3^- and 4^+ states. We work in three-body cluster models with $J^\pi = 0^+, 1^-, 2^+$ where all three-body continuum structures are included. Fortune bases his assignments on the bound-state shell-model and (t, p) calculations. Our conclusions are from three-body structure results including widths. Assignments as 0^+ and 1^- (or, perhaps, 3^-) resonances are the most natural within the three-body cluster model.

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The claims in the Comment of Fortune [1] are based on experimental data from 1994 and relatively simple shell-model considerations. The spin-parity assignment of the two established resonances at 0.89 and 2.03 MeV above the two-neutron separation threshold are almost unambiguously claimed to be 3^- , and 4^+ , respectively.

Our suggested assignments of 0^+ and 1^- are based on structure calculations in a three-body model with two neutrons and a ^{10}Be core [2]. This model was successfully used to describe the four known bound states [3], and it suggested that a 0^- structure should exist [4]. This three-body model rather naturally describes the bound spectrum within the space of $0^\pm$, $1^\pm$, and $2^\pm$ states. The extension to the continuum with the same interactions led to the suggested spin-parity assignments. Our original conclusions are consistent with published energies and widths, but a 3^- resonance is also possible as found by the extension of our original paper. A 4^+ resonance cannot be supported within our three-body space. This is illustrated in Fig. 1 where we show the lowest adiabatic potentials (obtained with the method and two-body interactions described in Ref. [2]) for the 3^- [Fig. 1(a)] and 4^+ [Fig. 1(b)] states in ^{12}Be . Whereas, for the 3^- states, one of the potentials shows a barrier that could hold a resonance, and for the 4^+ states, no barriers are observed, and therefore, the existence of such resonance, according to our method, is not very likely. Still, other states may be possible if they arise from degrees of freedom outside the three-body space.

Also, the analogy with the ^{14}C spectrum should be taken with care. It is well known that ^{11}Be shows the so-called parity inversion such that the spin and parity of its ground and first-excited states are $1/2^+$ and $1/2^-$, respectively. This means that the $s_{1/2}$ and $p_{1/2}$ waves are reversed compared to the usual ordering. This phenomenon is not observed in ^{13}C , whose ground and first-excited states have the expected spin and parities of $1/2^-$ and $1/2^+$, respectively. Only for this reason is the comparison between the ^{12}Be and the ^{14}C spectra not so direct. For instance, it would be natural to think that the analogous configuration in ^{12}Be for the $p_{1/2}-d_{5/2}$ configuration (that leads to a 3^- state in ^{14}C) should be an $s_{1/2}-d_{5/2}$ configuration (that would lead to a 2^+ state in ^{12}Be , instead of a 3^- state).

The arguments against our assignments as expressed in the Comment of Fortune are also based on shell-model (t, p) calculations of the cross section. The (t, p) population is not consistent with our suggested assignments. We compare measured and computed widths of the resonances, which have no counterpart in simple bound-state shell-model calculations. The widths in pure three-body calculations should be larger than measured values because the many-body nature at short distances cannot be described in a three-body model. The computed widths have to be multiplied by preformation probabilities or spectroscopic factors smaller than unity.

We have not computed transfer reaction cross sections in Ref. [2]. Our conclusions are almost entirely based on three-body structure calculations. The translation into the language of shell-model neutron-core states can be seen in our second Jacobi coordinate system. The 0^+ state can be made of a d^2 configuration that corresponds to about (62, 28, 10)% of (s, p, d) waves in the first Jacobi system, which describes the relative neutron-neutron configuration. In a one-step (t, p) process, the two neutrons have to be transferred in a relative s state. Thus, about two-thirds of that structure seems to allow a substantial (t, p) transfer of two neutrons.

FIG. 1. (Color online) Lowest adiabatic potentials for the (a) 3^- and (b) 4^+ states in ^{12}Be by using the same method and interactions as in Ref. [2].

In general, the shell-model description of spatially extended halo states is not very successful, and correspondingly, the continuum states described with a very limited Hilbert space are not very convincing. This word of caution is emphasized by the known shell-model inability to describe the $1/2^-$ to $1/2^+$ parity inversion in ^{11}Be . The shell-model computations of the bound states should first be made sufficiently reliable. Furthermore, the simple shell-model picture of only one-step processes is often not sufficient to explain cross sections, see, e.g., Refs. [5,6]. More complicated processes also rather likely contribute.

In the original experimental paper from 1994, the claims were not strongly expressed. Here also, only the two lowest bound states are correctly interpreted, the third (1^-) has the wrong tentative assignment of 0^+ , and the established 0^+ bound state is completely absent. The present claims are then from the subsequent shell-model calculations of resonance structure in the continuum and estimates of the cross section.

To summarize, in Refs. [2,3], we considered three-body $0^\pm$, 1^- , and 2^+ states and suggested the most natural spin-parity assignments of both bound states (0^+ , 2^+ , 1^- , 0^+) and the two resonances (0^+ , 1^-). In addition, we suggested another higher-lying 2^+ resonance and a signal of a 0^- structure immediately above the one-neutron threshold. In Ref. [2], we did not investigate other spin-parity states, such as 3^- and 4^+ . Subsequent preliminary tests of these possibilities in our three-body model reveal that 3^- would be a natural candidate for one of these states, whereas, 4^+ appears to be impossible. New, not yet published, experimental data have shown a substantial decay of the lowest resonance into the excited $^{11}\text{Be}(1/2^-)$ bound state [7]. This could indicate a significant contribution of a $^{11}\text{Be}(1/2^-) + n$ configuration in the lowest resonance. Contributions from two-step processes can be significant in the population of ^{12}Be resonances.

In conclusion, we find it premature to conclude that the two known resonances unambiguously are of 3^- and 4^+ character.

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