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# Energy and width of the excited $0^+$ state in $^{12}$O

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We review predictions for the energy of the excited $0^+$ state of $^{12}$O and present new calculations of its width. Results are compared with those of a recent experiment.

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Given the existence of a $2^+$ state [1–3] at 2.11 MeV in $^{12}$Be and an excited $0^+$ level [4] at 2.24 MeV, the mirrors of these two states are expected near 2 MeV in $^{12}$O. For these states not to exist in $^{12}$O would require a tremendous level of isospin violation—an amount never before encountered in nuclear physics.

Indeed, in 1985, a pion double-charge-exchange experiment $^{12}$C($\pi^+$,$\pi^-$) observed, with reasonable statistics, an excited state at 1.7 MeV in $^{12}$O [5]. Because the excited $0^+$ was not known at that time, this state was referred to as $2^+$. However, the angular distribution corresponding to that range of excitation [Fig. 7(b) of Ref. 5] appears to contain contributions from both a $0^+$ and a non-$0^+$ state. So, the peak in Ref. [5] probably contains both $0^+$ and $2^+$ states. In the reaction $^{16}$O($\alpha$,$^8$He)$^{12}$O, an excited state was suggested at 1.1 MeV [6].

Recently, in a very difficult experiment Suzuki *et al.* [7] investigated the $^{14}$O($p$,$t$)$^{12}$O reaction by using a secondary beam of $^{14}$O to bombard a thick solid hydrogen target. They observed two peaks—at excitation energies of 0.0(4) and 1.8(4) MeV, with total widths (analyzed as Gaussians) of 1.2(2) and 1.6(3) MeV, respectively. The resolution width was determined to be 1.0(5) MeV from the measured width of the ground state (gs) peak in the reaction $^{16}$O($p$,$t$)$^{14}$O.

Angular distributions of the two peaks appear to be virtually identical in shape, and the absolute cross sections are approximately equal (excited peak slightly weaker). The lower peak is undoubtedly the $0^+$ gs, which should be reached via angular momentum transfer $L = 0$. The authors could not choose between $L = 0$ and $L = 2$ for the excited peak. As pointed out earlier, from knowledge of $^{12}$Be, a $2^+$ and an excited $0^+$ state must exist in a reasonably narrow region of $^{12}$O. In $^{12}$Be, these states are at 2.11 and 2.24 MeV, respectively. Thus, the first two excited states of $^{12}$O should be $0^+$ and $2^+$, with the order unknown. The interesting physics is contained in the energies, widths, and (relative) cross sections of these two states. The authors did not consider the possibility that the 1.8-MeV peak contains two states. They refer throughout to “an excited state.” If two states indeed exist, treating the peak as a single state does not yield the energy or width of either.

The authors did not compare their results to those of $^{14}$C($p$,$t$). By isospin symmetry, the $^{14}$O($p$,$t$) reaction should have certain features in common with the reaction $^{14}$C($p$,$t$) [8] to the $T = 2$ states of $^{12}$C. It is customary to refer to the $^{12}$Be states as parents, to the $T = 2$ states of $^{12}$ C as double analogs, and to the $^{12}$O states as mirrors. For clarity, we use that language here. In particular, the $0_2^+/2^+$ cross-section ratio should be about equal in the two reactions leading to the double analogs and the mirrors. A subsequent analysis [9] of the latter reaction, by fitting the excited peak angular distribution with a sum of $L = 0$ and $L = 2$ components, concluded that both $0_2^+$ and $2^+$ double-analog states were being populated, with similar cross sections. We would thus expect that both states are being made in the $^{14}$O($p$,$t$) reaction.

In Ref. [7] the authors extracted intrinsic widths by subtracting, in quadrature, the resolution width from the total width. Of course, that procedure is appropriate only if the natural line shape of an unbound state were to be a Gaussian. However, it should be a Briet-Wigner shape. (For a single state, the error introduced by this incorrect treatment depends on the ratio of total width to resolution width. For example, if this ratio is 1.1, the extracted natural width is about 2.4 times the true value, while a ratio of 1.5 leads to an extracted value of about 1.4 times the true value.) Given the near equality of 1.0(5) MeV for the resolution width and 1.2(2) MeV for the total width of the gs peak, it is likely that the gs width is small. This would be consistent with a limit of $\Gamma < 100$ keV from $^{12}$C($\pi^+$,$\pi^-$) [10], and with several theoretical predictions of about 60 keV [11–13]. For the excited-state peak, convoluting a Gaussian and Breit-Wigner shape could produce an intrinsic width very different from the one obtained [7] assuming a Gaussian natural shape. However, as mentioned earlier, if two states are present, the observed width is not the width of either one. Even if one state is narrow, the *peak* corresponding to each state would be at least about 1 MeV wide from the resolution width.

The energy of the excited $0^+$ state provides an important test of different wave functions for the $T = 2$ $0^+$ states in $A = 12$. We have previously predicted [9] the energy of the excited $0^+$ state of $^{12}$O to be 1.95 MeV. This prediction was based on calculation of its Coulomb energy using a set of $0^+$ wave functions derived [14] from a variety of experimental considerations, but primarily $^{10}$Be($t,p$) [1] and the Coulomb energy of the $^{12}$O(gs) [14]. For the two $0^+$ states, these wave functions are orthogonal linear combinations of a pure $p$-shell $^{12}$Be(gs) and a $p$-shell $^{10}$Be(gs) coupled to two

TABLE I. Wave-function intensities for first two $0^+$ levels of $^{12}$O.

| Label | Reference | State | $s^2$ | $d^2$ | $p$ shell |
|---|---|---|---|---|---|
| FS | 9, 12, 14, 16 | gs | 0.53 | 0.15 | 0.32 |
| | | $0_2^+$ | 0.25 | 0.07 | 0.68 |
| B | 13, 17, 18 | gs | 0.33 | 0.29 | 0.38 |
| | | $0_2^+$ | 0.67 | 0.10 | 0.23 |

TABLE II. Calculated energies and widths (both in MeV) of the excited $0^+$ level in $^{12}$O.

| Label | $E_x$ | $\Gamma$[a] |
|---|---|---|
| FS | 1.95 | 0.85(15) |
| B | 1.19 | 2.28(40) |
| Expt. | 1.8(4)? | <0.8? |

[a] Computed for a state at 1.8 MeV.

$sd$-shell neutrons. In most models the two $sd$-shell neutrons are restricted to the $1d_{5/2}$ and $2s_{1/2}$ orbitals, referred to here as $d$ and $s$, respectively. In our model the $s^2/d^2$ ratio is taken to be the same in the two lowest $0^+$ states [where by $s^2/d^2$ ratio we mean the ratio of $(2s_{1/2})^2$ intensity to that for $(1d_{5/2})^2$ in the $sd$-shell part of the two-neutron wave function]. Wave-function intensities are listed in Table I (after correcting (see Refs. [16,17]) for an obvious typo in Ref. [9]). For comparison, we also list another set of wave functions that have been frequently used [13,17,18]. Predictions of the energy and width—the latter newly calculated here—of the excited $0^+$ state of $^{12}$O are given in Table II.

The expected energy of the excited $0^+$ state in $^{12}$O depends sensitively on the amount of $s^2$ in its wave function. One set (FS) of $0^+$ wave functions, that agrees with a wide range of experimental information, gives a $0_2^+$ energy of 1.95 MeV [9,16] Another set [19] has even more $s^2$ in the gs (and hence less in the excited state) than we do. A further set (B) has most of the $s^2$ configuration in the excited $0^+$ state and would predict [9,16,17] a $0_2^+$ energy of 1.19 MeV. We have calculated for both sets the $0_2^+$ width to be expected if its energy is 1.8 MeV, using the expression $\Gamma = S\Gamma_{\rm sp}$, where $S$ is the spectroscopic factor for $\ell = 0$ decay to $^{11}$N(gs) and $\Gamma_{\rm sp}$ is the single-particle width for that decay. (Decay to the $1/2^-$ first-excited state via $\ell = 1$ makes a negligible contribution to the width.) Here, $S$ is twice the $s^2$ intensity in the $0_2^+$ state. Obtaining $\Gamma_{\rm sp}$ has two difficulties: (i) The state is near the $^{11}{\rm N} + p$ barrier top, and (ii) the calculation must include integration over the natural width of $^{11}$N(gs) in a manner previously described [12,15]. Because of these two difficulties, the theoretical $\Gamma_{\rm sp}$ has a large uncertainty. The single-particle width can be as small as 1.4 MeV or as large as 2.0 MeV. We have chosen to use 1.7(3) MeV for $\Gamma_{\rm sp}$. The FS wave functions have $S = 0.50$, while for B $S$ is 1.33. Thus, we would predict $\Gamma = 0.85(15)$ MeV for the $0_2^+$ level, while B would give about 2.3 MeV. The B width of 2.3 MeV is clearly incompatible with the data of Ref. [7] if any of the peak observed in Ref. [7] is from the $0_2^+$. However, the data are consistent with our width. A more precise value of the measured width should allow a test of other models. These predicted widths are both for a state assumed to be at 1.8 MeV. Recall that wave function set B puts the $0_2^+$ state at 1.19 MeV, while FS would give 1.95 MeV. For any $0_2^+$ energy in $^{12}$O, set B will predict a width that is 2.7 times the width predicted with set FS. Furthermore, this ratio of the two calculated widths is independent of the value of $\Gamma_{\rm sp}$. For the $^{14}$C$(p,t)$ reaction, Barker has suggested [18] that the observed excited $T = 2$ peak is all $2^+$, because "the large width given by B would make the $0_2^+$ level indistinguishable from the background." And the width in $^{12}$O will be larger than in $^{12}$C.

Experiments of this type are extremely difficult and may seldom (or never) be repeated. However, repeating the $^{14}$O$(p,t)$ reaction with better statistics (and perhaps better resolution) should be able to determine whether both $0_2^+$ and $2^+$ states are being populated and, if so, whether the $0_2^+$ width is about 0.85 MeV or closer to 2.3 MeV.

To summarize, we have presented predictions for the energy and width of the excited $0^+$ state of $^{12}$O. Width calculations are new here. We have compared the results with recent measurements of Ref. [7]. We have pointed out what we perceive as inadequacies in the treatment of Ref. [7], and we emphasize the need for a better measurement of the width.

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