^{12}O ground-state decay by ^{2}He emission

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An upper limit of 5 keV on the width of the ^{12}O ground state due to ^{2}He emission is calculated using *R*-matrix formulas. This limit is much less than a recently published estimate.

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Experimental values for the total width of the ^{12}O ground state are 400 ± 250 keV [1] and 578 ± 205 keV [2]. The decay to ^{10}C + two protons can occur by one-proton sequential decay through the intermediate nucleus ^{11}N, or by diproton (^{2}He) emission. An experimental upper limit on the ^{2}He branching ratio is 7% [2], suggesting that one-proton decay dominates. A calculated upper limit on the width due to one-proton decay is, however, only 100 keV [3]. Sherr and Fortune [4] have recently estimated the width due to ^{2}He decay as about 340 keV, which would account for much of the experimental values for the total width, but is in conflict with the experimental branching ratio. Here we use *R*-matrix formulas to calculate the width due to ^{2}He emission.

Sherr and Fortune's estimate of 340 keV is based on the two protons forming a ^{2}He cluster with zero relative energy, so that the available ^{12}O decay energy is 1.78 MeV, and the spectroscopic factor $\mathcal{S}$ is unity. As pointed out by Kryger *et al.* [2], the effective decay energy should be much less than 1.78 MeV, because of the interaction between the protons (including the Coulomb interaction) and the available phase space. Also $\mathcal{S}$ could be less than one. Kryger *et al.* calculated the width due to ^{2}He decay to be 16 keV, which is consistent with the upper limit on the ^{2}He branching ratio [2] taken in conjunction with the experimental values [1,2] of the total width, but is inconsistent with this branching ratio if the calculated upper limit [3] on sequential decay through ^{11}N is correct.

Kryger *et al.* [2] give the formulas they use for calculating the ^{12}O width due to ^{2}He decay. As discussed in Ref. [3], the *R*-matrix formulas of Kryger *et al.* omit level-shift terms. Also the formula that they use for the density-of-states function, which comes from final-state-interaction theory, uses the Watson-Migdal approximation, and in addition their normalization of the density-of-states function is not the usual one.

To calculate the contribution to the width of the ^{12}O ground state due to ^{2}He decay, we use *R*-matrix formulas similar to Eqs. (10) and (11) of Ref. [3], to obtain

$$\Gamma^0(Q_{2p})=\frac{2\,\gamma_1^2\int_0^{Q_{2p}}P_{10}(Q_{2p}-U)\,\rho(U)\,\mathrm{d}U}{1+\gamma_1^2\int_0^{\infty}[\mathrm{d}S_{10}(E-U)/\mathrm{d}E]_{E=Q_{2p}}\,\rho(U)\,\mathrm{d}U}, \tag{1}$$

where $Q_{2p}=1.78$ MeV. The density-of-states function $\rho(U)$ may be used in a form similar to Eq. (2) of Ref. [3], but it is more convenient to express ρ in terms of the $p+p$ *s*-wave phase shift δ, which, in the same approximation, may be written

$$\delta(U)=\arctan\left(\frac{\frac{1}{2}\Gamma_2(U)}{Q_{1p}+\Delta_2(U)-U}\right)-\phi_{20}(U). \tag{2}$$

Here $\Gamma_2(U)$ and $\Delta_2(U)$ are given in terms of the $p+p$ *s*-wave penetration factor P_{20} and shift factor S_{20} by Eqs. (6) and (9) of Ref. [3], and $-\phi_{20}(U)$ is the hard-sphere phase shift. Thus

$$\rho(U)=c'\frac{\sin^2[\delta(U)+\phi_{20}(U)]}{P_{20}(U)}, \tag{3}$$

where the constant c' is chosen to make

$$\int_0^\infty \rho(U)\,\mathrm{d}U=1, \tag{4}$$

as in Eq. (3) of Ref. [3]. Exactly the same form (3) was obtained for ρ in the final-state-interaction theory by Hamburger and Cameron [5]. The Watson-Migdal approximation used by Kryger *et al.* [2] is obtained from Eq. (3) by omitting the ϕ_{20} term and using P_{20} calculated for zero channel radius. Also Kryger *et al.* normalized ρ to 1/3, instead of 1 as in Eq. (4), so that their estimate of the width is only 1/3 of what it would otherwise be, but this reduction does not seem to be justified.

The Coulomb functions *P*, *S*, and ϕ may be calculated as functions of energy for given values of the channel radii a_1 for $^{12}\mathrm{O}\to{}^{10}\mathrm{C}+{}^{2}\mathrm{He}$ and a_2 for $^{2}\mathrm{He}\to p+p$. We use the conventional formula $a=1.45$ fm $(A_1^{1/3}+A_2^{1/3})$, giving $a_1=4.95$ fm and $a_2=2.90$ fm. Experimental values of the phase shift δ may be used, but it is more convenient to use an analytical expression. The usual effective-range approximation is accurate only for low $p+p$ c.m. energies $U\lesssim10$ MeV. We use an effective-range formula for a potential with a hard core, developed for $\alpha+\alpha$ scattering [6] and also applied to low-energy $p+p$ scattering [7]. Kermode [6] gives his formula in the form

$$k\left(\frac{G'+F'\cot\delta}{G+F\cot\delta}\right)_{r=c}=-A+B\,k^2, \tag{5}$$

where k is the wave number, c is the hard-core radius, F and G are the usual regular and irregular Coulomb functions, the prime denotes differentiation with respect to kr, and A and B are expansion coefficients replacing the normal scattering length and effective range. The left-hand side of Eq. (5) may alternatively be expressed in terms of the Coulomb functions P, S, and ϕ normally used in R-matrix theory, but here evaluated at $r=c$:

$$\frac{1}{c}[P\cot(\delta+\phi)+S]=-A+B\,k^2. \tag{6}$$

This allows a representation of the $p+p$ s-wave phase shift that is sufficiently accurate for $U\lesssim 100$ MeV. (An effective-range expression valid to still higher energies can be obtained if the functions P, S, and ϕ are calculated for a potential including the one-pion-exchange potential as well as the Coulomb potential.) The parameter values used in Eq. (6) are $c=0.25$ fm, $A=-0.0045$ fm^{-1}, and $B=1.073$ fm. Then $\rho(U)$ is calculated from Eqs. (3) and (4) using $\delta(U)$ given by Eq. (6).

In this way we obtain $\Gamma^0(Q_{2p})$ as a function of γ_1^2, the reduced width for ^{12}O$\rightarrow$^{10}C+^{2}He breakup, as shown in Fig. 1. The small values of $\Gamma^0(Q_{2p})$ are due to the small value of the effective penetration factor $\int_0^{Q_{2p}} P_{10}(Q_{2p}-U)\,\rho(U)\,\mathrm{d}U$ that occurs in Eq. (1), which is about 1/40 of $P_{10}(Q_{2p})$.

An upper limit on γ_1^2 may be obtained by using the formulas (14)–(16) of Ref. [3]. We use parameter values for a real, central WS potential ($r_0=1.17$ fm, $a_0=0.72$ fm, $r_C=1.30$ fm) taken from fits to deuteron scattering data [8]. For a 2s state of ^{2}He, we obtain $\theta_{sp}^2=0.62$, leading to $\gamma_1^2=0.63\ \mathcal{S}$ MeV (for a 1s state of ^{2}He, $\theta_{sp}^2=0.27$). Kryger *et al.* [2] take a reasonable value of $\mathcal{S}$ as 0.6. We take $\mathcal{S}\leqslant 1$, giving an upper limit $\gamma_1^2\lesssim 0.63$ MeV. From Fig. 1, this corresponds to $\Gamma^0(Q_{2p})\lesssim 5$ keV, an upper limit on the ^{2}He contribution to the ^{12}O width that is much less than the estimated value of Sherr and Fortune [4] and the experimental values [1,2] of the total width, and that is consistent with the experimental ^{2}He branching ratio [2] and the calculated upper limit on sequential decay through ^{11}N [3].

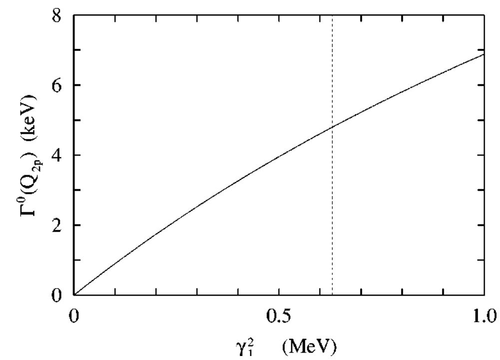

FIG. 1. Calculated width $\Gamma^0(Q_{2p})$ of the ^{12}O ground state due to decay to ^{10}C+^{2}He, as a function of the reduced width γ_1^2 for this channel. The vertical line shows an estimated upper limit on γ_1^2.

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