PHYSICAL REVIEW C **92**, 044328 (2015)

Addendum to "Determination of γ-ray widths in ^{15}N using nuclear resonance fluorescence"

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(Received 18 August 2015; published 27 October 2015)

The determination of absolute widths of two observed levels above the proton threshold in ^{15}N has been improved by a combined analysis of our recent ^{15}N$(\gamma,\gamma')^{15}$N* photon scattering data, resonance strengths $\omega\gamma$ of the ^{14}C$(p,\gamma)^{15}$N reaction, and γ-ray branchings $b_{\gamma,i}$ in ^{15}N. The revised data are compared to the adopted values, and some inconsistencies in the adopted values are illustrated.

DOI: 10.1103/PhysRevC.92.044328 PACS number(s): 21.10.Tg, 27.20.+n

In a recent study [1] photon scattering was used to determine level properties in ^{15}N. A clear signal was observed from two levels above the adopted proton threshold in ^{15}N at $S_p = 10\,207.4$ keV. In the following all adopted values are taken from the Evaluated Nuclear Structure Data File online database [2] which is in general based on the Triangular Universities Nuclear Laboratory update [3] of the latest compilation by Ajzenberg-Selove in 1991 [4]. Separation energies are in agreement with the latest atomic mass evaluation [5].

The present analysis focuses on two $J = 3/2$ levels at $E_x = 10\,702$ and $10\,804$ keV in ^{15}N. The partial radiation width to the ground state $\Gamma_{\gamma,0}$, the total radiation width Γ_γ, the proton width Γ_p, and the total width Γ were derived from the experimental photon scattering data in our recent paper [1] in combination with resonance strengths $\omega\gamma$ in the ^{14}C$(p,\gamma)^{15}$N reaction and γ-ray branchings $b_{\gamma,i}$ in ^{15}N. In our previous analysis the small proton partial width of these states was not properly taken into account. The improved reanalysis of the present study leads to some interesting discrepancies with the adopted values that have been considered as certain over the past decades.

This study is organized as follows. Because the determination of absolute widths in ^{15}N is based on the combination of our recent photon scattering data [1] and data from the literature, in the first part the required literature data are reevaluated. In particular, these required data are the resonance strengths $\omega\gamma$ of the ^{14}C$(p,\gamma)^{15}$N reaction and the γ-ray branchings $b_{\gamma,i}$ in ^{15}N. The second and main part of the paper describes the determination of absolute widths $\Gamma_{\gamma,0}$, Γ_γ, Γ_p, and Γ from the combination of our new photon scattering data and the reevaluated literature data. Special attention is paid to the error propagation. In the third and last part of this study the new results are compared to other data from the literature, and surprisingly discrepancies to the adopted values are found in some cases. These discrepancies are discussed in further detail. The new results are summarized in Table I.

Let us now start with the reevaluation of the literature data for the resonance strengths $\omega\gamma$ and the γ-ray branchings $b_{\gamma,i}$.

Resonance strengths $\omega\gamma$. The resonance strengths $\omega\gamma = \omega\Gamma_p\Gamma_\gamma/\Gamma$ of the ^{14}C$(p,\gamma)^{15}$N reaction were adopted in Refs. [2–4] from Görres *et al.* [6]. Earlier measurements for the two levels under study were done by Hebbard and Dunbar [7], Siefken *et al.* [8], and Beukens [9]; only a minor part of the Ph.D. thesis [9] has been published [10]. As there is no good agreement between the data of Refs. [7–9], and the unpublished data of Ref. [9] have been normalized to one particular resonance strength of Ref. [8], we confirm to adopt the latest resonance strengths $\omega\gamma$ by Görres *et al.* [6]: $\omega\gamma(10\,702) = 840 \pm 130$ meV and $\omega\gamma(10\,804) = 270 \pm 40$ meV. Note that $\omega = 2$ for the two $J = 3/2$ resonances.

Ground state resonance strengths $\omega\gamma_0$. The partial resonance strengths $\omega\gamma_0 = \omega\Gamma_p\Gamma_{\gamma,0}/\Gamma$ of ^{14}C$(p,\gamma)^{15}$N are also taken from Ref. [6]. The experimental quantities in Ref. [6] are the γ-ray yields for the transitions to the ith excited state in ^{15}N. Therefore, it is consistent to use here the given resonance strengths $\omega\gamma$ and the given ground state γ-ray branchings $b_{\gamma,0}$ of the same experimental work. This leads to $\omega\gamma_0(10\,702) = 352.8 \pm 64.1$ meV from $b_{\gamma,0} = 0.42 \pm 0.04$ for the 10 702-keV state and $\omega\gamma_0 = 118.8 \pm 20.6$ meV from $b_{\gamma,0} = 0.44 \pm 0.04$ for the 10 804-keV state. The uncertainties of the values come from the uncertainty of the resonance strengths and the uncertainty of the branching ratio from the same experiment. This overestimates the uncertainty of the actually measured $\omega\gamma_0$, because in the original work the branching ratios were derived from the measured partial strengths. But without further information on the error estimate for partial resonance strengths in Ref. [6] this choice seems to be a careful compromise. The ratio $\Gamma_p\Gamma_{\gamma,0}/\Gamma$ is a factor of $\omega = 2$ smaller than the above quoted numbers for $\omega\gamma_0$.

Ground state γ-ray branches $b_{\gamma,0}$. γ-ray branchings were adopted in Refs. [2–4] from the unpublished Ref. [9] data because of their very small uncertainties. However, the Ref. [9] data and the later Ref. [6] data were both derived from ^{14}C$(p,\gamma)^{15}$N experiments, and the later Ref. [6] data have smaller uncertainties for the resonance strengths, but larger uncertainties for the branching ratios; this leaves some doubt about the very small uncertainties of Ref. [9]. A weighted average of the three experiments with high-resolution detectors [6,8,9] is dominated by the tiny uncertainties of Ref. [9] and leads to $b_{\gamma,0}(10\,702) = (52.12 \pm 0.62_{\rm int} \pm 1.14_{\rm ext})\%$ and $b_{\gamma,0}(10\,804) = (50.82 \pm 0.37_{\rm int} \pm 1.18_{\rm ext})\%$. The unweighted average gives significantly lower values of $b_{\gamma,0}(10\,702) = 48.87\%$ and $b_{\gamma,0}(10\,804) = 47.50\%$. We finally adopt the

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TABLE I. Absolute widths and further properties of the two $J = 3/2$ levels in ^{15}N at $E_x = 10\,702$ and 10 804 keV. Note that all calculated results are given with a precision of at least four digits to avoid rounding errors; the number of significant digits is smaller (typically two) and can be seen from the given uncertainties.

Refs. [2–4]		Ref. [1]	Ref. [6]		This work[a]					
E_x (keV)	J_x	$A = \Gamma^2_{\gamma,0}/\Gamma$ (meV)	$\omega\gamma$ (meV)	$\omega\gamma_0$ (meV)	R_0	$b_{\gamma 0}$ (%)	$\Gamma_{\gamma 0}$ (meV)	Γ_γ (meV)	Γ_p (meV)	Γ (meV)
10 702	3/2	215.8 ± 17.2	840 ± 130	352.8 ± 64.1	1.223 ± 0.243	50.5 ± 1.7	603.7 ± 48.9	1195.4 ± 101.6	493.6 ± 75.3	1689.0 ± 126.4
10 804	3/2	103.8 ± 11.4	270 ± 40	118.8 ± 20.6	1.747 ± 0.360	49.2 ± 1.7	270.4 ± 26.5	549.6 ± 56.0	154.8 ± 23.3	704.4 ± 60.6

[a]Combination of various data; for further details see text.

average of the above numbers with an estimated 1σ uncertainty, which includes the higher weighted average and the lower unweighted average: $b_{\gamma,0}(10\,702) = (50.5 \pm 1.7)\%$ and $b_{\gamma,0}(10\,804) = (49.2 \pm 1.7)\%$. Note if we use the adopted γ-ray branchings throughout the analysis, the final results are reduced by about 3–8%, but still remain within the given error bars.

Now the required data from the literature are fixed, and we can combine the above literature data with our new data for the integrated photon scattering cross sections I_σ from the ^{15}N$(\gamma,\gamma')^{15}$N* experiment. This allows us to fix all widths. The integrated cross section for the transition $0 \to J_x, E_x \to 0$ in ^{15}N$(\gamma,\gamma')^{15}$N* photon scattering is given by

$$I_\sigma(0 \to J_x, E_x \to 0) = \frac{2J_x + 1}{2J_0 + 1}\left(\frac{\pi\hbar c}{E_x}\right)^2 \frac{\Gamma_{\gamma,0}\Gamma_{\gamma,0}}{\Gamma}, \quad (1)$$

with the ground state γ-ray branching $b_{\gamma,0} = \Gamma_{\gamma,0}/\Gamma_\gamma$ and the total width $\Gamma = \Gamma_p + \Gamma_\gamma$ for the states under consideration above the proton threshold and below the neutron threshold. Therefore, the value of $\Gamma^2_{\gamma,0}/\Gamma$ is fixed from our photon scattering data [1].

The ratio $R_0 = \Gamma_{\gamma,0}/\Gamma_p$. The integrated photon scattering cross section I_σ for the $0 \to J_x, E_x \to 0$ transition is proportional to the quantity $\Gamma^2_{\gamma,0}/\Gamma$ (hereafter A), and the ground state resonance strength $\omega\gamma_0$ is proportional to $\Gamma_{\gamma,0}\Gamma_p/\Gamma$ (hereafter B). Thus, the ratio $R_0 = \Gamma_{\gamma,0}/\Gamma_p = A/B$ can directly be derived from the ratio of the above two quantities I_σ from Ref. [1] and $\omega\gamma_0$ from Ref. [6]. The results $R_0(10\,702) = 1.223 \pm 0.243$ and $R_0(10\,804) = 1.747 \pm 0.360$ clearly show that the proton width Γ_p is smaller than the radiation width Γ_γ for both levels under study. This result is independent of the spin assignment J of the levels.

The partial radiation width to the ground state $\Gamma_{\gamma,0}$. The quantity $\Gamma^2_{\gamma,0}/\Gamma = \Gamma^2_{\gamma,0}/(\Gamma_p + \Gamma_\gamma)$ from the integrated photon scattering cross section I_σ can be combined with the ground state γ-ray branching $b_{\gamma,0} = \Gamma_{\gamma,0}/\Gamma_\gamma$ and the above ratio $R_0 = \Gamma_{\gamma,0}/\Gamma_p$. This leads to

$$\Gamma_{\gamma,0} = \left(\frac{\Gamma^2_{\gamma,0}}{\Gamma}\right)\left(\frac{R_0 + b_{\gamma,0}}{R_0 b_{\gamma,0}}\right) = A\left(\frac{1}{b_{\gamma,0}} + \frac{1}{R_0}\right), \quad (2)$$

where A is taken from I_σ from the photon scattering data [1], and the numbers R_0 and $b_{\gamma,0}$ in parentheses are determined above. To avoid double counting the uncertainties of the widths, the shown equations are transformed to be dependent only on the independent experimental values with known uncertainties and not on the correlating derived values; i.e., Eq. (2) becomes

$$\Gamma_{\gamma,0} = A\frac{1}{b_{\gamma,0}} + B, \quad (3)$$

where A is taken from I_σ from the photon scattering data [1], B is from $\omega\gamma_0$ from Ref. [6], and $b_{\gamma,0}$ are determined above. This leads to $\Gamma_{\gamma,0}(10\,702) = 603.7 \pm 48.9$ meV and $\Gamma_{\gamma,0}(10\,804) = 270.4 \pm 26.5$ meV.

The total radiation width Γ_γ. The total radiation width Γ_γ is directly related to the ground state radiation width $\Gamma_{\gamma,0}$ by $b_{\gamma,0} = \Gamma_{\gamma,0}/\Gamma_\gamma$. From the above numbers we find $\Gamma_\gamma(10\,702) = 1195.4 \pm 101.6$ meV and $\Gamma_\gamma(10\,804) = 549.6 \pm 56.0$ meV.

The proton width Γ_p. The proton width Γ_p is directly related to the ground state radiation width $\Gamma_{\gamma,0}$ by $R_0 = \Gamma_{\gamma,0}/\Gamma_p$. From the above numbers we find $\Gamma_p(10\,702) = 493.6 \pm 75.3$ meV and $\Gamma_p(10804) = 154.8 \pm 23.3$ meV.

The total width Γ. Finally, the total width Γ can simply be calculated by the sum of the partial widths: $\Gamma = \Gamma_p + \Gamma_\gamma$. The obtained values are $\Gamma(10702) = 1689.0 \pm 126.4$ meV and $\Gamma(10\,804) = 704.4 \pm 60.6$ meV. The relative uncertainties of the total widths Γ ($\approx$7% and 9%) remain smaller than for Γ_p because of $\Gamma_\gamma > \Gamma_p$ and the smaller uncertainties of Γ_γ. The given uncertainties were calculated using standard error propagation. However, this may slightly underestimate the real uncertainties of Γ because Γ_γ and Γ_p are not statistically independent. A more realistic estimate is about 10 %, i.e., similar to the uncertainty of Γ_γ.

Next, we compare the absolute widths from the present study to the adopted values [2–4]. In addition, we try to trace back to the origins of the adopted values.

The 10 804 keV state. In the "Energy Levels of ^{15}N" (Table 15.4 of Ref. [4]) one finds $J^\pi = 3/2^+$ and $\Gamma < 1$ eV. In Table 15.11, "Resonances in ^{14}C$+p$" of Ref. [4], one finds $J^\pi = 3/2^{(+)}$, and in addition $\Gamma_p = 220 \pm 100$ meV, and $\Gamma_\gamma = 270 \pm 140$ meV with a footnote $\omega\gamma = 270 \pm 40$ meV [6]. This is a minor inconsistency in Ref. [4] because the combination of $\omega\gamma = 270$ meV from Ref. [6] and the adopted $\Gamma_p = 220$ meV leads to $\Gamma_\gamma = 350$ meV; the adopted lower value of $\Gamma_\gamma = 270$ meV in Ref. [4] is only obtained if the earlier resonance strength $\omega\gamma = 240$ meV from Ref. [9] is used. The values $\Gamma_p = 220 \pm 100$ meV and $\Gamma_\gamma = 270$ meV are also found in earlier versions of Ajzenberg-Selove's work [11–13], and in Ref. [13], Ref. [9] is explicitly given as the reference. The adopted $\Gamma_p = 220 \pm 100$ meV is derived in Ref. [9] from the measured resonance strength $\omega\gamma$ and the ratio $\Gamma_\gamma/\Gamma = 0.55^{+0.25}_{-0.15}$ from a detailed study of electromagnetic transitions in $A = 15$ nuclei by Warburton *et al.* [14]. Earlier compilations [15,16] give only the resonance strength from earlier work, but no partial widths Γ_γ or Γ_p.

The proton width $\Gamma_p = 154.8 \pm 23.3$ meV of this study compares well to the adopted value of 220 ± 100 meV but has a significantly reduced uncertainty. This allows one to determine the total width $\Gamma = 704.4 \pm 60.6$ meV, which is consistent with the previous upper limit of 1 eV. The radiation width Γ_γ of this study is about a factor of 2 higher than the adopted value. The present results are also consistent with the result of Warburton *et al.* [14]: The present study finds $\Gamma_\gamma/\Gamma = 0.78$ and $\Gamma_{\gamma,0}/\Gamma = 0.38$, in agreement with the respective values of $0.55^{+0.25}_{-0.15}$ and $0.30^{+0.15}_{-0.09}$ of Ref. [14].

The 10 804-keV state has not been seen in proton transfer in the ^{14}C$(d,n){}^{15}$N reaction [17] or in ^{14}C$(p,p){}^{14}$C elastic scattering [7]. This is again consistent with a small proton width Γ_p.

For completeness it has to be noted that, instead of the adopted $J^\pi = 3/2^+$ in Ref. [4], $J^\pi = 3/2^-$ is reported earlier in the "Energy Levels" table of Ref. [16] which is based on γ-ray angular distribution measurements in Refs. [18,19]. The experimental data of Ref. [19] clearly show that $J = 3/2$ and prefer $J^\pi = 3/2^-$ but cannot exclude $J^\pi = 3/2^+$. The value $J^\pi = 3/2^-$ from Ref. [16] changes to $3/2^{(-)}$ in Ref. [15], $3/2^{(+)}$ in Ref. [13] (probably again based on Ref. [9]), and $3/2^+$ in Refs. [4,11,12]. However, $J^\pi = 3/2^{(+)}$ persists in the "Resonances in ^{14}C$+p$" tables up to Ref. [4]. The analysis of the angular distribution of the ^{14}N$(d,p){}^{15}$N reaction in Ref. [20] shows a clear signature of the $L = 1$ transfer; i.e., it indicates negative parity of this state. Because the spin $J = 3/2$ is well defined from γ-ray angular distribution and angular correlation measurements by Bartholomew *et al.* [19] and Ref. [8], $J^\pi = 3/2^-$ should be adopted instead of $J^\pi = 3/2^+$. Surprisingly, an electron scattering experiment reports conflicting results with $J^\pi = 3/2^+$ and $\Gamma^{\mathrm{M2}}_{\gamma,0} = 18 \pm 8$ meV (see Table 15.17 in Ref. [12], based on the experimental data of Ref. [21]).

The 10 702-keV state. The situation for the 10 702-keV state is even worse than for the 10 804-keV state. Reference [4] gives $J^\pi = 3/2^-$ and $\Gamma = 0.2$ keV in the "Energy Levels of ^{15}N" table; the same numbers are found in Refs. [11–13]. References [15,16] state $J^\pi = 3/2^+$, based on angular correlation measurements in Refs. [18,19] and ^{14}C$(p,p){}^{14}$C elastic scattering data from Ref. [7]. Similar to the 10 804-keV state, the 1976 change of the adopted values is based on Ref. [9], and the "Resonances in ^{14}C$+p$" table provides in addition $\Gamma = 0.2$ keV and $\Gamma_\gamma = 370 \pm 70$ meV; the latter value is taken from $\omega\gamma = 740 \pm 140$ meV in Ref. [9] and $\Gamma_\gamma \ll \Gamma_p \approx \Gamma$ and is kept until Ref. [4] (again, a footnote in Ref. [4] states $\omega\gamma = 840 \pm 130$ meV from Ref. [6], but this value is not used in Ref. [4] for further calculations).

The huge adopted proton width of $\Gamma_p = 0.2$ keV is a factor of about 400 above the result of the present study ($\Gamma_p = 493.6 \pm 75.3$ meV). A state with such a huge proton width would not be visible in photon scattering because such a state decays preferentially by proton emission because of $\Gamma_p \gg \Gamma_{\gamma,0}$. Thus, $\Gamma_p = 0.2$ keV for the 10 702-keV state is clearly ruled out by the present study.

A claim for the huge proton width of $\Gamma_p = 0.2$ keV was made from the ^{14}C$(p,p){}^{14}$C elastic scattering data of Ref. [7]. The proton width was estimated from the deviation of the elastic scattering cross section from Rutherford scattering, and these data were also used to pin down the positive parity of the 10 702-keV state, leading to the adopted $J^\pi = 3/2^+$ in Refs. [15,16]. As estimated in Ref. [7], the large proton width corresponds to about 20 % of the Wigner limit. Such a strong state should be clearly visible in the ^{14}C$(d,n){}^{15}$N transfer experiment [17], but also the 10 702-keV state was not detected in Ref. [17]. Therefore, the claim for the huge proton width $\Gamma_p = 0.2$ keV and the positive parity of the 10 702-keV state from Ref. [7] seems to be not well founded. Nevertheless, we finally recommend to adopt $J^\pi = 3/2^+$ because the ^{14}N$(d,p){}^{15}$N data of Ref. [20] show a clear signature of $L = 2$ transfer with a small contribution of $L = 0$ transfer, i.e., clear signature of a positive parity of the 10 702-keV state. Further confirmation of the positive parity of the 10 702-keV state is taken from the analysis of thermal neutron capture of ^{14}N by Jurney *et al.* [22].

The condition $\Gamma_p \gg \Gamma_\gamma$ does not hold for the newly derived Γ_p from this study. Consequently, earlier adopted values for Γ_γ are also inconsistent because they were derived from the resonance strength using $\omega\gamma \approx \omega\Gamma_\gamma$, which is not a valid approximation in the present case.

In conclusion, the present study has determined absolute widths $\Gamma_{\gamma,0}$, Γ_γ, Γ_p, and Γ for the two $J = 3/2$ states in ^{15}N at $E_x = 10\,702$ and 10 804 keV from a combination of integrated photon scattering cross sections I_σ from ^{15}N$(\gamma,\gamma'){}^{15}$N* and from resonance strengths $\omega\gamma$ and γ-ray branchings $b_{\gamma,i}$ from ${}^{14}C(p,\gamma){}^{15}$N. For the 10 804-keV state the results are roughly consistent with the adopted values [2–4] but have significantly lower uncertainties. However, the proton width Γ_p of the 10 702-keV state is about a factor of 400 lower than the adopted value; this affects also the earlier estimates of the radiation widths of this state, which are based on the incorrect assumption $\Gamma_p \gg \Gamma_\gamma$. Furthermore, the parity assignments of both states should be changed to $J^\pi = 3/2^+$ for the 10 702-keV state and $J^\pi = 3/2^-$ for the 10 804-keV state.

This work was supported by the Helmholtz Association through the Nuclear Astrophysics Virtual Institute (NAVI, Grant No. HGF VH-VI-417) and OTKA (Grants No. K101328 and No. K108459).

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