Widths of ^{26}P(1^+) and mass of ^{26}P(g.s.)

H. T. Fortune
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
(Received 5 September 2017; published 29 November 2017)

For the 1^+ first-excited state of ^{26}P, the lifetime and the upper limit on the proton width have been combined with shell-model spectroscopic factors to place an upper limit on the proton single-particle (sp) width. With a potential model, this limit on sp width allows an upper limit on the 1^+ resonance energy of $E_r < 124$ keV. Combining with the known 1^+ excitation energy provides a limit on the proton separation energy of ^{26}P(g.s.) of $S_p > 40$ keV, considerably better than a recent result of $S_p > -135$ keV from a similar procedure that used R-matrix sp widths.

DOI: 10.1103/PhysRevC.96.054329

In ^{26}Na, the ground state (g.s.) [1] is 3^+, but a 1^+ excited state is only 82.5(5) keV away [2]. In the mirror ^{26}P, the order is the same, but the spacing is larger: 164.4(1) keV [3]. This increased spacing is as expected from the so-called Thomas-Ehrman shift, because the 3^+ g.s. has a larger s-wave component than does the first-excited state. The 1^+ excited state of ^{26}P is probably unbound, but Γ decay competes successfully with proton decay because of the low energy and large barrier for the latter. However, there is no definitive evidence as to whether the g.s. is bound. The mass evaluation [4] lists $S_p = 140(200)$ keV from systematics. Using parameters of a recent fit to energies of $2s_{1/2}$ states in lighter nuclei [5], my estimate is $S_p = 85$ keV. For comparison, for ^{27}P, that same fit produces $S_p = 879$ keV, for which the experimental value is 870(26) keV [4]. In Ref. [5], the root-mean-square deviation was about 30 keV, and that was suggested as an approximate uncertainty in the predictions.

A new paper [6] has just appeared confirming the energy and half-life of the 1^+ state—although with larger uncertainties, as listed in Table I. This new paper used the known half-life, together with the limit on the proton branching ratio [3], to deduce a limit on the proton width. Then, with an R-matrix analysis, they placed an upper limit on the resonance energy of the 1^+ state, $E_r < 300$ keV. I have repeated that procedure, but using widths computed in a potential well, and my result is considerably different. That is the subject of this paper.

Table II summarizes the known width information for the 1^+ state. The γ width is 3.80(29) [3] or 4.39(59) [6] neV, and the limit on the proton branching ratio is $\Gamma_p/\Gamma_{tot} < 0.13$ [3], resulting in a limit on the proton width of $\Gamma_p < 0.51(4)$ neV, where I have used the weighted average of the two γ widths. The proton width is related to the spectroscopic factor and a single-particle (sp) width by the relation $\Gamma_p = C^2S\,\Gamma_{sp}$. One shell-model calculation [6] has $C^2S = 0.13$ for $d_{5/2}$ and 0.23 for $d_{3/2}$; another [7] has 0.11 and 0.29, respectively. For the present purposes, I need only the sum, for which I use 0.36, which should be accurate to within about 10%. Thus, the experimental limit on the proton width translates into a limit on the sp width of $\Gamma_{sp} < 1.42(11)$ neV.

The g.s. of ^{25}Si is $5/2^+$, so that the 1^+ state of ^{26}P corresponds to $\ell = 2$. For $\ell = 2$, and as a function of energy, I have computed sp widths in a Woods-Saxon potential well having radius $R_0 = r_0 A^{1/3}$ and diffusivity a, together

TABLE I. Properties of ^{26}P(1^+).

Quantity	Previous	New
E_x (keV)	164.4(1)	164.4(3(2))
$T_{1/2}$ (ns)	120(9)	104(14)
Γ_γ	3.80(29)	4.39(59)
Ref.	[3]	[6]

TABLE II. Widths (neV) and deduced resonance energy (keV) for ^{26}P(1^+).

Quantity	Value	Ref.
Γ_γ	3.91(26)	Weighted average from [3,6]
Γ_p/Γ_{tot}	<0.13	[3]
Γ_p	<0.51(4)	[3,6]
C^2S[a]	0.36	[6]
Γ_{sp}[b]	<1.42(11)	Present
E_r	<124.1	Present

[a]Sum for $d_{3/2}$ and $d_{5/2}$.
[b]Using $\Gamma_p = C^2S\,\Gamma_{sp}$

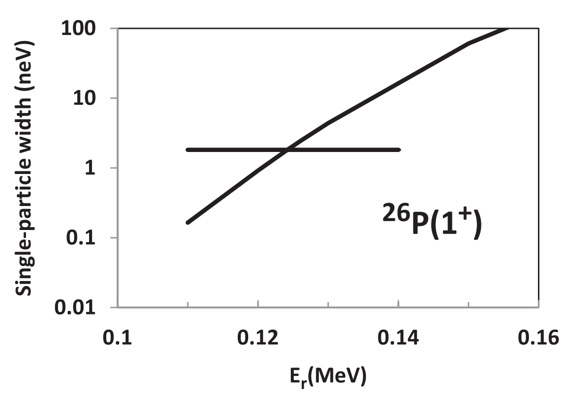

FIG. 1. Single-particle width for ^{25}Si + p, $\ell = 2$, computed in a Woods-Saxon well, is plotted vs resonance energy. The horizontal line is at the upper limit deduced from shell-model spectroscopic factors and the upper limit on the proton width for the 1^+ state.

TABLE III. Final results.

Quantity	Value (keV)	Ref.
$E_r(1^+)$	<124.1	Present
$E_x(1^+)$	164.4(1)	[3]
$S_p(3^+ \text{ g.s.}) = E_x(1^+) - E_r(1^+)$	>40	Present

with the Coulomb potential of a uniform sphere of radius $R_{0c} = r_{0c}A^{1/3}$, with r_0, a, and r_{0c} equal to 1.26, 0.60, and 1.40 fm, respectively. Results are plotted in Fig. 1 for the relevant region. It can be noted that the sp width is a rapid function of energy (as is well known, of course). The horizontal line is at the upper limit mentioned above, $\Gamma_{sp} < 1.42(11)$ neV. Thus, the limit on the resonance energy is $E_r < 124.1$ keV. The resonance energy is related to the excitation energy and the g.s. separation energy through the equation

$$S_p(3^+\text{g.s.}) = E_x(1^+) - E_r(1^+),$$

for which the result is $S_p > 40$ keV (Table III). This is a much tighter limit than the value of $S_p > -135$ keV derived in Ref. [6].

Table IV summarizes various estimates of this separation energy. An improved Kelson-Garvey (ImKG) prediction is $-119(16)$ keV [8]. Accompanying a β-decay study of ^{26}P, Thomas *et al.* used a semiempirical expression for Coulomb energies and an energy of the analog state in ^{26}Si of 13.015(4) MeV to estimate $S_p(^{26}\text{P}) = 0(90)$ keV [9]. Among these values, only the ImKG estimate is inconsistent. The present result of $S_p > 40$ keV is consistent with the value of 85(30) keV from the $2s_{1/2}$ fit mentioned above. From the present work, it would thus appear that the g.s. of ^{26}P is indeed bound.

TABLE IV. Summary of results for the separation energy of ^{26}P.

Source	S_p (keV)	Ref.
Potential-model analysis	>40	Present
R-matrix analysis	>−135	[6]
From mass evaluation	140(200) from systematics	[4]
Coulomb energy	0(90)	[9]
Improved Kelson-Garvey	−119(16)	[8]
$2s_{1/2}$ fit	85(30)[a]	[5], present

[a]Using parameters from a fit to $2s_{1/2}$ energies in lighter nuclei [5].

If S_p is 85 keV, then the 1^+ resonance energy is 79.4 keV. At this energy, the sp width is 5.5×10^{-5} neV, so the computed proton width is 2×10^{-5} neV, making its possible observation challenging.

[1] P. M. Endt and C. van der Leun, Nucl. Phys. A **214**, 1 (1973).
[2] J. P. Dufour *et al.*, AIP Conf. Proc. **164**, 344 (1987).
[3] D. Nishimura *et al.*, EPJ Web Conf. **66**, 02072 (2014).
[4] M. Wang, G. Audi, A. H. Wapstra, F. G. Kondev, M. MacCormick, X. Xu, and B. Pfeiffer, Chin. Phys. C **36**, 1603 (2012).
[5] H. T. Fortune, Phys. Rev. C **88**, 024309 (2013).
[6] D. Pérez-Loureiro *et al.*, Phys. Rev. C **96**, 014306 (2017).
[7] G. L. Wilson *et al.*, Phys. Lett. B **759**, 417 (2016).
[8] Junlong Tian, Ning Wang, Cheng Li, and Jingjing Li, Phys. Rev. C **87**, 014313 (2013).
[9] J.-C. Thomas *et al.*, Eur. Phys. J. A **21**, 419 (2004).