PHYSICAL REVIEW C **72**, 034304 (2005)

^{18}Na: Mass excess and low-lying states

H. T. Fortune
Department of Physics and Astronomy, University of Pennsylvania, Philadelphia, Pennsylvania, 19104, USA

R. Sherr
Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

(Received 8 June 2005; published 21 September 2005)

We present estimates of the mass excess of ^{18}Na and properties of some of the low-lying states, using information from the mirror nucleus ^{18}N for guidance. We offer explanations for three peaks observed in $^{18}\mathrm{Na} \rightarrow {}^{17}\mathrm{Ne} + p$ decay.

DOI: 10.1103/PhysRevC.72.034304 PACS number(s): 21.10.Dr, 21.60.−n, 27.20.+n

Our interest here is the mass excess and low-lying states of ^{18}Na. We use properties of the mirror ^{18}N [1] for guidance.

In ^{18}N the lowest four states are predominantly a $p1/2$ proton hole coupled to the ground and first-excited states of ^{19}O [1] at excitation energies of 0 and 96 keV, with $J^\pi = 5/2^+$ and $3/2^+$, respectively. These two ^{19}O states are primarily $(d5/2)^3$ in character. Even if the relevant nucleons are in d orbits, the Coulomb energy for mirror states depends slightly on excitation energy and on excitation energy of the core state to which the last nucleon is bound. In the present case, we have investigated this dependence in a simple potential model containing nuclear (Woods-Saxon), angular momentum, and Coulomb terms. If no $\ell = 0$ nucleons are involved, these calculations demonstrate that the energy splittings in the mirror ^{18}Na (a $p1/2$ neutron hole in ^{19}Na) will be approximately equal (to within 0–50 keV) of those in ^{18}N. (We consider the influence of $s1/2$ admixtures below.) The next negative-parity states in ^{18}N would involve coupling a $p1/2$ proton hole to the $1/2^+$ state at 1.47 MeV [1] in ^{19}O, whose dominant structure is $(d5/2)^2{}_0(2s1/2)$ [2]. The 0^-, 1^- doublet arising from this coupling could come quite low in ^{18}Na. For example, in ^{19}Na the $1/2^+$ state is 725 keV [3] lower than in ^{19}O. Thus, one or both of these $1/2^+$-coupled states could lie in the region of the third and fourth levels in ^{18}Na. We thus expect five or six states below 1 MeV in ^{18}Na. The relevant states are depicted schematically in Fig. 1.

Weak coupling can provide the expected energies of the $3p$-$1h$ states in ^{18}N, using the Bansal-French-Zamick [4] prescription. This formalism has allowed for an understanding of a large number of particle-hole states in nuclei near closed shells. The essence of weak coupling is the assumption that in an mp-nh state (with particles and holes in different major shells), the interactions among the mp are the same as in the mp-$0h$ state, and similarly for the n holes. The interaction between the mp and nh is taken [4] to be $mna + b\mathbf{T}_{mp} \cdot \mathbf{T}_{nh} + m_\pi n_\pi c$, where a and c are independent of m and n, $\mathbf{T}$ is isospin, and the subscript π refers to protons. In the present case, the Coulomb term does not enter, and the parameters a and b occur only in the combination $a + b/4$. This procedure (in the present case) will actually yield the centroid energies for the various doublets. Thus,

$$M(^{18}\mathrm{N}) = M(^{19}\mathrm{O}) + M(^{15}\mathrm{N}) - M(^{16}\mathrm{O}) + 3a + 3b/4,$$

where the M's are mass excesses. Because the g.s. of ^{18}N is known to have $J^\pi = 1^-$, it must belong to the $3/2^+ \mathrm{x} 1/2^-$ doublet arising from the first-excited state of ^{19}O at 96 keV. Thus, using the mass excess of ^{19}O(g.s.) [5] + 96 keV in the formula above will give the expected mass excess of the 1^-, 2^- centroid from this coupling. With known masses, we get

$$M(1^-, 2^- \text{ centroid}) = 8.267\,\mathrm{MeV} + 3(a + b/4).$$

Now, we can estimate the quantity $a + b/4$ from ^{16}N [6], because

$$M(^{16}\mathrm{N}) = M(^{17}\mathrm{O}) + M(^{15}\mathrm{N}) - M(^{16}\mathrm{O}) + a + b/4.$$

The 2^-, 3^- centroid from this coupling is at $E_x = 0.174$ MeV in ^{16}N, i.e., with a mass excess of 5.856 MeV. Thus, we get $a + b/4 = 1.826$ MeV, giving $M(1^-, 2^-$ centroid in $^{18}\mathrm{N}) = 13.744$ MeV. (We used the 2^-, 3^- states in ^{16}N to estimate $a + b/4$ because the first two states of ^{19}O involve very little $2s1/2$ occupancy.) In ^{18}N, the first-excited state at 115 keV [1] is undoubtedly 2^- from the $5/2^+ \mathrm{x} 1/2^-$ coupling. The next two states at 587 and 747 keV are suggested as (2^-) and (3^-), respectively, in the latest compilation [1]. We have a slight preference for the other ordering, but it makes very little difference in computation of the centroids. We present both possibilities in Table I. We thus see that weak coupling reproduces the absolute ^{18}N mass excess to within about 200 keV—the weak-coupling prediction is 160–260 keV above the actual value.

Now, we can use weak coupling to estimate the mass excess of ^{18}Na in two ways. The first involves the relationship

$$M(^{18}\mathrm{Na}) = M(^{19}\mathrm{Na}) + M(^{15}\mathrm{O}) - M(^{16}\mathrm{O}) + 3(a + b/4),$$

where we now use $a + b/4 = 1.732$ MeV from the 2^-, 3^- doublet in ^{16}F [6] (because now the particles are protons and the hole is a neutron). For ^{19}Na(g.s.), we use a mass excess of 12.929(12) MeV [5]. This computation provides a mass excess of 25.718 MeV for the 2^-, 3^- centroid in ^{18}Na . If the *relative* energies of the lowest four states in ^{18}Na are as in ^{18}N, the g.s. mass excess of ^{18}Na is then 25.23 MeV.

The second method usually depends on the Coulomb parameter c [4,7], but in the present instance is parameter

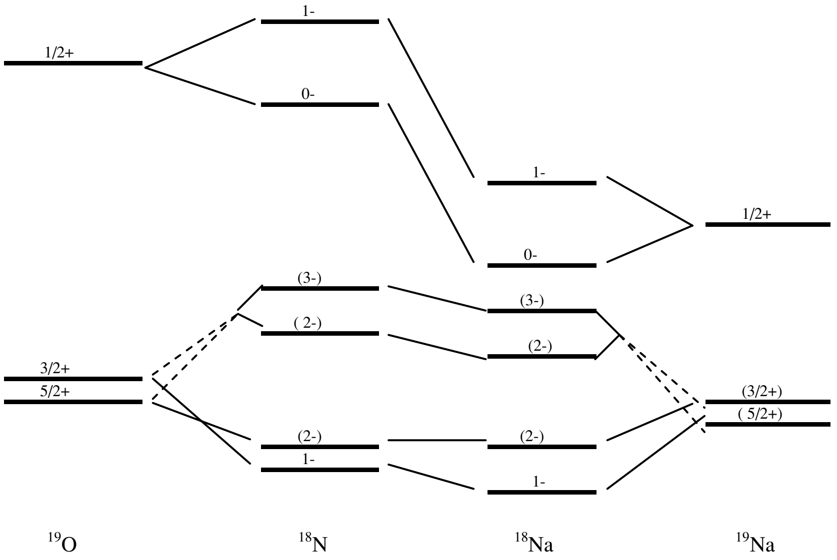

FIG. 1. Schematic low-lying energy levels (known and expected) in ^{19}O, ^{18}N, ^{18}Na, and ^{19}Na.

free in weak coupling because we have

$$M(^{18}\text{Na}) - M(^{18}\text{N}) = M(^{19}\text{Na}) - M(^{19}\text{O}) + M(^{15}\text{O}) - M(^{15}\text{N}).$$

Inserting the ^{18}N(g.s.) mass provides a mass excess of 25.47 MeV for the g.s. of ^{18}Na. These two results are summarized in Table II, along with a recent experimental result [8] and other predictions [5,9,10]. If weak coupling misses ^{18}Na by about the same amount as in ^{18}N, we would thus expect the mass excess of ^{18}Na to be in the range 25.01–25.25 MeV.

From Table II, it appears quite reasonable that the peak at 25.04 MeV in Ref. [8] corresponds to the g.s. to g.s. $^{18}\text{Na} \rightarrow {}^{17}\text{Ne} + p$ decay (one of the two scenarios considered in Ref. [8]). The peak at 24.19 MeV would then belong to decay of an excited state of ^{18}Na to an excited state of ^{17}Ne. What, then, are we to make of the widths [8]—$\Gamma_{\text{obs}}(24.19) = 0.34(9)$ MeV and $\Gamma_{\text{obs}}(25.04) = 0.54(13)$ MeV, where the experimental resolution width [8] is 250(50) keV ? Reference [8] presents convincing evidence that the spectroscopic factors and single-particle (sp) widths are such that these cannot be decay widths. The lowest states of ^{18}Na contain almost no $\ell = 0$ strength and the extracted widths are even larger than the $\ell = 0$ sp width, and therefore certainly larger than any $\ell = 2$ width. The first two states would decay predominantly to ^{17}Ne(g.s.) + p independently of their decay widths. It is virtually certain that the 25.04 MeV peak contains decay from both states. The width of the peak is not then related to the decay width but rather to the separation (and relative population in the formation process) of these two states. In Fig. 3 of Ref. [8] is an example of a "g.s." peak that includes decay of two close-lying states in ^{19}Na.

It seems to us that the 24.19 MeV peak then must contain contribution(s) from one or more excited states, decaying probably to ^{17}Ne(first exc) at 1.288 MeV [11]. (This possibility was also considered in Ref. [8]). For this peak, the observed width of 0.34(9) MeV is such that it might be equal to the resolution width of 0.25(5) MeV and hence involve only one ^{18}Na state. As stated in Ref. [8], the state involved would have an excitation energy of 0.44 MeV in ^{18}Na—but relative to the centroid of the 25.04 MeV peak, which we suggest contains decay from two states. The excitation energy in ^{18}Na is then somewhat higher than 0.44 MeV. We return to this point below. To explain the results, the decay to ^{17}Ne(first exc) would need to be via $\ell = 0$ in order to compete with $\ell = 2$ decay to the g.s., limiting the J^π of this excited state to 1^- or 2^-. The 2^- could be the other member of the doublet containing the 1^- g.s. This state would have an extremely hindered decay to the g.s., because $(d5/2)^3$ coupled to $3/2^+$ has no connection to

TABLE I. Mass excesses (MeV) in ^{18}N.

	Exp[a]	w.c.[b]
g.s.	13.117	—
$(3/2^+ \text{x} 1/2^-)1^-, 2^-$ centroid	13.484[c] or 13.584[d]	13.744
$(5/2^+ \text{x} 1/2^-)2^-, 3^-$ centroid	13.553[c] or 13.507[d]	13.648

[a] References [1,5].
[b] Using $a + b/4 = 1.826$ MeV from ^{16}N($2^-, 3^-$) [6].
[c] If 2^-_2 at 0.587 MeV.
[d] If 2^-_2 at 0.747 MeV.

TABLE II. Mass excesses (MeV) in ^{18}Na.

Weak coupling	
$2^-.3^-$ centroid	25.718[b]
g.s.[a]	25.23[b]
g.s.[a]	25.47[c]
Ref. [5]	25.3(4)
Ref. [8]	25.4(2)
Ref. [9]	25.7(2)
Exp	24.19(16) or 25.04(17)[d]

[a] Assuming the same splitting in ^{18}Na and ^{18}N.
[b] Using $a + b/4 = 1.732$ MeV from ^{16}F.
[c] Parameter free within weak coupling.
[d] Reference [8]. Systematic uncertainty of 150 keV included.

TABLE III. Mass excesses of ^{18}Na from Ref. [8] and our conclusions.

Peak	Mass excess (MeV)[a]	Total counts	Source
1	24.19(16)	16	^{18}Na*(1 or 2 states) $\rightarrow$ ^{17}Na*
2	25.04(17)[b]	22	^{18}Na (g.s. + at least 1 other) $\rightarrow$ ^{17}Ne(g.s.)
3	25.88(20)[c]	12	^{18}Na*(at least 2 states) $\rightarrow$ ^{17}Ne(g.s.)

[a] Uncertainty includes 150 keV systematic uncertainty.

[b] Width is then not decay width, but rather arises from unresolved states. We suggest a separation of 0.24(5) MeV.

[c] Our analysis of data of Ref. [8].

a $J^\pi = 0^+$ two nucleon state (the g.s. of ^{17}Ne is predominantly a p1/2 hole in a 0^+ state). If 1^-, it most likely would be the state arising from the coupling ^{19}Na$(1/2^+)$x$1/2^-$, which might be low enough in ^{18}Na to fit the data. But that state would strongly prefer an $\ell = 0$ decay to the g.s.

We also note another peak in the spectrum of Ref. [8] at 25.89(20) MeV which appears to contain at least two states. These would most likely be excited states of ^{18}Na decaying to the g.s. of ^{17}Ne. We summarize our suggestions in Table III.

The uncertainties in the energies in Ref. [8] and Table III include a systematic uncertainty in the absolute energy scale of 150–100 keV from comparing their measurements for masses of other known nuclei, and 50 keV from the uncertainty in the ^{17}Ne(g.s.) mass. If we allow for an offset Δ in the energy scale, we can write $M_{\text{true}} = M_{\text{meas}} + \Delta$, and use only the statistical uncertainty on M_{meas}. If we assume an uncertainty in the mean of $\Delta M = \text{std dev}/\sqrt{N}$, where $N = 16$, 22, and 12 for peaks 1, 2, and 3, respectively, then *differences* in the M's will have significantly smaller uncertainties than the absolute energies. Before proceeding, we need to examine peak 2 more closely. As it arises from two peaks, we have attempted a fit with two gaussians of width 250 keV. We have no desire to overdo the analysis for a peak with only 22 counts, but we do obtain reasonable agreement with two peaks separated by 240(50) keV, with the upper one being 1.5–2 times as strong as the lower one. The masses are then 24.88(5) MeV + Δ and 25.12(5) MeV + Δ. The lower of these corresponds, presumably, to the g.s. of ^{18}Na and the upper one to the first-excited state. If the g.s. has as much $\ell = 0$ occupancy as listed in Table 2 of Ref. [8] the 1^-, 2^- separation would be expected to be larger in ^{18}Na than in ^{18}N. Simple potential-model calculations yield an additional splitting of 55–90 keV, making the total 160–205 keV. This would lower the predicted mass excess somewhat, giving us an estimate of $\Delta = 60$–300 keV. Further discussion below is independent of this value.

Then, if peak 1 corresponds to a single excited state of ^{18}Na decaying to an excited state of ^{17}Ne, we have $E_x(^{17}\text{Ne}) - E_x(^{18}\text{Na}) = 0.69(7)$ MeV, independent of Δ. If the excited state of ^{17}Ne is the $3/2^-$ at 1.288 MeV, then we have $E_x(^{18}\text{Na}) = 0.60(7)$ MeV. If the decay is to the $5/2^-$ at 1.764 MeV [11], the excited state in ^{18}Na would be at 1.00(7) MeV. We clearly prefer the former and suggest that it is the 2^-, which could decay to $3/2^-$ via $\ell = 0$. The 3^- would require $\ell = 2$ to $3/2^-$, and the 3^- has an appreciable $\ell = 2$ connection to the g.s.—suggesting g.s. decay would dominate for 3^-. We thus have possible identification of three states of ^{18}Na—the (presumably) 1^- g.s., a 2^- at $E_x = 0.24(5)$ MeV, and another 2^- at 0.60(7) MeV. The relevant decays are illustrated schematically in Fig 2.

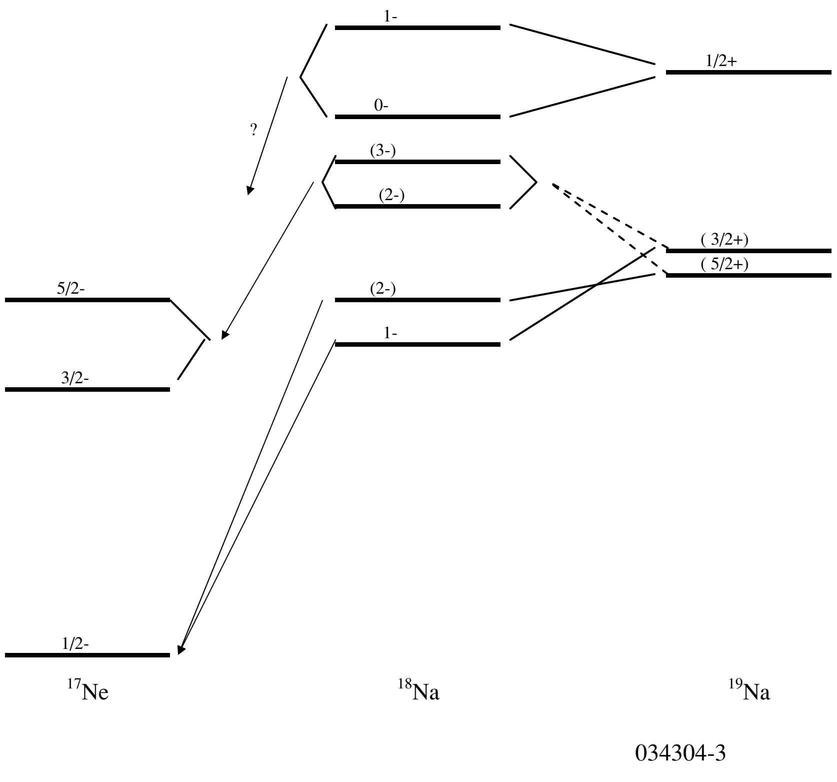

FIG. 2. Levels of ^{19}Na, ^{18}Na, and ^{17}Ne indicating parentage and possible decays of ^{18}Na states.

Let us now look at peak 3, which appears to involve decays of two or more states to the g.s. The average excitation energy of these states is thus $E(\text{peak } 3) - E(\text{lower of peak } 2) = 1.0(8)$ MeV. We suggest that it probably contains all three of the 3^-, 0^-, and 1^-states, the latter two of which can decay to the g.s. via $\ell = 0$. Because the sp width for such decays is about 1 MeV, these 0^-, 1^- states could have decay widths of several hundred keV. The counts above 26.2 MeV in Fig. 4 of Ref. [8] could belong to the tails of these states, in which case the average energy would be somewhat larger than the one mentioned above.

In conclusion, we have presented results of weak coupling and simple potential-model calculations for the g.s. mass of ^{18}Na and the excitation energies of several low-lying states. We suggest the peak at a mass excess of 25.04 MeV in Ref. [8] corresponds to decay of the g.s. and first-excited state of ^{18}Na to the g.s. of ^{17}Ne. We suggest the two states are separated by 0.24(5) MeV and that the upper one is somewhat stronger (in the formation process). Their widths are immeasurably small compared to the experimental resolution. We believe the peak at 24.19 MeV in Ref. [8] is primarily due to decay of a state (presumably 2^-) at 0.60(7) MeV in ^{18}Na to the 1.288 MeV $3/2^-$ state of ^{17}Ne. The peak near 25.9 MeV in the data of Ref. [8] (not analyzed by them), appears to correspond to the decay of two or three states of ^{18}Na (probably 3^-, 0^-, and 1^-) to the g.s. of ^{17}Ne. We think a future experiment on ^{18}Na would clarify these points and perhaps provide a slightly larger g.s. mass for ^{18}Na than suggested in Ref. [8]. We expect that more sophisticated calculations will confirm our results.

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