Suitability of the lowest 1^-, $T = 1$ and 1^+, $T = 1$ states in ^{20}Ne for parity nonconservation experiments

J. M. Davidson and M. M. Lowry
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
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The properties of the 1^-, $T = 1$ state of ^{20}Ne at 11278 ± 4 keV excitation were studied by means of the $^{16}O(\alpha,\gamma)^{20}Ne$ reaction. The level parameters determined for this state are not in complete agreement with those reported in a recent study. The implication of this discrepancy for the feasibility of a measurement of parity nonconservation in ^{20}Ne is discussed.

[NUCLEAR REACTIONS $^{16}O(\alpha,\gamma)^{20}Ne$, $E = 8.18$ MeV; measured E_γ, $I(\Theta_\gamma)$; ^{20}Ne resonance deduced excitation energy, J, π, $\omega\gamma_0$, T. Natural targets. Ge(Li) and NaI(Tl) detectors.]

The recent report[1] of a 1^- state of probable $T=1$ character at $E_x = 11\,259 \pm 8$-keV excitation in ^{20}Ne raises the possibility that an exceptionally favorable system for studying the parity nonconserving (PNC) nucleon-nucleon force might be provided by this state and the $1^+, T=1$ state reported[2] at $E_x = 11\,261 \pm 5$ keV. The small separation in energy of these two states would lead to a considerable enhancement of their parity mixing and might enable the system to be treated as a case of simple two-level mixing. Moreover, the α width of the 1^+ state would provide a direct measurement of the $\Delta T = 1$ PNC matrix element between the 1^+ state and the $T=0$ isospin impurity[1,3] in the 1^- state, and could thus provide information on the character of neutral weak currents[4] and, in particular, whether they violate parity conservation in an isoscalar-isovector mixture as in the Weinberg-Salam theory.[5] A pseudoscalar quantity associated with the γ-ray decay of these states (e.g., the γ-ray circular polarization) contains both neutral and charged weak current contributions; however, it has the attractive features of providing a direct measure of the $\Delta T = 0, 2$ PNC matrix elements between these states,[6] and of involving only the analog states, states of relatively simple structure, in the theoretical estimate of the size of the observable effects.

In this communication, we report a measurement of the properties of the 1^- ^{20}Ne state, in which we find $E_x = 11\,278 \pm 4$ keV, differing by over two standard deviations from the value given in Ref. 1. Using the value of E_x from the present work, the expected PNC effects are substantially reduced from those predicted using the earlier value.[1] In the case of the PNC α width of the 1^+, $T=1$ state, it is shown to arise predominantly from its mixing with a third ^{20}Ne state, the broad ($\Gamma = 175$-keV) $1^-, T=0$ state at $E_x = 11.23$ MeV (Ref. 7).

The 11.28-MeV ^{20}Ne state was populated via the 8.18-MeV resonance in the $^{16}O(\alpha,\gamma)^{20}Ne$ reaction. The ONR-CIT tandem Van de Graaff accelerator provided a beam of $^4He^{++}$ nuclei. The targets were anodized layers of Ta_2O_5, ranging in thickness from 50 $\mu g/cm^2$ to 150 $\mu g/cm^2$, on thick tantalum backings. Gamma rays were detected with a Ge (Li) detector of 100-cm^3 volume and a 10.2-cm $\times$ 12.7-cm diameter cylindrical NaI(Tl) detector.

Measurements of the angular distribution and thick-target yield of γ rays from the $11.28 \to 0.0$-

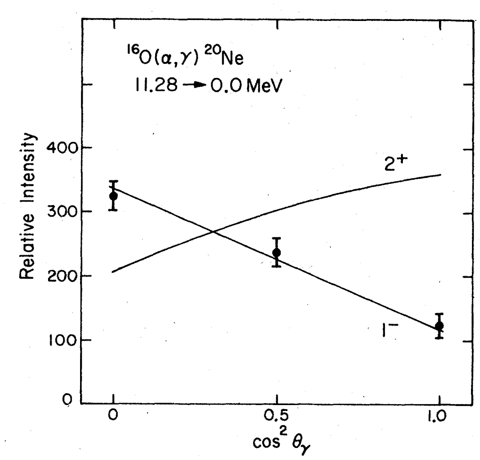

FIG. 1. Angular distribution of the γ rays from the $11.28 \to 0.0$ MeV ^{20}Ne transition. Theoretical angular distribution profiles (Ref. 8) for initial state spins of 1 and 2 are shown. The state is known to have natural parity from its α-decay width.

TABLE I. Properties of the lowest 1^-, $T=1$ state of ^{20}Ne.

Reference	$\omega\gamma_0^{\text{c.m.}}$ (eV)	E_x (keV)
Ref. 3	0.7 ± 0.3[a]	11270 ± 30
Ref. 1	0.58 ± 0.05	11259 ± 8
Ref. 12	1.2 ± 0.3	
Present work	1.0 ± 0.3	11278 ± 4

[a] The value quoted in Ref. 3 has been multiplied by $\frac{16}{20}$ to express it in the center-of-mass system.

MeV ^{20}Ne transition determined the spin and absolute strength of the resonance. The observed angular distribution leads to an unambiguous assignment of $J^\pi = 1^-$ for the initial state (see Fig. 1) in agreement with the assignment of Steck.[1] The thick-target yields were observed at $\theta_\gamma = 55°$ using the NaI(Tl) detector. The absolute efficiency of this detector was determined from standard tables.[9] The absolute strength $\omega\gamma_0$ of the 8.18-MeV resonance in the ^{16}O$(\alpha,\gamma)^{20}$Ne reaction is found to be $\omega\gamma_0^{\text{c.m.}} = (2J+1)\Gamma_\alpha\Gamma_{\gamma_0}/\Gamma = 1.0 \pm 0.3$ eV. This value is compared with previous reports in Table I.

An assignment of $T=1$ for the 1^- 11.28-MeV ^{20}Ne state is consistent with the experimental value of $\omega\gamma_0$ determined in this work. From this resonance strength, it follows that the ground-state radiative width is $\Gamma_{\gamma_0} \geq 0.3 \pm 0.1$ eV. The corresponding lower limit for $B(E1)$ is 4.4×10^{-4} Weisskopf units (W.u.) which is typical of isospin-allowed transitions,[10] although $T=0$ for the 11.28-MeV state cannot be rigorously ruled out based on this evidence alone. The upper limit on the total width, $\Gamma \leq 0.3$ keV, reported by Steck[1] and the existence of a 1^- state at $E_x = 0.984$ MeV in ^{20}F (Ref. 11) also give strong circumstantial evidence that the 11.28-MeV ^{20}Ne state is $T=1$. Conclusive evidence, however, for a $T=1$ assignment is provided by Fifield,[12] who observed the γ ray from the decay of the 11.28-MeV ^{20}Ne state to the 8.85-MeV $1^-, T=0$ state to have a $B(M1)$ of ≥ 0.66 W.u., which strictly rules out $T=0$ for the initial state.[10] In the present work, this γ ray was obscured by low-energy background from contaminant reactions.

The excitation energy of the $1^-, T=1$ ^{20}Ne state was determined by making a precise measurement of the energy of the γ ray from the $E_x(1^-, T=1) \to 0.0$-keV transition. The Ge(Li) detector was placed at 90° with respect to the beam direction and at a distance of approximately 11 cm from the reaction site. The energy scale of the γ-ray spectrum was calibrated with the γ rays from the 2046.2 ± 0.2-keV resonance in the ^{27}Al$(p,\gamma)^{28}$Si reaction.[13] In this calibration procedure, care was taken not to excite the nearby weak resonance at 2049.4 keV. The fortuitous near coincidence in energy between the γ-ray single-escape peak from the transition leading from the ^{28}Si resonant capture state to the 1778.88 ± 0.09-keV state, and the γ-ray full-energy peak from the $E_x(1^-, T=1) \to 0.0$-keV ^{20}Ne transition, provided a very accurate calibration in the vicinity of the ^{20}Ne γ ray (see Fig. 2). The combined results of several data collection runs determined the excitation energy of the $1^-, T=1$ state to be $E_x = 11\,278 \pm 4$ keV, based on a Q value of $11\,585.3 \pm 0.6$ keV for the ^{27}Al$(p,\gamma)^{28}$Si reaction[14] and on the aforementioned resonance energy[13] in that reaction. Appropriate corrections were made for the recoils of the γ-ray emitting nuclei and for Doppler shifts resulting from a slight displacement (discovered after much of the data was collected) of the Ge(Li) crystal from the geometric center of its aluminum vacuum covering and thus from 90°. A correction accounting for the transverse Doppler shift was made in the energy of the ^{20}Ne γ ray. The quoted uncertainty includes an estimated error of $\pm 0.5°$ in the placement of the Ge(Li) detector. The present value for the excitation energy is compared with values from previous measurements in Table I.

We now consider the question of a PNC α width for the 11.26-MeV $1^+, T=1$ ^{20}Ne state. In the simple two-level approximation, this width is given

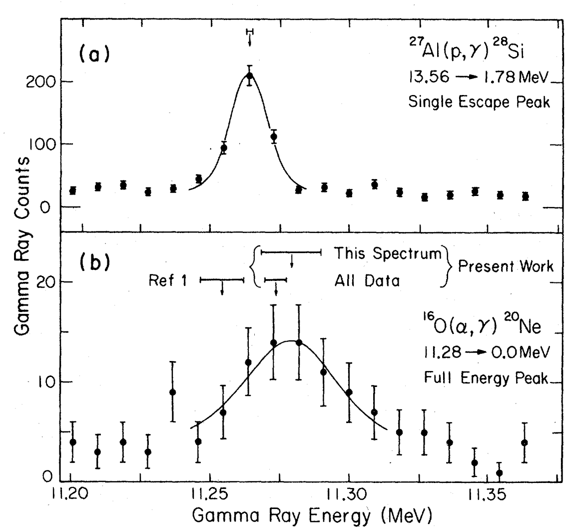

FIG. 2. Portions of the γ-ray spectra from the present work for $\Theta_\gamma = 90°$. The broadening of the peaks results from the large center-of-mass motion [especially in (b)] and the nonzero angle subtended by the Ge(Li) detector. The solid lines are Gaussian profiles which have been fitted to the data by a least-squares procedure. The arrows in (b) denote the location of and uncertainty in the peak centroid for the data displayed in (b), for all data taken in this work, and for the initial-state excitation energy quoted in Ref. 1.

by

$$\Gamma_\alpha^{\rm PNC} = |A|^2\,\Gamma_\alpha(1^-)\,, \qquad (1)$$

where the amplitude A is given by[15]

$$A = \frac{\langle 1^+ | V_{\rm PNC}^{\Delta T=1} | 1^- \rangle}{(E_- - E_+) - (i/2)(\Gamma_- + \Gamma_+)}\,. \qquad (2)$$

In Eq. (1), $\Gamma_\alpha(1^-)$ is the parity-allowed α width of the admixed 1^- state. In Eq. (2), $V_{\rm PNC}^{\Delta T=1}$ is the isovector part of the parity nonconserving nucleon-nucleon potential, $E_{+(-)}$ and $\Gamma_{+(-)}$ denote the excitation energy and total width of the 1^+ (1^-) state, respectively. Using the value from the present work for the excitation energy of the $1^-, T=1$ state and the value of Ingalls[2] for the excitation energy of the $1^+, T=1$ state (see Fig. 3), we find $E_- - E_+ = 17$ keV, leading to a value for $\Gamma_\alpha^{\rm PNC}$ which is a factor of approximately 50 smaller than that obtained using the earlier value[1] for $E_x(1^-, T=1)$ for which $E_- - E_+ = -2$ keV. In fact, for $\Delta E = 17$ keV the amplitude coupling the $1^+, T=1$ and the $1^-, T=1$ states has a considerably smaller modulus than that coupling the $1^+, T=1$ state to the $1^-, T=0$ state at 11.23 MeV (for which $\Gamma = 175$ keV), assuming similar values for the PNC matrix element for the two cases. If the further simplifying assumption is made that the $T=0$ impurity in the 11.28-MeV state arises predominantly from its isospin mixing with the 11.23-MeV $1^-, T=0$ state, then it may be shown in a three-level treatment that

$$0.9\times 10^{-5}\ {\rm eV}^{-1} \le \frac{\Gamma_\alpha^{\rm PNC}}{|\langle 1^+, T=1 | V_{\rm PNC}^{\Delta T=1} | 1^-, T=0\rangle|^2} \le 3.6\times 10^{-5}\ {\rm eV}^{-1}\,, \qquad (3)$$

where it has been assumed that $\Gamma_\alpha(1^-, \Gamma=1) = 0.3$ keV and $E_- - E = 10$ keV, which are the respective upper[1] and lower limits (one standard deviation) for these quantities. The range of values then follows from the fact that the phase of the isospin mixing matrix element connecting the $1^-, T=0$ and $1^-, T=1$ states is unknown. For smaller $\Gamma_\alpha(1^-, T=1)$ and larger ΔE, this range decreases, converging to 2×10^{-5} eV^{-1}. Thus, the PNC α width of the $1^+, T=1$ ^{20}Ne state is dependent predominantly on its parity mixing with the $1^-, T=0$ state, although the effect of the $1^-, T=1$ state could be significant if its width were as large as 0.3 keV and ΔE were as small as 10 keV.

In the calculation of a PNC pseudoscalar quantity, for example, the circular polarization P_γ of the 11.28-MeV γ ray from the 11.28 → 0.0-MeV ^{20}Ne transition, it may be shown that

$$P_\gamma = -2\frac{\|E1\|}{\|M1\|}\frac{\langle 1^+, T=1 | V_{\rm PNC}^{\Delta T=0,2} | 1^-, T=1\rangle}{\Delta E}\,, \qquad (4)$$

where $\|E1\|$ and $\|M1\|$ denote reduced matrix elements for the $E1$ and $M1$ ground-state transitions deexciting the 11.28- and 11.26-MeV states, respectively. The value from the present work for $E_x(1^-, T=1)$, inserted in Eq. (4), leads to a value for P_γ smaller by almost an order of magnitude than that obtained using the earlier value.[1] Using $\Gamma_{\gamma_0} = 0.3$ eV for the ground-state radiative width of the 11.28-MeV state and the value from Berg[16] of $\Gamma_{\gamma_0} = 11.4$ eV for the ground-state radiative width of the 11.26-MeV state, we obtain

$$\left|\frac{P_\gamma}{\langle 1^+, T=1 | V_{\rm PNC}^{\Delta T=0,2} | 1^-, T=1\rangle}\right| = 8\times 10^{-4}\ {\rm eV}^{-1}\,. \qquad (5)$$

(The presence of the $1^-, T=1$ state at 11.23 MeV should not affect P_γ or any other electromagnetic quantity, because the amplitude for the isospin-forbidden $E1$ transition to the ^{20}Ne ground state will be very small.)

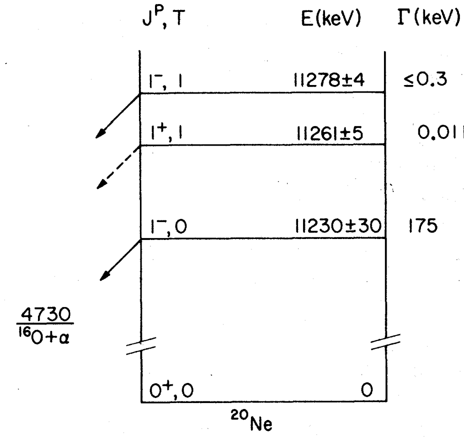

FIG. 3. Levels of ^{20}Ne involved in the discussion of parity mixing contained in the text. The next nearest known ^{20}Ne level of spin 1 is at 11 953-keV excitation (Ref. 7).

In summary, we have measured the properties of the lowest-lying $1^-, T=1$ ^{20}Ne state and find $E_x = 11\,278 \pm 4$ keV, differing by over two standard deviations from a recently published value.[1] Using the value from the present work, we find that the parity mixing of the $1^-, T=1$ state and the $1^+, T=1$ state at $E_x = 11\,261 \pm 5$ keV (Ref. 2) is substantially reduced over that predicted using the earlier value,[1] although the observable effects could still be relatively large, depending on the values of the PNC matrix elements.[17] As a case for studying the PNC nucleon-nucleon force, the system consisting of the three levels shown in Fig. 3 has the additional attractive feature of separately manifesting the effects of the isovector and isoscalar-isotensor parts of the weak Hamiltonian in the PNC α width of the $1^+, T=1$ state and in the various pseudoscalar quantities associated with the electromagnetic decays of these states, respectively. Further, the PNC α width could provide information relating to the character of neutral weak currents,[4] although an attempt to measure this width could encounter serious problems with the background from the broad $1^-, T=0$ state which overlies the entire region shown in Fig. 3. A second drawback to the measurement of Γ_α^{PNC} for the 11.26-MeV ^{20}Ne state arises in the interpretation of the result; because of the unknown structure of the $1^-, T=0$ ^{20}Ne state, it may be difficult to calculate the PNC matrix element in Eq. (3) with an accuracy sufficient to enable a meaningful test of any theory of weak interactions. On the other hand, a measurement of the circular polarization P_γ of the γ ray from the $11.28 \rightarrow 0$ transition (or some other pseudoscalar quantity associated with this transition) is more likely to provide a useful probe of the nucleon-nucleon weak force, because the matrix elements which must be evaluated [in Eq. (4)] involve only the analog states, for which the nuclear structure may be comparatively simple. Such a measurement would be very difficult technically, however, owing to the high energy of that γ ray.

Further information which would be useful in estimating the size of the PNC effects includes (i) an improved measurement of the width of the 11.28-MeV state, which could narrow the range of values permitted in Eq. (3) (ii) an improved measurement of the excitation energy of the 1^+, $T=1$ state, because the uncertainty in that energy is now the dominant uncertainty in ΔE and also because two unpublished values[16,18] of which we are aware disagree with the published excitation energy of Ingalls[2]; and (iii) theoretical estimates of the PNC matrix elements in Eqs. (3) and (4). Considering the fundamental importance of experimental evidence bearing on the character of the PNC nucleon-nucleon force and especially on the character of neutral weak currents, efforts in obtaining the above information are warranted.

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