Study of the Properties of the 4.97-Mev Level in Ne^{20} using the $F^{19}(p,\gamma)Ne^{20}$ Reaction

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The reaction $F^{19}(p,\gamma)Ne^{20}$ has been studied at two resonances, 669 kev and 1092 kev, to obtain information about properties of the 4.97-Mev level in Ne^{20}. It is shown that this 4.97-Mev level is fed by a direct transition from the 1+ resonance at 669 kev, that it does not have spin 0 and that its transition to the ground state of Ne^{20} is less than 5% of the transition to the first excited state. It is concluded that the most likely assignments to the 4.97-Mev level are 2± or 3+.

INTRODUCTION

The properties of the 4.97-Mev level in Ne^{20} are of particular interest because of the possible role this level plays in stellar nuclear reactions.[1] Levels above an excitation energy of 4.753 Mev in Ne^{20} can, in principle, be formed by the addition of an alpha particle to O^{16}. For this to occur, of course, the levels must have right combination of spin and parity (i.e., 0+, 1−, 2+, etc.) and, depending on the spin, the reduced width for formation must be greater than a certain fraction of the single particle limit.[2] Once formed there must also be an appreciable probability for the level to decay to the ground state of Ne^{20} by gamma ray emission.

The positions of low-lying levels in Ne^{20} have been most carefully studied by Buechner and Sperduto[3] employing the $Na^{23}(p,\alpha)Ne^{20}$ reaction. They found levels at 0, 1.635, 4.248, 4.969, and 5.631 Mev, all with an accuracy of ±6 kev. Many other reactions have been employed to study Ne^{20}, in particular the reaction $F^{19}(p,\gamma)Ne^{20}$.[4] The reaction has recently been used by Kane *et al.*[5] to study a resonance at 669 kev.

In the present work[6] gamma-gamma coincidence measurements were carried out at two resonances in the $F^{19}(p,\gamma)Ne^{20}$ reaction at 669 and 1092 kev.[4] These correspond to levels in Ne^{20} at 13.51 and 13.91 Mev, respectively.

APPARATUS

The reaction was initiated by protons from the Chalk River 3-Mev electrostatic accelerator and the gamma rays were detected in two 5-in. diam by 4-in. long NaI(Tl) crystals coupled to Dumont photomultiplier tubes. For coincidence work a fast-slow coincidence arrangement[7] was employed with a resolving time 2τ of about 40 nsec. The target was CaF evaporated on a tantalum backing. Its thickness was about 45 kev for 700-kev protons.

RESULTS

Studies of the $F^{19}(p,\gamma)Ne^{20}$ reaction are rendered difficult by competing reactions which give rise to gamma rays. For example, Fig. 1 shows the principal modes of decay of a level in Ne^{20} at 13.51 Mev formed by adding 669-kev protons to F^{19}.[4] The principal capture gamma-ray transition to the first-excited state of Ne^{20} has a partial width of 2.2 ev. In competition with this is the $F^{19}(p,\alpha)O^{16}$ reaction which gives rise to gamma rays of 6 to 7 Mev and whose partial widths are 110 and 25 ev, about two orders of magnitude greater in intensity. Gamma-ray decay of low-lying levels in Ne^{20} can be studied however, in coincidence with capture gamma rays provided sufficiently short resolving times are employed in the coincidence circuits to minimize random counts.

Figure 2 shows the direct gamma-ray spectrum measured at the 669-kev resonance. This resonance is known to have spin and parity 1+.[4] The predominant capture gamma ray of this level is an 11.88-Mev transition to the first-excited state of Ne^{20} at 1.635 Mev. The most intense gamma rays observed in the spectrum are the 6.13- and 7.12-Mev gamma rays from the $F^{19}(p,\alpha\gamma)O^{16}$

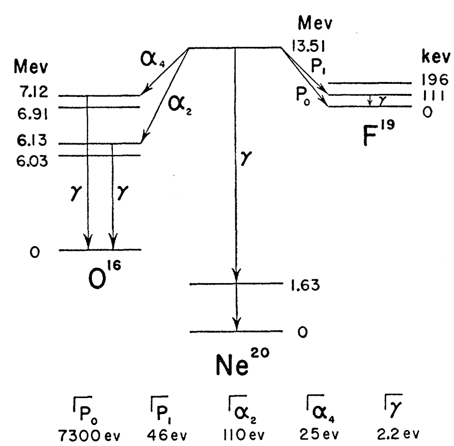

Fig. 1. Principal decay modes of the 13.51-Mev level in Ne^{20} with the partial widths for each listed below.

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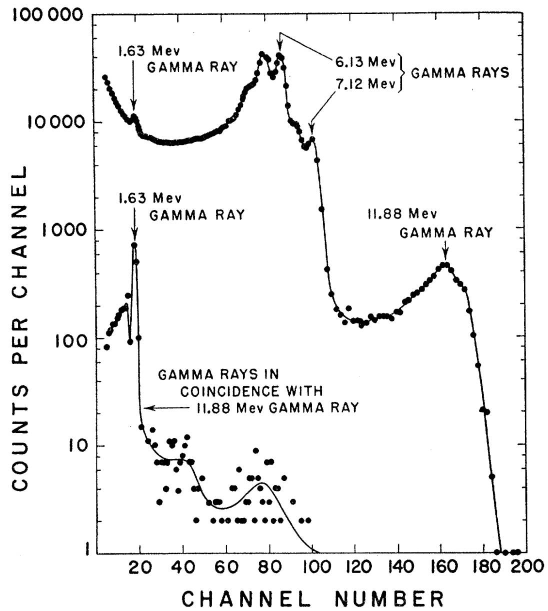


FIG. 2. The upper curve shows the direct gamma-ray pulse spectrum measured at the 669-kev resonance in the proton bombardment of F^{19}. The lower curve is the spectrum in coincidence with pulses corresponding to 11.88-Mev gamma rays.

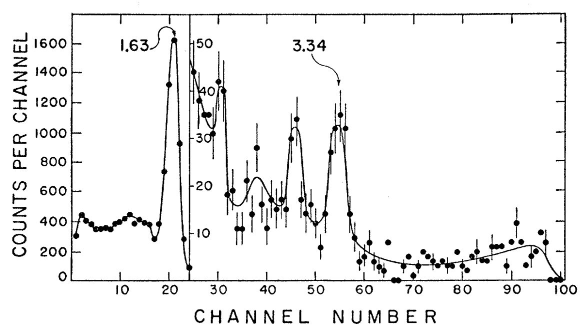


FIG. 3. The pulse spectrum at the 669-kev resonance corresponding to gamma rays in coincidence with gamma rays of energy greater than 7 Mev measured in a second detector.

reaction. The 1.63-Mev gamma rays is also observed in the spectrum. When a gate on the second crystal is set on the 11.88-Mev peak, the coincidence spectrum shown in the lower part of Fig. 2 is observed. The short coincidence resolving time reduces chance counts from the intense 6.13- and 7.12-Mev gamma rays to negligible proportions and only the 1.63-Mev gamma rays are observed in the spectrum.

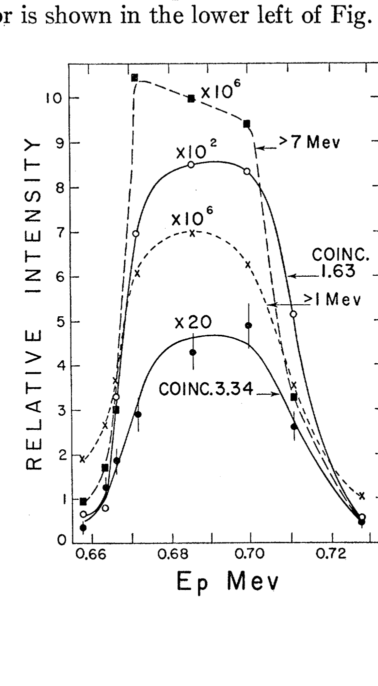
The gate on the second crystal was then adjusted until its lower limit was just above the pulses produced by the 7.12-Mev gamma rays and its upper limit remained as before above the 11.88-Mev gamma-ray pulses. The coincidence spectrum observed under these conditions is shown in Fig. 3. In addition to the 1.63-Mev gamma ray a weak 3.34-Mev gamma ray is observed. This is interpreted as arising from a weak primary transition from the capturing state to the 4.97-Mev level which in turn cascades to ground through the first excited state by a 3.34-Mev transition.

To establish that the level in Ne^{20} at 4.97 Mev is fed by a primary transition from this 1+ resonance at 669 kev, the yield curves shown in Fig. 4 were measured. Two of these are direct yields of all gamma rays of energy greater than 1 and 7 Mev, respectively, and two are coincidence yield curves with one crystal counting gamma rays of energy greater than 7 Mev and the other measuring 1.63- and 3.34-Mev gamma rays in coincidence. Because the intensity of the primary transition feeding the 4.97-Mev level is only about 5% of that feeding the first-excited state the counting rate for this 3.34-Mev coincidence yield curve is low. However, the evidence for a gamma transition between the 1+ level in Ne^{20} at 13.51 Mev and the 4.97-Mev level is reasonably convincing. This argues that the spin of the 4.97-Mev level is 3 or less.

To test whether the 4.97-Mev level had spin zero and to measure its branching ratio more accurately, a resonance in the $F^{19}(p,\gamma)$ reaction at a proton energy of 1092 kev was investigated. This resonance has the advantage that it decays principally to the 4.97-Mev level. The results are shown in Fig. 5. The spectrum in the upper left of this figure shows the gamma rays in coincidence with those of energy greater than 7 Mev measured in the second crystal. No sign of a 4.97-Mev gamma ray is observed in this spectrum; if present, it should occur in channel 35 and an upper limit of 5% can be placed on its intensity compared to the 3.34-Mev transition to the first-excited state.

With the position of the 3.34-Mev peak established in the coincidence spectrum the gates shown in Fig. 5 (upper left) were set sequentially on the direct spectrum to encompass, first the 3.34-Mev peak (gate 1) and then, an equal number of channels just above the 3.34-Mev peak (gate 2). The coincidence spectrum observed in the second detector is shown in the lower left of Fig. 5.

FIG. 4. Yield curves measured at the 669-kev resonance in the proton bombardment of F^{19}. They are, respectively, the yield of all gamma rays of energy greater than 1 Mev (crosses), of all gamma rays of energy greater than 7 Mev (squares), of 1.63-Mev gamma rays in coincidence with 11.88-Mev gamma rays (open circles), and of 3.34-Mev gamma rays in coincidence with primaries feeding the 4.97-Mev level in Ne^{20} (closed circles).



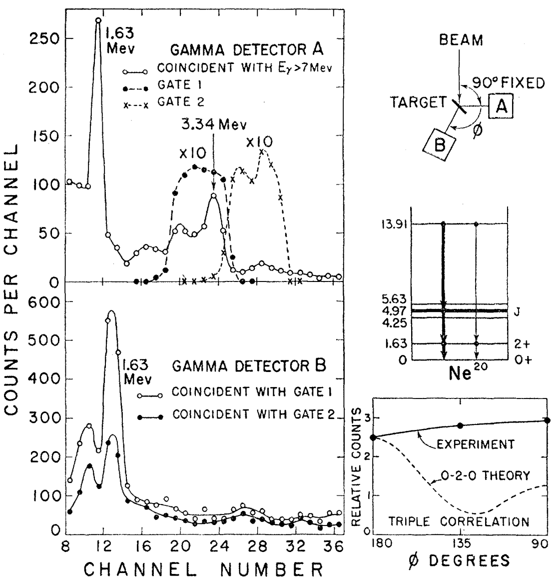


FIG. 5. Measurements made at the 1092-kev resonance in the proton bombardment of F^{19}.

The residual 1.63-Mev gamma peak observed using gate 2 is due to coincidences with the pulses in the tails of the spectrum of the higher energy gamma rays which feed both the 4.97- and 1.63-Mev levels.

With the gate 1 setting, the angular correlation between the 3.34- and 1.63-Mev gamma rays were measured using the geometry illustrated schematically in the upper right of Fig. 5. Since the experiment could only distinguish between spin 0 for the 4.97-Mev level and all other spins, it was only necessary to make the measurement at three angles θ. The results are shown in the lower right of Fig. 5, along with the theoretical correlation to be expected if the 4.97-Mev level had spin 0. Because, when the gate is moved above the 3.34-Mev peak there is still a residual number of 1.63-Mev coincidence counts one would expect some attenuation in the variation with angle over that predicted theoretically for a 0-2-0 distribution but not as much as observed. It is therefore possible, with reasonable confidence to eliminate spin 0 for the 4.97-Mev level in Ne^{20}.

CONCLUSIONS

Figure 6 shows an energy level diagram for Ne^{20} summarizing the results presented here. The coincidence yield curve proved that a 3.34-Mev gamma rays is in coincidence with one of energy greater than 7 Mev at the 1+ level at 13.51 Mev and the observation of this 3.34-Mev gamma ray in the coincidence spectrum at a resonance 400-kev higher shows that it is not a primary. Hence the 1+ level at 13.51 Mev feeds the 4.97-Mev level. Combining the observed[4] $\Gamma_\gamma = 2.2$ ev for the transition to the 1.63-Mev level with the branching ratio reported here yields $\Gamma_\gamma = 0.12$ ev for the transition to the 4.97-Mev level. In addition, it was shown that the

TABLE I. Comparison between Γ_γ measured at the 13.51-Mev resonance and the Weisskopf value, Γ_W.

Multipole	Γ_W(ev)	$\|M\|^2$
13.51 Mev → 4.97 Mev, $E_\gamma = 8.54$ Mev, $\Gamma_\gamma = 0.116$ ev		
$E1$	312	3.7×10^{-4}
$M2$	0.005	23
$M1$	13.1	8.9×10^{-3}
$E2$	0.121	0.96
13.51 Mev → 1.63 Mev, $E_\gamma = 11.88$ Mev, $\Gamma_\gamma = 2.2$ ev		
$M1$	35.3	6.2×10^{-2}
$E2$	0.631	3.5

4.97-Mev level does not have $J=0$ and that it decays to the ground state of Ne^{20} with less than 5% probability of its decay to the first-excited state.

Because it is fed by a 1+ level its spin is 1, 2, or 3. The partial width for the decay $\Gamma_\gamma = 0.12$ ev can be compared to the Weisskopf limit for various possible spins and parities of 4.97-Mev level following the procedure of Wilkinson.[8] The results are given in Table I.

It follows from an examination of this table that if the 4.97-Mev level had $J=3-$, the 8.54-Mev $M2$ transition would be enhanced by a factor of 23. No such enhancement has ever been observed in any region of the periodic table[8] and there is no reason to expect that it will be. $J=1+$, $2+$, and $3+$ are all consistent with $|M|^2$ observed for light elements while $J=1-$ or $2-$ give a value of $|M|^2$ which is consistent with other $E1$ transitions in light nuclei which violate the isotopic spin selection rule.

Since this work was completed, a comprehensive series

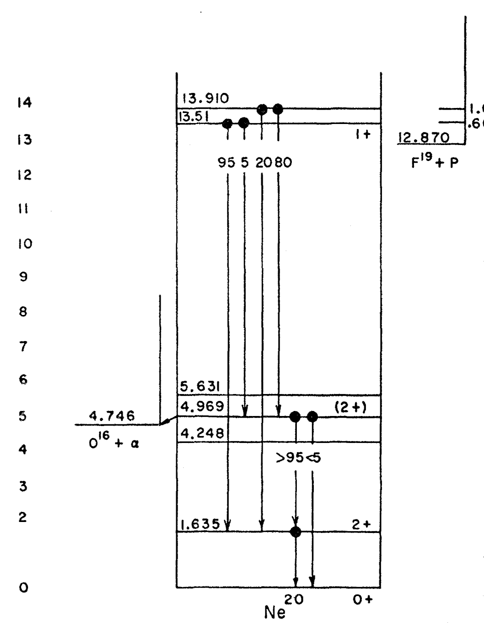


FIG. 6. Partial energy level diagram of Ne^{20} summarizing the information obtained in this experiment.

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of experiments designed to measure the properties of levels in Ne^{20} have been undertaken at Chalk River.[9] In particular the 4.97-Mev level has been found to have $J\pi=2-$.[10] The astrophysical significance of this and a recent measurement of $J\pi=3-$ for the 5.63-Mev level[11] has been discussed.[12] Sufficient information on levels in Ne^{20} now exists to reveal the existence of several rotational bands.[13]

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Capture of 14.4-Mev Neutrons by Protons and Deuterons

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A counter telescope in connection with a two-dimensional analyzer has been applied to determine the ratio of the 14.4-Mev neutron capture and elastic scattering cross sections. The cross section for the capture by protons was determined to be 31.6 ± 3.1 μb. This value is in reasonable agreement with the theoretically predicted value. The cross section for the capture of neutrons by deuterons was found to be 29.4 ± 5.8 μb.

THE photodisintegration of deuterons and tritons and their inverse processes are among the simplest nuclear reactions and the study of these reactions can give informations about the deuteron and triton wave functions, the final continuum states, and the interaction mechanism.

It has been shown by De Swart and Marshak[1,2] that a successful fit to the experimental data on photodisintegration of deuterons in the medium energy region can be obtained if one uses for the deuteron the Gartenhaus wave function (6.7% D-state probability) and for the final-state interaction the Signell-Marshak potential.[3] Around 10 Mev the $E1$ transition is dominant, $M1$ contributing only $\sim2\%$ and $E2\sim0.15\%$. In this energy region accurate measurements of the total cross section and of the anisotropy are desirable for better understanding of the magnetic transitions. Hsieh[4] pointed out that the measurement of the total cross section around 10 Mev can provide additional information about the sign of the tensor potential in the triplet odd states.

For the capture of neutrons by deuterons, Burhop and Massey[5] in 1947 calculated the cross section using the wave functions constructed by a resonating-group structure method. Their cross section depends sensitively upon the type of nuclear forces; at 11.47 Mev it amounts to 45.8 μb for ordinary forces, and to 30.7 μb for exchange forces.

Accurate measurements of the fast neutron capture cross sections by light nuclei have been made possible through the development of counter telescopes.[6–8] This method permits precise determination of the ratio of capture and elastic scattering cross sections, as in either process charged particles are detected at the same counter and target setting. Although the fast neutron capture cross sections are very small, due to kinematics all particles formed by capture are emitted within a forward cone of a small aperture and have a narrow energy distribution. The counter telescope[8] in connection with a two-dimensional 100-channel analyzer[9] allowed a good discrimination between protons, deuterons, and tritons above 3 Mev. As the capture cross section can be related to the photodisintegration cross section by assuming the validity of the principle of detailed balance, measurements of the capture of fast neutrons by protons and deuterons seemed to be of some interest.

14.4-Mev neutrons were supplied by a 200-kev Cockcroft-Walton accelerator.[10] The targets were a 1×1 cm, 6.1 mg cm^{-2} polyethylene foil and a 1×1 cm, 8.4 mg cm^{-2} heavy paraffin mold, respectively, each

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