Properties of the Excited States of Na^{22} from the $Ne^{21}(p,\gamma)$ Reaction*

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Proton capture resonances in Ne^{21} have been observed at 775 kev, 865 kev, 1010 kev, 1120 kev, 1215 kev, 1296 kev, and 1354 kev for proton bombarding energies ranging between 600 kev and 1500 kev. Pulse-height spectra of the resultant gamma radiation are presented for the two lowest resonances. At the 776-kev resonance the transitions are predominantly to the ground state, whereas the 865-kev resonance seems to decay mainly to the 2.25-Mev state. Arguments are presented showing that this is consistent with identifying this level as the second $T=1$, $J=2^+$ state in Na^{22}.

INTRODUCTION

SODIUM-22 is one of the least investigated members of a series of nuclei with $A=4n+2$. The energies of the first and second $T=1$ states are not well established. Recently Temmer and Heydenburg[1] have investigated the reactions $Ne^{20}(He^3,p)Na^{22}$ and $F^{19}(\alpha,n)Na^{22}$ and conclude that the first $T=1$ state is at 666 kev above the ground state. In support of this conclusion they cite that the systematics of the Coulomb energy differences calculated for mirror nuclei in this region of mass predicts a state at about this energy. But this procedure does not allow for the difference in symmetry properties of the protons in A and $A-1$ mass nuclei. Also if this were indeed the first $T=1$ state, the second $T=1$ state should be expected at about 2 Mev above the ground state. Browne and Cobb[2] have however reported convincing evidence for α-particle groups to both the 1.95- and 1.99-Mev states resulting in the $Mg^{24}(d,\alpha)Na^{22}$ reaction, a process that is not expected to lead to $T=1$ states. It is at the same time interesting to note that the α-particle group leading to the 2.25-Mev level in Na^{22} is very much less certain. The compound nucleus in the $Mg^{24}(d,\alpha)$ reaction is highly excited which leads one to expect rather strong T mixing in the resonance levels. Using this argument to excuse the appearance of $T=1$ states rather than expect them one may conjecture that the 2.25-Mev state is the second $T=1$ state. This would require the first $T=1$ state at approximately 940 kev, considerably higher than proposed by Temmer and Heydenburg. Assuming a uniform charge distribution inside the nucleus a $T=1$ state at about this energy is predicted if one uses a nuclear radius $R=1.43\ A^{\frac{1}{3}}\times10^{-13}$ cm. In the present paper we are concerned with testing this hypothesis by investigating the γ-ray spectra resulting from the proton capture reaction in Ne^{21}.

EXPERIMENTAL PROCEDURE

The Ne^{21} targets, used in this experiment, were prepared[3] by absorbing the neon gas onto a suitable metallic backing after the three stable isotopes had been mass spectroscopically separated. The precise isotopic abundance of the Ne^{21} could not be obtained from the Harwell laboratory. Experience indicated however that considerable overlap exists between the mass 21 and mass 22 beams since all of the resonances resulting from the $Ne^{22}(p,\gamma)$ reaction[4] were observed in the range of proton energies investigated.

The gamma rays were detected with a 3 in. diameter, $2\frac{3}{4}$ in. thick NaI crystal which was mounted on a Dumont 6263 Photomultiplier tube. Because of the low cross section of the reaction the counter was placed within a few millimeters from the target allowing the crystal to subtend a solid angle of over π steradians. The pulses were amplified and analyzed on a RCL 256-channel pulse-height analyzer. Simultaneously the total number of gamma rays of energy greater than 3 Mev were recorded on a conventional scaler.

A systematic search was made for resonances resulting from the $Ne^{21}(p,\gamma)$ reaction for proton bombarding energies ranging between 600 kev and 1.5 Mev. To minimize target deterioration, the beam current was restricted to 0.5 microampere. This interval was covered in approximately 5-kev steps except at those regions at which a resonance structure was apparent. Observations were then repeated and the pulse-height spectra observed. A genuine Ne^{21} resonance could, in this way, be readily distinguished from resonances resulting from contaminants. The most prominent resonances were analyzed by comparing the distributions with standard pulse profiles from the 9.18-Mev gamma ray from the $C^{13}(p,\gamma)$ reaction, the 6.14-Mev gamma ray from the $F^{19}(p,\alpha\gamma)$ reaction, the 4.43-Mev gamma ray from the $B^{11}(p,\gamma)$ reaction and the 1.37-, 1.63-, and 2.76-Mev gamma rays from the $Na^{23}(p,\alpha)$ and $Na^{23}(p,\gamma)$ reactions.

EXPERIMENTAL RESULTS

In the range of energies investigated a number of resonances could positively be associated with the $Ne^{21}(p,\gamma)$ reaction. They occur at proton energies of 775 kev, 865 kev, 1010 kev, 1120 kev, 1215 kev, 1296 kev, and 1354 kev. Of these only one resonance, reported

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[1] G. M. Temmer and N. P. Heydenburg, Phys. Rev. **111**, 1303 (1958).

[2] C. P. Browne and W. C. Cobb, Phys. Rev. **99**, 644(A) (1955).

[3] The targets were supplied by the Atomic Energy Research Establishment, Harwell, England.

[4] J. J. Singh, V. W. Davis, and R. W. Krone, Phys. Rev. **115**, 170 (1959).

by Brostrom *et al.*[5] at 765 kev, had previously been observed. This resonance is well isolated and has an experimental width of about 6 kev. The 865 kev resonance is partially masked by the Ne^{22} resonance at 859 kev and the close-lying strong F^{19} resonance at 876 kev. Its experimental width is less than 2 kev. The higher energy resonances are less intense and are masked by a continuum of gamma rays resulting from target contaminations. Figure 1 shows the resonance structure up to approximately 1 Mev. With the few targets available it seemed uneconomical to make a careful study of the entire excitation function. A detailed investigation of the resonances above 1 Mev was therefore not attempted.

The pulse-height distributions of the 776-kev and 865-kev resonances were examined in detail. Figure 2 shows the results for the 776-kev resonance. Experimental distributions observed both on and off resonance are indicated. The resultant genuine spectrum is shown by the solid line. An extensive investigation of the nature of the background radiation was carried out to justify this method of background subtraction. With the actual target in place, pulse-height distributions were examined at proton energies ranging between 700 kev and 900 kev. These distributions indicated a constant background of γ rays below 3 Mev and an energy dependent background of γ rays above 3 Mev, the latter notably due to F^{19} contamination. At 859 kev there is some indication of approximately 9-Mev γ radiation which is evidently the result of the Ne^{22} resonance at this energy. This same resonance gives also rise to a 2.7-Mev γ ray; its contribution to the background spectrum is however percentage-wise so small that no energy dependence can be detected. Three low-energy γ rays are observed: a relatively intense 1.43-Mev γ ray and weaker γ rays at 2.15 Mev and 2.6 Mev. Measurements indicate that this radiation is present in the laboratory background and therefore independent of bombarding energy.

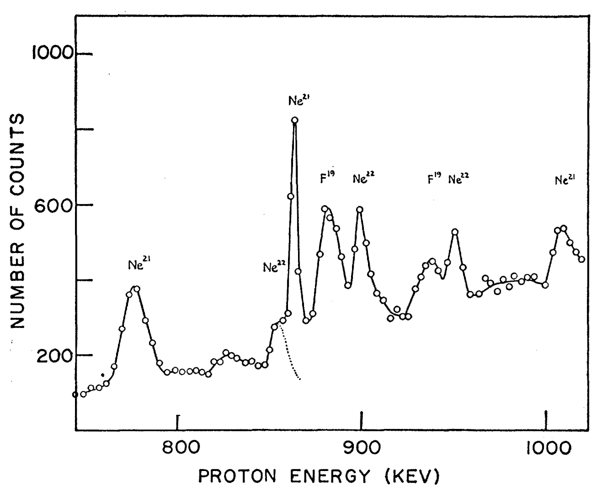

FIG. 1. Excitation curve for $Ne^{21}(p,\gamma)$ for $E_p=750$ kev to 1020 kev.

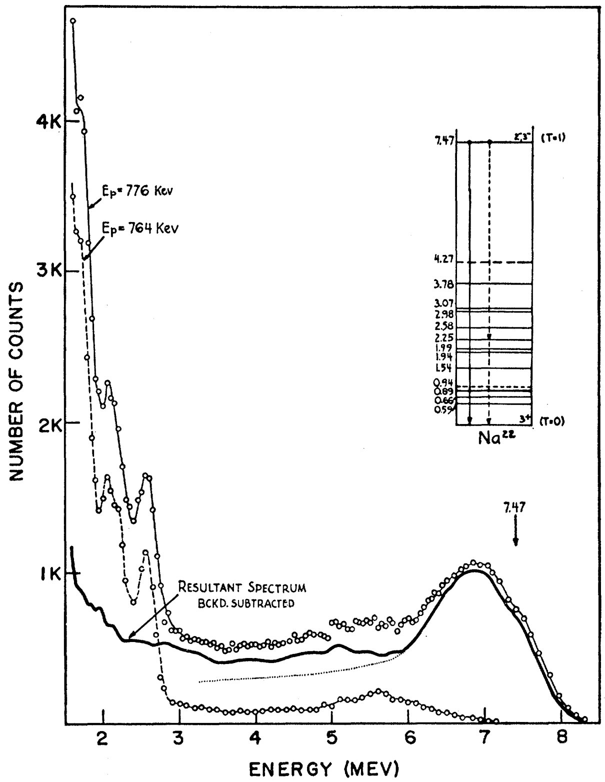

FIG. 2. Pulse-height distribution observed at the 776-kev resonance. Plotted are the results obtained both for $E_p=776$ kev and $E_p=764$ kev. The resultant genuine spectrum is indicated by the heavy line.

The predominant mode of decay of the 776-kev resonance level is to the ground state, although weak secondary cascades cannot be entirely ruled out. The strong background γ rays of 2.15 Mev and 2.60 Mev mask the low-energy spectrum to such an extent, to make it difficult to assign secondary decays with certainty. A very different spectrum is observed for the 865-kev resonance. Figure 3 shows the pulse-height distributions for both the high-energy γ rays (with the off resonance contribution at 859 kev already subtracted) and the low-energy γ rays for which the on and off resonance distributions have been included. The analysis of the high-energy spectrum is indicated by the dotted and dashed curves. The background contributions resulting from the 873-kev F^{19} resonance is sufficiently smaller at 859 kev than at 865 kev to account for the 6.14-Mev component in the subtracted spectrum. It should be emphasized that the structure above 5.5 Mev cannot be accounted for by the emission of high-energy gamma rays leading to the low lying states in Na^{22} (notably the 0.89-Mev state). The most intense gamma rays observed have energies of 5.3 Mev and 4.5 Mev. They fit well into the known level scheme for Na^{22} accounting for transitions through the 2.25-

[5] K. J. Broström, T. Huus, and J. Koch, Nature **160**, 498 (1947).

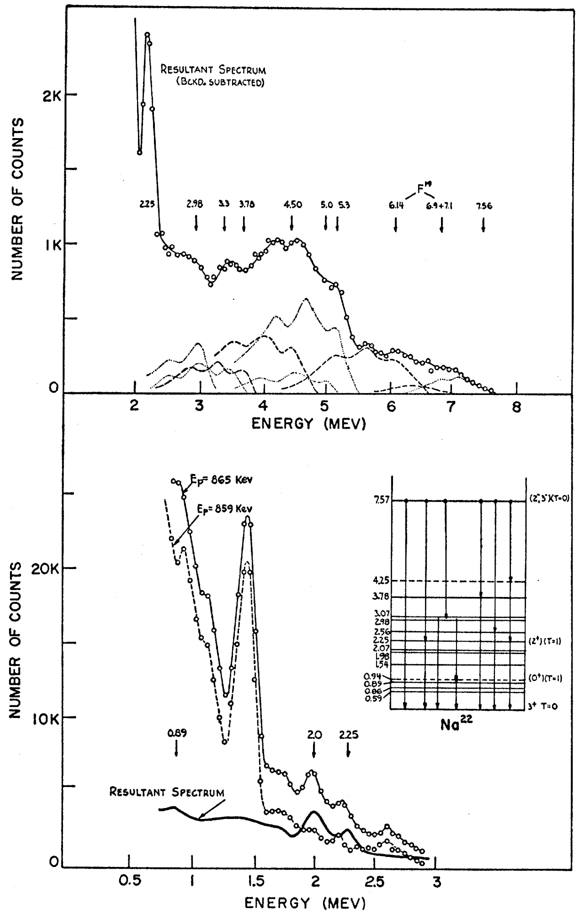

FIG. 3. Pulse-height distribution observed at the 865-kev resonance. The diagram on top gives the resultant spectrum above 2.75 Mev and shows its decomposition into various gamma rays. The bottom diagram shows in detail the low-energy spectrum observed at this resonance.

Mev and either one or both of the 2.98-Mev and 3.07-Mev states. Aside from this the spectrum is complex. Weak alternate cascades may however be identified. One of these confirms the existence of a state at 3.78 Mev, the other requires a 4.25-Mev state not previously reported. It is of interest to note that the three step cascade through such a 4.25-Mev state would account for the fact that the 2.25-Mev and 2-Mev gamma rays are more intense than their respective feeder gamma rays. A $T=1$ state at about this energy would be expected if the 2.25-Mev level were the $T=1$, $J=2^+$ analog of the 1.28-Mev state in Ne^{22}. The alternate cascade going from such a 4.25-Mev state to either the 1.98-Mev or 2.07-Mev states, and from there to the ground state can of course not be ruled out. Such a mode of decay, if it were very prominent, would indeed lend support to the contention that the second $T=1$ state is located at approximately 2 Mev. The low intensity of this cascade (less than 10%) and the fact that an intense transition is observed to the 2.25-Mev state rather than either the 1.98-Mev or 2.07-Mev states suggest however that this assignment is unlikely.

DISCUSSION

The most notable feature of the two pulse-height distributions is the marked difference by which the two resonance levels decay. The 776-kev resonance decays almost entirely to the ground state, whereas the 865-kev resonance shows very weak transitions to any of the states below 2.25 Mev. This indicates that angular momentum selection rules alone are not sufficient to explain these results as one would expect that at least one of the low lying states would have a spin and parity that would permit favorable competition with the observed modes of decay. One is therefore led to believe that isotopic spin selection rules are operative in this instance.

Coupled with the observation by Browne, *et al.* that the α-particle group to the 2.25-Mev state in the $Mg^{24}(d,\alpha)Na^{22}$ reaction is the most questionable, one is tempted to assume that this is the $T=1$, $J=2^+$, state in Na^{22}. The preferential decay to this state may then be accounted for by assuming that the transition is $E1$ which in turn would require the 865-kev resonance level to be $T=0$, $J=1$, 2, 3. The absence of a decay to the $T=1$, $J=0^+$ state can be understood if one restricts the J value of the compound state to 2^- or 3^- as this would require either $M2$ or $E3$ radiation to a 0^+ state.

The predominant groundstate transition from the 776-kev resonance can be made consistent by assigning to this resonance level $T=1$ and $J=2^-$, 3^-. This would make the 7.47-Mev gamma radiation $E1$, forbidding at the same time a transition to the 2.25-Mev state by $E1$ radiation. From this discussion it is clear that these two resonance levels may have the same spin and parity but a different value of isotopic spin. One would therefore expect some isotopic spin mixing as a result of the Coulomb interaction.[6] In view of the small experimental width of either resonance one can estimate the expected isotopic spin impurity in each state to be about six or seven percent. This is not inconsistent with the observed intensity ratio of the transitions to the ground state and the 2.25-Mev state at the two resonances.

The well known state at 890 kev cannot be identified with the postulated 940-kev state because it is known to decay exclusively to the 3^+ ground state. A 940-kev $T=1$, $J=0^+$ state would be expected to decay to either the 593-kev or the 666-kev state, if its spin is less than 3. It is however disturbing that such a 940-kev level has not been observed in $Na^{23}(d,t)Na^{22}$ reaction[7] for which transitions to $T=1$ states are not forbidden.[8]

[6] D. H. Wilkinson, *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North-Holland Publishing Company, Amsterdam, 1958), p. 175.

[7] W. F. Vogelsang and J. N. McGruer, Phys. Rev. **109**, 1163 (1958).

[8] Neither does this reaction show any evidence of the 666-kev state reported by Temmer and Heydenburg.