Radiative Capture of Protons by F^{19} at a Bombarding Energy of 669 kev*

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The ground-state transition from the 13.51-Mev state of Ne^{20} formed by bombarding fluorine with protons of 669 kev is anomalously weak. This is interesting because the 13.51-Mev state has a large reduced width for proton emission to the ground state of F^{19} and a large $M1$ width for radiation to the first excited (1.63-Mev) state of Ne^{20}. A simple explanation would be that the ground state of Ne^{20} is close to $(2s_{\frac{1}{2}})^4$. The ground-state radiation is sought and found using a 3-in.×3-in. NaI(Tl) crystal. The radiative width is approximately 1.0×10^{-2} ev corresponding to $|M|^2\sim2\times10^{-4}$. The 13.51-Mev state is found also to radiate to the 4.97-Mev state with a width of approximately 0.24 ev. The 4.97-Mev state itself chiefly cascades via the first excited state: An upper limit on the relative strength of the ground-state transition is 0.07.

INTRODUCTION

THE radiative capture of protons by fluorine has been the subject of several investigations[1] and has been established at 10 resonances. A curious feature of the results is that in no case has capture to the ground state of Ne^{20} been established; the 2+ first excited state of Ne^{20} at 1.63 Mev is found to be favored wherever adequate study of the spectrum has been made. In only two of the cases where the spectrum has been determined, the resonances at $E_p=669$ and 1420 kev (states of Ne^{20} at 13.51 and 14.22 Mev), are the spin and parity of the capturing state known: 1+ for both states. For the state at 13.51 Mev the ground-state capture is not greater than 1% of that to the 1.63-Mev state,[2] while for the state at 14.22 Mev the corresponding limit is probably about 5%.[3] This shunning of the ground state is interesting and is clearly of importance for discussions of the structure of that state; in particular, a very simple explanation within the independent-particle model framework would be given[2] if the spectroscopic configuration were $(2s_{\frac{1}{2}})^4$ which is inaccessible to pure $M1$ transitions. So simple a configuration at $A=20$ is not to be expected in view of results such as those of Elliott and Flowers[4] on configuration mixing in $A=18$ and 19, but it is possible that the potential closing of the $2s_{\frac{1}{2}}$ shell at Ne^{20} purifies the wave function through action such as that of the pairing forces. It is therefore of interest to see to what degree the ground state of Ne^{20} can, in fact, be reached through pure $M1$ transitions. We have carried out such an investigation and have concentrated our attentions on the proton resonance at 669 kev, since that is the best studied so far.

A subsidiary reason for interest in this investigation is the possible importance of such $M1$ transitions for the balance of nuclear species in certain types of star. Ne^{20} may be built up through the reaction of $O^{16}(\alpha,\gamma)Ne^{20}$. Its subsequent fate is decided by, among other things, its photodisintegration which, if sufficiently strong, can inhibit further build-up. Photon capture into a 1+ state cannot directly lead to alpha-particle breakup to the ground state of O^{16}, but it can do so indirectly following a gamma-ray transition to a state of type $J(-)^J$. Thus, states which cannot contribute to the synthesis of Ne^{20} may be important for its destruction if $M1$ transitions involving the ground state are possible.

The 13.51-Mev state of Ne^{20} is probably fairly simply related to certain low-lying states of F^{19} and Ne^{20} as is evidenced by its large reduced width for s-wave proton emission to the ground state of F^{19} (10% of a single-particle unit[5]) and its large $M1$ radiative width to the 1.63-Mev state of Ne^{20} (6.5% of a single-particle unit). Its radiative properties towards other low-lying states of Ne^{20} are therefore likely to be useful in discussing the structure of those states and have been sought in this investigation insofar as they lead to gamma-ray cascades.

GROUND-STATE TRANSITION

The search for the 13.51-Mev ground-state transition is clearly a delicate matter, since it is alraedy known to be no more than 1% of the 11.88-Mev first excited state transition whose own strength is only 2% of that of the combined 6- and 7-Mev radiations from the 6.14-, 6.92-, and 7.12-Mev states of O^{16} which are populated by $F^{19}(p,\alpha)O^{16}$. The search was made directly using a 3-in.×3-in. NaI(Tl) crystal. The crystal was placed 12 in. away from a target of BaF_2 of thickness approximately 40 kev for protons of 700 kev (the width of the state is 7 kev). The crystal was at 90° to the proton beam of 1–5 μa. The resonance is known to be predominantly s-wave in formation so no care was necessary over angular distributions.

The low-energy region of the spectrum found at a proton energy of 690 kev is shown in Fig. 1 and suffices to indicate the resolution of the crystal.[6] The attribu-

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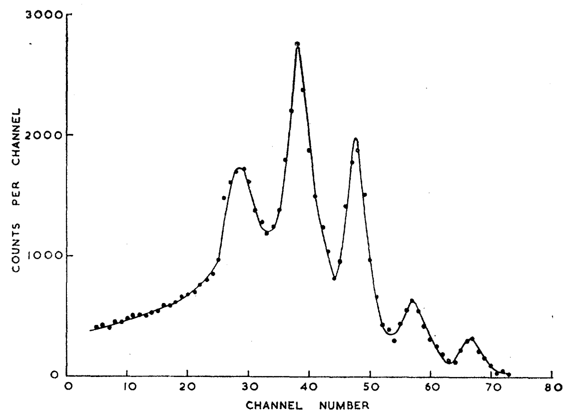

FIG. 1. Gamma-ray spectrum observed in 3-in.×3-in. NaI(Tl) crystal at a proton bombarding energy of 690 kev. These peaks are due to the gamma rays from states in O^{16} at 6.14 and 7.12 Mev excited in the ratio 4.4:1 in the reaction $F^{19}(p,\alpha)O^{16}$ (the excitation of the 6.91-Mev level is very weak). The peak at channel 28.5 is the 2-quantum escape peak of the 6.14 Mev gamma ray; that at channel 38 is the 1-quantum escape peak of the same radiation. The peak at channel 66.5 is the full energy peak of the 7.12-Mev gamma ray and that at channel 57 is the 1-quantum escape peak. The peak at channel 47.5 is the superposition of the full-energy peak of the 6.14-Mev gamma ray and the 2-quantum escape peak of the 7.12-Mev radiation.

tions of the peaks are given in the legend to the figure and their relative intensity accords well with the known relative populations[1] of the states of O^{16} in the reaction $F^{19}(p,\alpha)O^{16}$. The high-energy region of the spectrum is shown in Fig. 2. The three peaks due to the 11.88-Mev gamma-ray transition in the reaction $F^{19}(p,\gamma)Ne^{20}$ to the first excited state of Ne^{20} are well seen; their expected positions are indicated by the three arrows; the measured energy is 11.91±0.04 Mev. Above the exponentially falling tail due to this transition, there is a clear bump around channels 57 to 66 before the flattening off to the cosmic-ray background. The second set of arrows indicates the expected positions of the three peaks due to the possible 13.51-Mev ground-state transition; the bump is at the correct location to correspond to this transition. (The cosmic-ray background is an obvious nuisance in this work. It was militated against by surrounding the crystal as far as possible by a liquid-phosphor anticoincidence counter; this cut down the counts in the high channels by a factor of about 2.5 without affecting the counting rate due to the target.)

Several points must be checked before a result such as this can be accepted as establishing the transition being sought:

(i) Are the large pulses in the bump due to addition between the elements of the 11.88–1.63 Mev cascade?

(ii) Are they due to pile-up between 12 and 6–7 Mev gamma rays or between 6–7 and 6–7 Mev gamma rays?

(iii) Are they due to a multiplier defect which manufactures a small high-energy tail to the 11.88-Mev distribution?

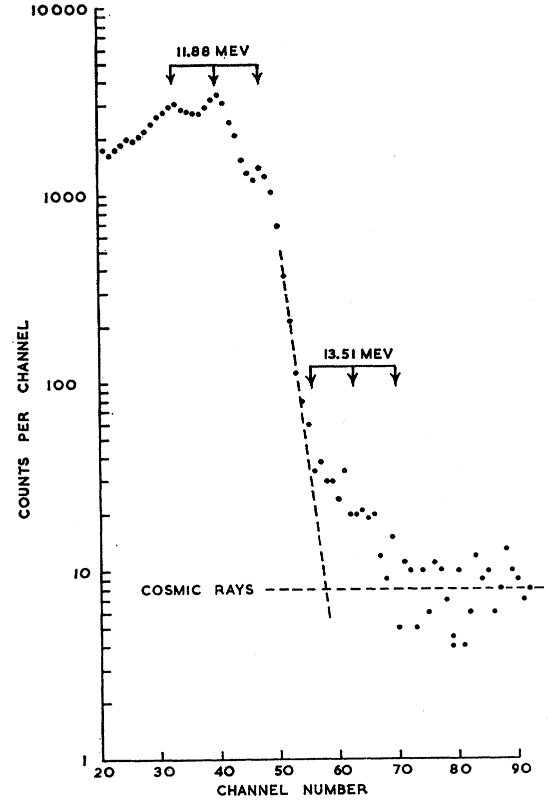

FIG. 2. The continuation to higher energy (without normalization) of the spectrum of Fig. 1 (note that the ordinate scale is now logarithmic). The two sets of three arrows show the expected positions of the two sets of three peaks for gamma rays of 11.88 Mev (transition between the 13.51- and 1.63-Mev states of Ne^{20} in $F^{19}(p,\gamma)Ne^{20}$) and 13.51 Mev (ground state transition from the 13.51-Mev level). The horizontal dashed line shows the separately determined cosmic-ray background. The slanting dashed line shows the exponential extrapolation of the pulses due to the 11.88-Mev gamma rays.

(iv) Even if the 13.5-Mev gamma rays are genuine, do they come from the 13.51-Mev state or may they be due to the tails of remote states or to nonresonant proton capture?

The first point is satisfactorily dealt with by computation: With the crystal so far from the target the addition pulses would be an order of magnitude less abundant than those observed. The second point was dealt with directly by repeating this experiment but with a greatly modified pulse form from the amplifier. Figure 3 shows the two pulse forms. That used for the results shown in Fig. 2 is square-topped and relatively prone to pile-up while that used for the check experiment is sharp-topped and will obviously have very much diminished propensities for pile-up. The two runs were made with the same target current to within 5%; they showed the same ratio of bump to 11.88-Mev pulses. The third point was checked by irradiating the crystal with gamma rays of similar energy to those investigated here unaccompanied by radiation of higher energy. These gamma rays were

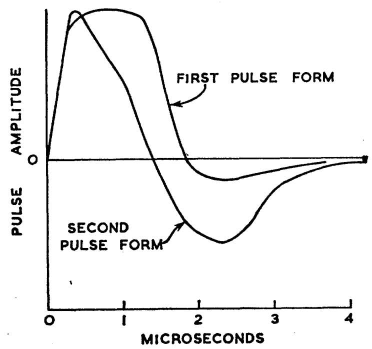

FIG. 3. The two pulse forms used to test for pile-up in the amplifier.

derived from the resonance in $N^{15}(p,\gamma)O^{16}$ at a proton energy of 1030 kev; this yields gamma rays of 13.09 Mev which, since they lead to the ground state of O^{16}, cannot be accompanied by a component of higher energy. It was arranged that the counting rate due to the O^{16} gamma rays of 13.1 Mev was roughly the same as that for the 11.9-Mev gamma rays of Ne^{20}. The results are shown in Fig. 4 where the exponential fall at high energy is seen to run directly into the cosmic-ray background without any suggestion of a bump such as is found in Fig. 2. The fourth point was checked by running off resonance—at a proton energy of about 770 kev. A contribution not due to the 669-kev resonance might be due either to nonresonant capture or to the tails of other resonances. The only states in the latter category that need to be considered are those[1] formed at proton energies of 650 and 710 kev of respective widths 200 and 35 kev. Both are of 1−. If the ground-state transition seen in Fig. 2 were due to the first of these states, we should expect approximately 1.4 times as much radiation at the proton energy of 770 kev as at 690 kev after allowance is made for the p-wave penetrability. The corresponding factor for the proton energy of 770 kev is about 2 as it also is for nonresonant capture. In fact, some slight ground-state capture was found at 770 kev. This is illustrated in Fig. 5 where the distributions found at proton energies of 690 and 770 kev are compared for approximately the same proton charge on the target. On this figure the cosmic-ray backgrounds have been subtracted and also the exponential extrapolation of the tails due to the lower energy radiations.

When allowance is made for the yield at 770 kev, we find that the ground-state transition from the 13.51-Mev state has an intensity of 0.0044 ± 0.0015 relative to the transition to the first excited state. The error in this figure covers the uncertainty in the correction of the yield at 770 kev to that expected from the same source at 690 kev. The measured energy of the transition is 13.4 ± 0.3 Mev.

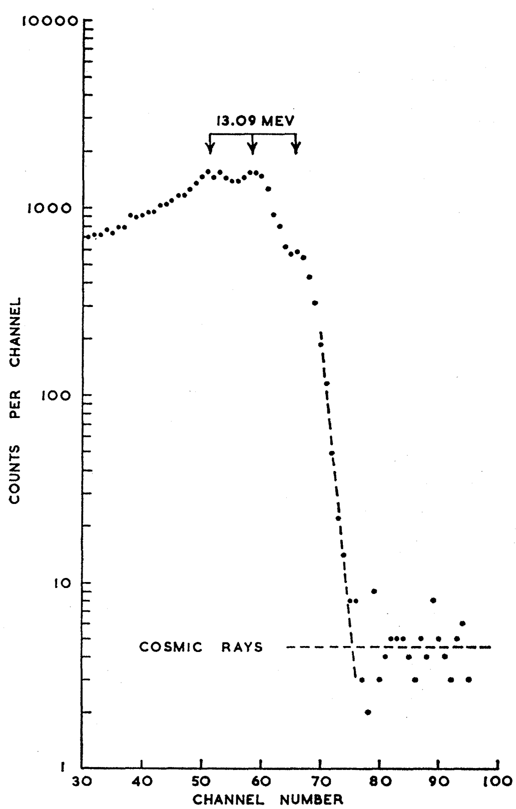

FIG. 4. The 13.09-Mev gamma rays from the reaction $N^{15}(p,\gamma)O^{16}$ at a proton bombarding energy of 1.03 Mev observed under the same conditions as Fig. 2. There is now no excess of pulses between the exponential tail and the cosmic-ray background.

GAMMA-RAY CASCADES

To seek gamma-ray cascades, we placed a large NaI(Tl) crystal (5-in. right cylinder) close up to the target at 90° to the proton beam and the smaller crystal

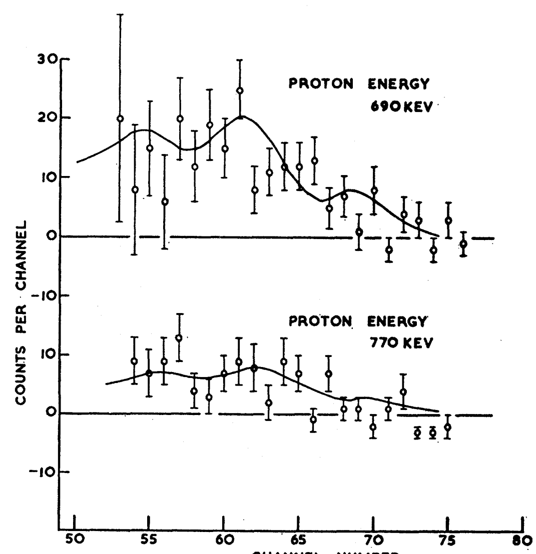

FIG. 5. Spectra due to the ground-state transitions in $F^{19}(p,\gamma)Ne^{20}$ at proton bombarding energies of 690 kev and 770 kev. Corrections have been made for the contribution from gamma rays of lower energy and for the effect of cosmic rays. The full lines show the expected distributions. These two sets of data represent approximately the same number of protons incident on the target.

used for the earlier investigation at 90° on the other side of the target and with its front face 3-in. away. A proton current of about 0.5 μa was used. The coincidences were displayed using a 2000-channel (32×64) analyzer constructed at Brookhaven National Laboratory under the direction of Mr. R. Chase.

It was immediately apparent that a cascade indeed takes place via the level at 4.97 Mev which itself decays predominantly via the first excited state. This is seen in Fig. 6 where we display the pulse distribution seen in the smaller crystal in coincidence with pulses from the larger crystal in the energy range 7.8 to 9.2 Mev (the expected energy of the first element of this cascade is 8.54 Mev. As well as the very intense line at 1.63 Mev due to the chief cascade from the 13.51-Mev level, we see clearly the three peaks of a line whose energy is found to be 3.36±0.03 Mev. This is to be compared with the 3.337±0.007 Mev expected for a transition between the 4.97- and 1.63-Mev states.[1]

That the cascade is a triple one was confirmed by examining the spectrum of high-energy pulses in the larger crystal in coincidence with the two peak channels 30 and 31 of Fig. 6. This is shown in Fig. 7. The peak in channel 3 is due to the 6-Mev gamma rays from O^{16} seen in random coincidence. The arrows show the expected positions for the peaks of gamma rays of 8.54 Mev (corresponding to the triple cascade) and 10.15 Mev (corresponding to the other member of a double cascade involving an unknown state at 10.15 Mev or an unknown state at 3.36 Mev). We conclude that the coincident gamma ray is of 8.5 Mev (measured energy 8.60±0.15 Mev) and that the triple cascade is established. The same conclusion is found in unpublished work of the Chalk River group.[7]

The question of the possible ground-state transition of the 4.97-Mev state arises. Return to Fig. 6. The pulses in channels 50–63 are due to the 6-Mev gamma rays from O^{16} seen in chance coincidence. The line drawn in this region represents their expected distribution. It is seen that there is a significant excess of pulses in the region of channels 35–50. The positions of the three peaks due to the possible line of 4.97 Mev are indicated. If all excess pulses in this region were interpreted as due to the ground-state transition, the corresponding intensities of the ground state relative to the cascade transition would be 0.07±0.03. (The effects of addition between the 3.34- and 1.63-Mev lines are negligible.) However, the observed pulses do not represent the expected form of the distribution at all well and the dirt effects of the setup are not well enough investigated for us to do more than regard this figure as an upper limit on the possible strength of the cross-over.

The relative strength of the triple cascade is estimated by comparing the results shown in Fig. 6 with those of Fig. 8 where the spectrum seen in the smaller crystal in

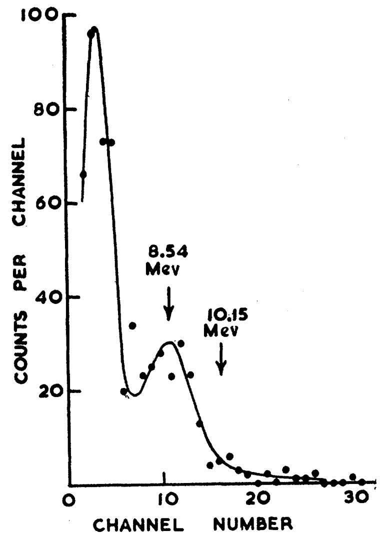

FIG. 7. Gamma-ray spectrum seen in coincidence with channels 30 and 31 of Fig. 6.

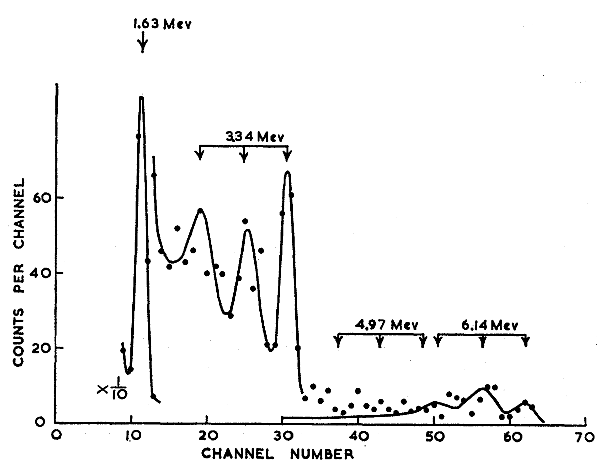

FIG. 6. Gamma-ray spectrum seen in coincidence with the gamma-ray energy range 7.8 to 9.2 Mev.

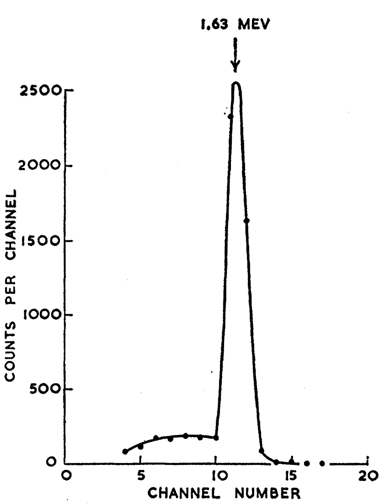

FIG. 8. Gamma-ray spectrum seen in coincidence with the gamma-ray energy range 10.1 to 13.0 Mev.

[7] H. E. Gove, A. E. Litherland, and A. J. Ferguson, Bull. Am. Phys. Soc. 3, 36 (1958).

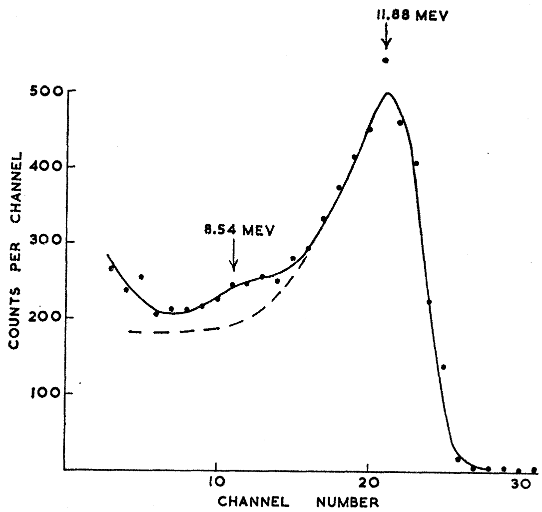

FIG. 9. Gamma-ray spectrum seen in coincidence with the photopeak of the 1.63-Mev gamma ray.

coincidence with pulses of 10.1 to 13.0 Mev in the larger crystal is displayed. It is the pure 1.63-Mev line as expected. The result is that the intensity of the 8.54-Mev transition to the 4.97-Mev state is 0.11 ± 0.03 of the intensity of the 11.88-Mev transition to the 1.63-Mev state.

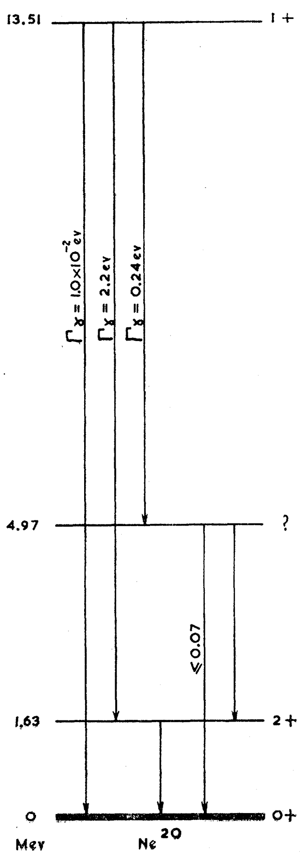

FIG. 10. Decay schemes of the levels of Ne^{20} of concern in this investigation.

As a check on this we show in Fig. 9 the pulse distribution in the larger crystal (whose resolution was not very good) in coincidence with the photopeak of the 1.63-Mev line (channels 11 and 12 only of Figs. 6 and 8). The 11.88-Mev line (measured energy 11.9 ± 0.1 Mev) is found (together with some 6-Mev radiation at low channel numbers in chance coincidence). The dashed line indicates the expected form of the 11.88-Mev spectrum and a clear excess of events around channel 11, the expected position of an 8.54-Mev line (see Fig. 7), is seen. The form and magnitude of this excess are consistent with a branch of relative intensity about 10% although uncertainty in the dashed extrapolation prevents an accurate figure being quoted from these results.

DISCUSSION

If we use the earlier figure of 2.2 ev as the radiative width of the transition to the 1.63-Mev state,[1] we find 1.0×10^{-2} ev for the radiative width of the ground-state transition and 0.24 ev for that to the 4.97-Mev state.

The conclusions are summarized in Fig. 10 and Table I.

The ground-state transition has a strength of $|M|^2 = 1.9\times10^{-4}$ single-particle units[8] which is very small. The first excited state transition has $|M|^2=0.065$ and is of "normal" strength.[9] The comparison between these two $M1$ transitions from the same state shows that we cannot understand the weakness of the ground-state transition in terms of an inhibition due to the isotopic spin of the 13.51-Mev state.[10] We are thrown back on some special explanation which must be to do with the configuration of the ground state. (Note that although both $M1$ and $E2$ radiations are possible to the first excited state it is known that in fact the bulk of the radiation is $M1$.[2]) It will be of considerable interest to extend these observations to other 1+ levels.

TABLE I. Measured gamma-ray energies in the reaction $F^{19}(p,\gamma)Ne^{20}$.

States (Mev)	Transition energy (Mev)
$13.51 \rightarrow 0$	13.4 ± 0.3
$13.51 \rightarrow 1.63$	11.91 ± 0.04
$13.51 \rightarrow 4.97$	8.60 ± 0.15
$4.97 \rightarrow 1.63$	3.36 ± 0.03

The $|M|^2$ values for the 8.54-Mev radiation to the 4.97-Mev state are 7.6×10^{-4}, 1.8×10^{-2}, or 2.0 for $E1$, $M1$, or $E2$ transitions, respectively. Any of these is possible. The large logft value (>6.5) of the beta decay from F^{20} to this state[11] is another clue to its possible

[8] V. F. Weisskopf, Phys. Rev. **83**, 1073 (1951).
[9] D. H. Wilkinson, in *Proceedings of the Rehovoth Conference on Nuclear Structure*, edited by H. J. Lipkin (North Holland Publishing Company, Amsterdam, 1958), p. 175.
[10] G. Morpurgo, Phys. Rev. **110**, 721 (1958).
[11] R. W. Kavanagh, Bull. Am. Phys. Soc. **3**, 316 (1958).

characteristics but the spin of F^{20} is not yet sure ($J=2$ or 3) although the parity is established to be even, as expected.[1] However, the observation[7] that $J\neq 0$ for the 4.97-Mev state taken together with this large $\log ft$ value suggests it has odd parity, or if even parity, then $J=1$. The relative weakness of the ground-state transition argues, though not powerfully, against $J=1$. It would clearly be of considerable value to improve our knowledge both of the ground-state transition from this state and also of the F^{20} beta decay.

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Extension of the Shell Model for Heavy Spherical Nuclei

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The Bardeen-Bogoliubov-Belyaev treatment of the pairing correlations is applied to spherical nuclei with a general nuclear force. The interaction between quasi-particles is treated by the method of linearized equations of motion. An advantage of this treatment is that the same equations describe single-particle excitations and collective excitations, so that the former are orthogonal to the latter and the total number of states is correct. Another advantage is that the spurious states due to the fluctuations in the number of particles are automatically eliminated. The equations to be solved resemble those for a two-body shell model calculation. Simple estimates, based on delta-function or quadrupole forces, are made for the vibrational frequencies in various modes and transition matrix elements. It is concluded that the method is as powerful as other known methods for dealing with collective states by the shell model, and that the same order of magnitude for the effective nuclear force seems capable of fitting all the data.

1. INTRODUCTION

THE past two years have seen some important developments in the theory of nuclear structure. The recent success in the theory of superconductivity[1] stimulated the application of the same ideas to nuclear physics.[2–5] According to the new point of view, the pairing correlations and the energy gap must play a fundamental role in our understanding of many nuclear properties. Belyaev[6] has discussed the influence of pairing correlations on the collective behavior of nuclei; and Kisslinger and Sorensen[7] have obtained good agreement with many detailed properties of single-closed-shell spherical nuclei, by using a simple interaction composed of a pairing force and a quadrupole force and treating it by the new methods. In a different line of research, there has been increasing success in accounting for collective effects starting from the ideas of the shell model. Here, we mention the work of Brown and Bolsterli[8] who showed that the location of the giant photoresonance could be explained by taking into account particle-hole interactions.

The present work represents another extension of these ideas. The aim is to develop an approximation suitable for calculating the properties of all low-lying levels of heavy spherical even-even nuclei, starting from a general shell-model Hamiltonian. To do this, we first perform the Bogoliubov-Valatin transformation[9] on the Hamiltonian (Sec. 2). The result can be interpreted in terms of a Hamiltonian of "quasi-particles" and an interaction between these quasi-particles. It is the existence of a gap in the spectrum of quasi-particles which restricts the low excited levels to two quasi-particles and makes possible a simple shell-model type of calculation. This is not quite true, however, because a few levels containing many quasi-particles may be brought down by collective effects. Fortunately, there is a well-known method which was devised to deal with this difficulty in other many-body problems, the method of linearized equations of motion. We use it (Sec. 3), and the resulting equations apply equally well to collective states and to noncollective states of two quasi-particles. This is a great advantage, as in the past one has had to treat the two kinds of states by different methods, with the result that one ended up with too many states and that often they were not mutually orthogonal. Also, one can now treat states which are only weakly collective, and for which the standard methods of dealing with collective states are not valid. Finally, we shall see that the spurious states due to the

[1] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957), referred to in the following as BCS.
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