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GAMMA RADIATION FROM EXCITED STATES OF LIGHT NUCLEI

$({}_1{}^9F + \alpha, {}_0{}^8O + p, {}_0{}^6He + {}_2{}^8He, \text{ and } {}_1{}^9F + d)$

by

THOMAS A. RABSON

A THESIS

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DOCTOR OF PHILOSOPHY

Approved T. W. Bonner

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April, 1959
CONTENTS

I. Introduction ................................................................. 1

II. Description of the Apparatus ........................................... 3
    Pair spectrometer ...................................................... 3
    Photo-conversion spectrometer .................................... 7
    Internal conversion spectrometer .................................. 9

III. Gamma Radiation From $^{18}$F ...................................... 11

IV. Gamma Radiation From $^{19}$F + a .................................. 17

V. Gamma Radiation From $^{19}$F + d .................................. 22

VI. References ................................................................. 27

VII. Acknowledgements ...................................................... 30
1. Introduction

In order to gain a better understanding of the nuclear structure and the character of nuclear forces it is necessary to gain knowledge of the properties of the excited states of nuclei, such as the angular momentum, parity, and energy of excitation. Information about these excited states of nuclei can be obtained by a number of different methods. The work described in this thesis is an attempt to gain information of this type through the measurement of the energy, intensity, and internal conversion coefficients of the gamma radiation emitted by nuclei.

The nuclei were excited by charged particle bombardment from a 6 Mev Van de Graaff accelerator. The measurement of the gamma radiation was primarily done by means of an intermediate image magnetic lens spectrometer. The use of this spectrometer for such work will be described below.

By measuring the intensity of gamma radiation one is able to obtain branching ratios between different modes of de-excitation and hence make comparisons with theoretical values predicted by different nuclear models. Internal conversion coefficients when compared with theoretical values, give good indications of the multipolarity of the radiation involved and hence of the spins and parities of the excited states involved. Accurate energy measurements are useful in identifying the energy of excitation of the states and, if charged particle data is available, what two states are involved in the transition. The energy of a gamma ray measured in the lab will not always correspond to the energy difference between two states in a nucleus, however; if the radiation occurs while the radiating nucleus is
still in motion a Doppler shift may occur. If such a Doppler shift can be detected this gives an indication of the lifetime of the radiating nucleus. A complete discussion of this effect and how its magnitude may be estimated has been given by Sipple, Bent, and McCrary.
II. Description of the Apparatus

The intermediate image magnetic lens spectrometer employed in this work has been described previously in its capacity as a pair spectrometer\(^4\) and as a photo-conversion and internal conversion spectrometer\(^5\). (A diagram of the spectrometer is shown in Figure 1.) Numerous changes have been effected in the last two years in an effort to improve the range and effectiveness of this spectrometer in detecting and measuring the energy of gamma rays. In order to describe the changes made and to give some indication of their significance, a brief description of each method of spectroscopy for which the spectrometer is useful will be given, its advantages and limitations stated, and finally a description of the changes that have been made in the spectrometer in order to overcome some of the limitations will be given.

Pair spectrometer

At energies above 1 Mev there are three ways in which a nucleus in an excited state may de-excite and produce an electron-positron pair. One method is by pair internal conversion. The absolute probability of internal pair formation is greatest for large excitation energy, for small \(Z_p\) and for small \(I\).

Nuclear pairs are produced in the case of a transition between two states of 0 angular momentum and the same parity. Because gamma radiation cannot compete with this reaction it is a very strong effect when it occurs alone; however, there are only a few known instances of 0 \(\rightarrow\) 0 transitions. These generally occur when the ground state and first excited state are both 0.
Figure 1: Diagram of intermediate image magnetic lens spectrometer.

SPECTROMETER

Fig. 1
The third type of de-excitation which may result in pair production is the emission of a high energy gamma ray and the conversion of this quantum to an electron-positron pair in the field of some nucleus other than the one which emitted the gamma ray.

All of these effects can be utilized in the observation of gamma rays by the spectrometer under discussion. The latter process is useful in case there is a large background due to B particles. Then some absorber of high density and low Z₀ such as diamond, is placed between the target and the external converter to absorb the B particles. Since the pair production cross section goes as Z²₀ a high Z converter is advantageous. The background may also be reduced by pulsing the incident beam and allowing the B activity to decay while the beam and counters are turned off.

The method in which the spectrometer used in the present work detects electron-positron pairs produced by any of the above mentioned methods is as follows:

Both the electron and positron members of the pair are transmitted and focused by the spectrometer, only when each has approximately half of the total kinetic energy available and the spectrometer current has been adjusted to pass an electron of such an energy. The manner in which the electron and positron are focused and resolved is identical to that in a conventional intermediate image B spectrometer. However, the electrons and positrons will spiral in opposite directions when moving through the spectrometer. Upon being focused at the exit end of the spectrometer they are detected by two scintillation counters with semi-circular plastic scintillating elements on the ends of 16" lucite light-pipes. In 50 per cent of the cases the electron and positron will be stopped in
different scintillating elements giving two pulses in coincidence from the detectors. The coincidence circuit is based on a design by Fisher and Marshall\textsuperscript{6} utilizing a 6BN6 gated-beam tube.

The magnetic field of the spectrometer is proportional to the current since it is free of magnetic materials; therefore, by measuring the current necessary to focus an electron of known momentum one can calibrate the spectrometer. The maximum energy of gamma radiation that it is possible to detect by this method is set by the current carrying capacity of the coils of the magnet and the current producing capacity of the motor-generator set supplying the current. This limit is about 600 amps which is sufficient to focus 6.5 Mev electrons or positrons. This corresponds to pairs from a gamma ray of 14 Mev. The lower limit is set by the fact that at lower energies the external pair production cross section decreases logarithmically with energy\textsuperscript{7} and the amplitude of the input pulses to the coincidence circuit becomes quite small. At present the lower limit corresponds to 2.8 Mev gamma radiation.

In order to decrease the background relative to the true counting rate and increase the range of the spectrometer several changes were made. To increase the pulse amplitude of the detectors and decrease their rise time, 6810-A, 14 stage photo multipliers were substituted for the previous 5819 tubes. Because of their high gain it is possible to use them without any preamp and obtain pulses of sufficient size. Ten volt pulses with a width at half height of $11 \times 10^{-9}$ sec. can be produced in this manner. The output of these preamps are fed to the 6BN6 coincidence circuit described previously. The output of the 6BN6 coincidence circuit is sent to a twenty channel pulse height analyzer. Here one can select the pulses
whose magnitude corresponds to an exact coincidence between two pulses having an amplitude equal to that produced by the complete absorption of a focused electron or positron in each of the crystals. Using this method, which has been previously described by McCrady\textsuperscript{3}, a resolving time of about two millimicroseconds can be realized.

Presently an attempt is made to utilize a fast-slow coincidence circuit of the type described by Bell\textsuperscript{8}. (A block diagram is shown in Figure 2.) For this application the positive pulses for the fast coincidence circuit are obtained from the 14th dynode. The negative pulses from the anode are lengthened and amplified in a standard linear amplifier as are the pulses from the fast coincidence circuit. These amplified pulses are then sent through pulse height discriminators which select pulses of the desired amplitude. The outputs of the three discriminators are then sent to a triple coincidence circuit. By this method it should be possible to retain the short resolving time of the fast coincidence circuit and still be able to introduce some discrimination in the size of the pulses which are selected. The output of one of the discriminators is sent to a register in order to monitor the chance coincident rate. The major difficulty in this method is that the time delays introduced in the discriminator circuits are of such magnitude and variability that it is difficult to obtain the same delay in each of the three channels. Also the singles discriminators are required to handle all the singles pulses from the detector which may be as many as 60,000 counts/sec.

These difficulties may be overcome by using a slow-fast coincidence circuit in which the output of the fast coincidence circuit is used, to gate the input to the single discriminators. This overcomes both of these
Figure 2: Block diagram of fast-slow coincidence circuit.
difficulties. Up to the present time both of these methods have been tried and have proven less satisfactory than simply displaying the output of the fast coincidence circuit on the 20 channel pulse height analyzer as mentioned previously.

The chance rate is equal to $2N_1 N_2 \tau$ where $\tau$ is the resolving time of the circuit. In general, $N_1$ will equal $N_2$ and $\tau$ is a constant; therefore, the chance rate will be proportional to the square of the singles rate because they will be equal to each other as long as the crystals are properly located at the focus. This fact emphasizes the importance of a short resolving time. If one tries to increase the true counting rate, by such methods as increasing the beam current or the transmission of the spectrometer, then the chance counting rate is increased as the square of this and is therefore increased linearly with respect to the true coincidence rate. This also makes it imperative to maintain a constant beam while taking data if the chance rate is appreciable. A more complete analysis of the chance rate as a function of singles rate is given by Ranken$^9$.

**Photo-conversion spectrometer**

In the energy range from 0.300 Mev to 3.0 Mev the spectrometer can be used to observe the photo-conversion spectra produced by placing a high Z converter in back of the target. The use of a photo-conversion spectrometer has been described at some length by Thomas and Lauritsen$^{10}$.

The detection system in this case consists of a cylindrical $\frac{1}{4}'' \times \frac{1}{2}''$ plastic detecting element mounted on a 20'' tapered lucite light pipe which is attached to a 6342 RCA 10 stage photomultiplier tube. The pulses are
amplified and sorted by the 20 channel pulse height analyzer mentioned previously. In order to keep the pulse height from a circulated electron the same height for different magnetic field settings, the gain must be changed with each magnet current setting as long as the crystal stops the electron. Only the pulses corresponding to full energy loss of an electron of the selected energy are counted. The energy of the gamma ray is determined by adding to the energy of the electrons in the photo-peak, the K binding energy of the electrons in the converter material, and the average energy loss of the electrons in the converter.

Because bombardment of light nuclei with positively charged particles often produces isotopes which are positron emitters, a helical shaped baffle of the type described by Deutsch, et al., was placed in the spectrometer just back of the central annular slit. While this baffle effectively prevented any positrons from reaching the detector, it reduced the transmission of the spectrometer for electrons by 25 per cent. Elimination of the background from β-emitters can only be accomplished by beam pulsing techniques.

The relative yield of different energy gamma rays is rather difficult to calculate by means of the yields of the ejected photoelectrons. If one assumes the converter not too thick and the resolution of the spectrometer good the ratio of the gamma intensities is given by:

\[
\frac{I_{r1}}{I_{r2}} = \frac{\left[ A_{r1}/\gamma_K(E_{r1}) \right]}{\left[ A_{r2}/\gamma_K(E_{r2}) \right]}
\]

\(A_{rn} = \) Area under the photo-peak of the N/B curve.

\(\gamma_K(E_{rn}) = \) Cross section for K photo-conversion of a gamma ray of energy \(E_{rn}\).

\(N = \) Number of counts with spectrometer set at BP.
This formula neglects the change in angle between the direction of the photoelectron and the incident gamma ray and the anistropy in the gamma radiation emitted from the target.

Internal conversion spectrometer

Detection of internal conversion electrons from low Z nuclei is rather difficult because of the $Z^3$ dependence of the internal conversion coefficient. However at low energies or for gamma rays of high multipolarities the internal conversion electron spectrum may be observed.

This method is especially useful at low energies because photoconversion spectroscopy is rather difficult at energies below 200 kev, because of the large binding energy of the K electron of high Z elements and the energy loss of the electrons in the converter.

In order to increase the transmission of the spectrometer at lower energies an end window 3/4" in diameter was put in the exit cup. The window was made of aluminum coated plastic which was approximately 1 mg/cm$^2$ in thickness. Also the plastic detector was replaced by a geiger counter whose end window was approximately 1.2 mg/cm$^2$ in thickness. In order to measure the decrease in transmission of the spectrometer at low values of energy due to scattering and absorption in the windows and air the spectrum of a thin Pm$^{147}$ source was measured in the spectrometer. The Fermi plot of this is shown in Figure 3. The deviation of this plot from a straight line projection offered a measure of the relative transmission at various electron energies.

Steady magnetic fields are difficult to obtain at low magnet current values because of the large size of the generator. To help overcome this
Figure 3: Fermi plot of the β spectrum from Pm$^{147}$. 

\[ \sqrt{\frac{N}{\beta_{0f}}} \]
difficulty more gain was added to the error sensing feedback loop. This improved the current control considerably, but it is believed that even more improvement can be obtained by using a rectifier type, series transistor regulated power supply for low energy measurements.

More information can be obtained from the internal conversion spectrum by measurement of the absolute gamma yield and calculation of the internal conversion coefficient of the radiation. The best method for measuring the absolute gamma yield of low energy radiation was found to be by use of a NaI crystal. For these measurements the target was removed from the spectrometer and placed in a thin walled target holder to prevent attenuation of the low energy gammas. In each case the yield was measured as a function of the total beam current incident on the target as measured by a current integrator.

The measured internal conversion coefficient could then be compared to the theoretical values which differ for different $Z$, gamma energy, and multipolarity and parity change of the gamma ray. By this method it is possible to gain more information about the spins and parities of nuclear levels. This will be illustrated by various examples later.

Unfortunately, exact calculation of the internal conversion coefficients have only been made for nuclei of $Z > 24$. Mills\textsuperscript{12} has made a rather detailed study of the best method of estimating what these coefficients should be for $Z < 25$. He plotted the ratio of the exact Rose values to the Born approximation calculations\textsuperscript{13} of Danzoff and Morrison\textsuperscript{14}, as a function of $Z$. He then said that at $Z = 0$ the ratio was equal to 1 and drew in smooth curves from the point $Z = 25$ to $Z = 0$. 

10
This is shown in Figure 4. The Dancoff and Morrison formulae are as follows:

\[ \lambda^K = \frac{2 \pi^3 \gamma^4}{v^3} \left( \frac{v+2}{v} \right)^{1-v^{\frac{1}{2}}} \left[ \frac{(v+1)v^{2}+4\gamma}{v+1} \right] \]

\[ \beta^K = \frac{2 \pi^3 \gamma^4}{v} \left( \frac{v+2}{v} \right)^{2+v^{\frac{1}{2}}} \]

\[ \gamma = \frac{1}{137} \]

\[ \nu = \frac{Er}{m_0 c^2} \]

It is believed that the coefficients calculated by this method are accurate within 10 per cent.

III. Gamma Radiation From F\(^{18}\)

Recently there has been considerable interest in the energy levels in F\(^{18}\). This is partly because of the desire to check the theoretical prediction of levels in mass 18 nuclei\(^{15}\) and partly because of the apparent discrepancies in reported data.

To study the radiation from the excited states of F\(^{18}\) two reactions were used: \( O^{18} (p, n) F^{18} \) and \( O^{16}(He^3, p) F^{18} \).

The photo-conversion spectrum was observed in the first reaction and the internal conversion spectrum was observed in the latter reaction. Also the radiation from the latter reaction was observed with a 1\(^{\text{st}}\) X 1\(^{\text{st}}\) NaI (T) crystal.

The target used in the \( O^{18} (p, n) F^{18} \) reaction was a 12.7 mg/cm\(^2\) Thorium foil which had been oxidized on the surface. The foil was oxidized by heating it with an induction heater to approximately 1000\(^0\) C in an atmosphere of heavy water 85 per cent enriched in \( O^{18} \) at a pressure of about 2mm of Hg. The apparatus for doing this is shown in Figure 5.
RATIO OF SCREENED INTERNAL CONVERSION COEFFICIENTS

$$\frac{\alpha_k^I(\text{ROSE})}{\alpha_k^I(\text{BORN})} \text{ VS. } Z$$

$$\alpha_k^I(\text{ROSE}) \text{ ROSE ET AL.}$$

$$\alpha_k^I(\text{BORN}) \text{ DANCOFF ET AL.}$$
RATIO OF SCREENED TO BORN APPROXIMATION
CONVERSION COEFFICIENTS — ELECTRIC DIPOLE

\[ \frac{\alpha_{\text{ROSE}}}{\alpha_{\text{BORN}}} \text{ vs. } Z \]

\[ \alpha_{\text{ROSE}} \text{ (ROSE ET AL. (OAK RIDGE REPORTS))} \]

\[ \alpha_{\text{BORN}} \text{ (DANCOFF AND MORRISON (PR 55,122))} \]

Fig. 4a
RATIO OF SCREENED TO BORN APPROXIMATION
INTERNAL CONVERSION COEFFICIENTS - MAGNETIC D

$\frac{\beta_k^I(ROSE)}{\beta_k^I(BORN)}$ VS. Z

$\beta_k^I(ROSE)$ ROSE ET AL. (OAK RIDGE REPORTS)

$\beta_k^I(BORN)$ DANCOFF AND MORRISON (PR 55, 122)
OF SCREENED TO BORN APPROXIMATION
CONVERSION COEFFICIENTS – ELECTRIC QUADRUPOLE

\[ \frac{\alpha_k^2 \text{ (ROSE)}}{\alpha_k^2 \text{ (BORN)}} \quad \text{VS.} \quad Z \]

\[ \alpha_k^2 \text{ (ROSE)} \quad \text{ROSE ET AL. (OAK RIDGE REPORTS)} \]

\[ \alpha_k^2 \text{ (BORN)} \quad \text{DANCOFF AND MORRISON (PR 55, 122)} \]

\( \text{Fig. 4c} \)
TO BORN APPROXIMATION
DIFFUSIENCES - ELECTRIC QUADRUPOLE

Fig. 4c

CHINCOFF AND MORRISON (PR 55,122)

k = 2.0
0.4
0.6
0.8
1.0
1.5

k = 2.0
1.0
0.8
0.6
0.4

0
50
60
70
80
90

x
RATIO OF SCREENED TO BORN APPROXIMATION
INTERNAL CONVERSION COEFFICIENTS - MAGNETIC QUAD

\[
\frac{\beta_k^2(\text{ROSE})}{\beta_k^2(\text{BORN})} \quad \text{VS.} \quad Z
\]

\[\beta_k^2(\text{ROSE}) \quad \text{ROSE ET AL. (OAK RIDGE REPORTS)}\]

\[\beta_k^2(\text{BORN}) \quad \text{DANCOFF AND MORRISON (PR 55, 122)}\]
Figure 5: Diagram of apparatus used in making $\text{O}^{18}$ targets.

Fig. 5
The curve obtained when the target described above was bombarded with 4.6 Mev protons is shown in Figure 6. The reactions which are energetically possible are:

\[ 0^{18} (p, p^+ ) \ 0^{18} \]
\[ 0^{18} (p, n ) \ 1^{18} \]
\[ 0^{18} (p, \alpha ) \ N^{15} \]

\[ Q = -2.543 \text{ Mev} \]
\[ Q = 3.969 \text{ Mev} \]

The energies of the observed gamma radiation are \( 0.511 \pm 0.004 \text{ Mev}, \)
\( 0.666 \pm 0.005 \text{ Mev}, \)
\( 0.730 \pm 0.006 \text{ Mev}, \)
\( 0.938 \pm 0.006 \text{ Mev}, \)
\( 1.043 \pm 0.008 \text{ Mev}, \) and
\( 1.990 \pm 0.01 \text{ Mev}. \) An energy level diagram of \( F^{18} \) is shown in Figure 7.

The levels are those found by Rao, et al.\(^1\), by means of magnetic analysis of the protons from \( 0^{16} (\text{He}^3, p) F^{18} \). The spins and parities are those which seem to be most consistent with the data available at the present time.

The \( 0.511 \text{ Mev} \) radiation is annihilation radiation from the positrons emitted by \( F^{18} \). The \( 0.666 \text{ Mev} \) gamma is apparently a cascade gamma between the \( 1.708 \text{ Mev} \) level and \( 1.049 \text{ Mev} \) level in \( F^{18} \). The \( 0.730 \text{ Mev} \) radiation is from the coulomb excitation of \( \text{Th}^{232} \).

The \( 0.938 \) and \( 1.043 \text{ Mev} \) radiations are from ground state transitions in \( F^{18} \) which have been observed previously.\(^{17,18} \) The Saclay group reported a Doppler shift for the \( 1.04 \text{ Mev} \) gamma radiation but not for the \( 0.938 \text{ Mev} \) radiation.\(^{19} \) The \( 1.990 \text{ Mev} \) radiation is from the inelastic scattering of protons in \( 0^{18} \).

Because a level in \( F^{18} \) was known to exist at \( 1.089 \text{ Mev}\)\(^{20} \) the region around \( 1 \text{ Mev} \) was inspected at various proton bombardment energies. At \( 4.0 \text{ Mev} \) bombarding energy a \( 1.082 \text{ Mev} \) gamma ray was observed. (This is shown in Figure 8.) The excitation curves for the \( 0.666, 0.938, 1.043, \) and
Figure 6: Photoconversion spectrum obtained by bombarding $^18_O$ on a 12.7 mg/cm$^2$ Th foil with 4.6 MeV protons.
Figure 7: Energy level diagram of $^{18}_F$.

\[
\begin{array}{c}
\text{1.708} \\
\text{1.130} \\
\text{1.049} \\
\text{0.943} \\
1^+ 0 \\
\end{array}
\Rightarrow
\begin{array}{c}
\text{2.034} \\
O^{16} + HE^3 - P \\
(0^+, 0^-) (0) \\
(0^+, 1^-) (0) \\
(3^+) 0 \\
\end{array}
\]

Fig. 7

\[
- \frac{2.453}{0^{18} + P - N}
\]
Figure 8: Photoconversion spectrum obtained by bombarding $^{18}O$ on a 12.7 mg/cm$^2$ Th foil with 4.0 Mev protons.
1.082 Mev gamma rays are shown in Figure 9. These curves are corrected for efficiency of detection. A tabulation of relative intensities of the gamma rays observed at different bombarding energies is shown in Table I.

No gamma radiation was seen from the 1.13 Mev level in F\(^{18}\) so a search was made with a NaI crystal for a possible cascade between this level and one of the lower levels. This proved inconclusive, however, because F\(^{19}\) contamination in the target produced 109 and 197 kev gammas from inelastic scattering of protons, although comparison of the spectrum with a spectrum obtained from protons on a thorium blank did indicate the presence of gamma radiation of about 185 kev.

There were several reasons why it was considered more advantageous to use the reaction \(^{16}\)O\(.(\text{He}^3, \text{p})\) F\(^{18}\) to look for the cascade radiation from the 1.13 Mev level. In the first place, the protons from this reaction had been observed and it was known which bombarding energies were more favorable for making F\(^{18}\) in the 1.13 Mev excited state\(^{20, 21}\). The other reason was that it was necessary to make a self-supporting target with no backing if the internal conversion electrons from this cascade were to be observed. This is much easier to do with \(^{16}\)O than with \(^{18}\)O. It was decided to make a thin SiO foil by evaporation. The SiO was evaporated onto a 0.1 mil Ni sheet which was mounted on an Al holder. The Ni was then etched off with an acid solution leaving a self-supporting SiO film approximately 0.1 mg/cm\(^2\) in thickness. The use of this technique in the fabrication of thin carbon foils is described by Kashy et al\(^{22}\). To help cool the foil when it was under bombardment and to prevent the beam from building up electrostatic charges which might break the foil, a coating of silver was evaporated onto the back of the target.
<table>
<thead>
<tr>
<th>Ep (Mev)</th>
<th>0.666</th>
<th>0.938</th>
<th>1.043</th>
<th>1.082</th>
<th>1.990</th>
</tr>
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<tbody>
<tr>
<td>4.89</td>
<td>85</td>
<td></td>
<td></td>
<td></td>
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<td>4.82</td>
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<td>4.67</td>
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<td>4.60</td>
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<td>208</td>
<td>262</td>
<td>26</td>
<td>133</td>
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<td>4.54</td>
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<td>4.50</td>
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<td>375</td>
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<tr>
<td>3.90</td>
<td>87</td>
<td>45</td>
<td>13</td>
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</table>
Figure 9: Excitation curves of the 0.666, 0.938, 1.043, and 1.082 MeV gamma rays produced by bombarding an $^{18}$O target on 12.7 mg/cm$^2$ Th with protons.
The low energy internal conversion spectrum obtained when this target was bombarded by 2.83 Mev He\(^3\) particles is shown in Figure 10. The only detectable radiation is at 0.189 Mev and is apparently from the 1.13 - 0.94 Mev cascade in F\(^{18}\). The low energy gamma spectrum obtained from this same target with a NaI crystal is shown in Figure 10.

The internal conversion coefficient for the 189 kev gammas calculated from this data is \((2.54 \pm 0.20) \times 10^{-3}\). Table 2 gives the ratio of the experimental to the theoretical value of the coefficient for E1, M1, E2, M2 and M3 radiations.

**Table 2**

Internal Conversion Coefficient of .189 Mev Gamma Radiation

\[ \text{From } {}^{16}\text{He} \,({}^{18}\text{F}) \]

<p>| | | | | | | |</p>
<table>
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<tbody>
<tr>
<td>E1</td>
<td>M1</td>
<td>E2</td>
<td>M2</td>
<td>E3</td>
<td>M3</td>
<td></td>
</tr>
<tr>
<td>5.8\pm1.2</td>
<td>9.3\pm1.9</td>
<td>1.02\pm0.2</td>
<td>1.46\pm0.3</td>
<td>1.34\pm0.03</td>
<td>3.0\pm0.06</td>
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</tbody>
</table>

The higher energy gamma spectrum obtained by bombarding a thick quartz target with 2.83 Mev He\(^3\) particles is shown in Figure 11. The energy of the radiations observed are 0.51\pm0.01, 0.66\pm0.02, 0.95\pm0.02, 1.07\pm0.02, 1.72\pm0.03, 2.14\pm0.03, 2.54\pm0.03, 3.11\pm0.05. The energies and relative yields of these gamma rays are shown in Table 3.
Figure 10: Internal conversion electron spectrum from bombarding a thin SiO target with 2.83 Mev He particles.
Figure 11: Low energy gamma ray spectrum from bombarding a thin SiO target with 2.83 MeV He³ particles, taken with a 1" x 1" NaI crystal.
Figure 12: Gamma ray spectrum from bombarding a thick quartz target with 2.83 MeV He³ particles, taken with a 2"x2" NaI crystal.
Table 3  
Relative Yields of Gamma Radiation  
From $^6\text{He}_3 (p) F^{18}$ at $E_{\text{He3}} = 2.83$ Mev  

<table>
<thead>
<tr>
<th>E (Mev)</th>
<th>0.51</th>
<th>0.66</th>
<th>0.95</th>
<th>1.07</th>
<th>1.71</th>
<th>2.14</th>
<th>2.54</th>
<th>3.11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Yield</td>
<td>---</td>
<td>1537</td>
<td>1580</td>
<td>1330</td>
<td>75</td>
<td>178</td>
<td>89</td>
<td>19</td>
</tr>
</tbody>
</table>

The ratio of the cascade of the 1.71 Mev state to the 1.05 Mev state to the ground state transition is 7.1.

DISCUSSION OF RESULTS:

Lifetime measurements and angular distribution measurements from $^6\text{He}_3 (p) F^{18}$ by Bromley, et al.\textsuperscript{23} imply that $1 \leq J \leq 3$ for the 0.938 Mev state. Angular distribution of the deuterons from $F^{19}(p, d) F^{18}$ imply plus parity for the 0.938, 1.043, and 1.7 Mev states\textsuperscript{24}. This fact, together with the fact that no Doppler shift was observed for the 0.938 Mev radiation suggests that the 0.938 Mev state is that predicted by Elliot and Flowers with $T = 0$ and $J = 3$.

The data in the literature concerning the 1.04 Mev level and the 1.08 Mev level is rather confused because of the difficulty in identifying the radiation from these closely spaced levels. Also, early observers did not know of the existence of two states of these energies. One of them is apparently the analog of the $T = 1$, $0^+$ ground state of $^6\text{He}^{18}$. The other is probably a $T = 0$, $0^-$ state. This is based on Bromley's observation that this assignment corresponds to a removal of a $\frac{1}{2}^+$ neutron from the $^6\text{He}^{16}$ core, which is consistent with a small reduced width for the $F^{19}(p, d) F^{18}$ reaction to this level and Bennett's observation of only $\ell = 0$ and $\ell = 2$. 

15
components in the pickup pattern to the unresolved states near 1 Mev. Also Bromley reports that the gamma ray angular distribution and \((p, \gamma)\) angular correlation measurements from \(^{16}\text{He}^3, p\) \(^{18}\text{F}\) involving the 1.04 and 1.08 Mev gamma rays show spherical symmetry.

The data presented in this paper leads to the assignments shown in Figure 6. That is, \(T = 1, 0^+\) for the state at 1.04 Mev and \(T = 0, 0^-\) for the 1.08 Mev level. The level at 1.71 Mev has an isotopic spin of zero because it is populated by the reaction \(^{16}\text{Ne} \beta^0 \ (d, \alpha) \ F\) which can only make \(T = 0\) states\(^17\). A gamma ray with an energy of 0.666 Mev is observed; this is most likely a cascade from the 1.71 level to the 1.04 Mev level. The errors in the energy determinations are not sufficient to allow this radiation to be between the 1.71 and 1.08 levels. The maximum possible Doppler shift for the 0.666 Mev radiation would be 5 kev.

Further proof that this radiation could not be a 1.71-1.08 Mev cascade is that at proton energies of 4.4 to 4.6 Mev the 0.67 Mev radiation is of greater intensity than the 1.08 Mev gamma radiation. This result would be clearly impossible for such a cascade. The 0.67 Mev radiation is not, however, more intense than the 1.04 Mev gamma ray. The only explanation that can be made for this 1.71-1.04 Mev cascade being so much more intense than a transition to the ground state (1+) or to any of the other states around 1 Mev which are believed to be \(3^+, 0^-\) and \(5^+\) is that it is not isotopic spin forbidden. In charge self conjugate or self mirror nuclei theoretical calculations indicate that EI transitions with \(\Delta T = 0\) are forbidden\(^25\) and that MI transitions with \(\Delta T = 0\) are inhibited by a factor of 100\(^26\). Warburton\(^27\) has shown that experimentally there is an upper limit to the average inhibition for MI transitions of \(\sim 10\). In the present case if the 1.71 Mev state is a \(T = 0, 1^+\) state, then a 1.71-1.08 Mev
cascade would be a forbidden E1 transition; the 1.04 Mev ground state transition would be an M1 transition inhibited by a factor of ~10 and the 1.71-1.04 Mev transition would be M1 and have $\Delta T = 1$. Lending weight to this argument is the fact that Naggar et al. observed the 1.04 Mev radiation from $^6\text{O}^8 (p, n) ^8\text{F}^1$ to be Doppler shifted, suggesting it to be M1 or E1 radiation and have $\Delta T = 1$.

The internal conversion coefficient measured for the 1.189 Mev radiation from $^6\text{He}^3 (p, p') ^8\text{F}^1$ agrees closely with that expected for E2 radiation. Since this is probably from the 1.13-0.94 Mev cascade one is led to the conclusion that the 1.13 Mev level is the $5^+, T = 0$, state predicted by Elliot and Flowers. The 2.14, 2.54, and 3.11 Mev gamma rays are from ground state transitions in $^8\text{F}^1$.

IV. Gamma Radiation from $^9\text{F}^1$ + $^4\text{He}^3$

Gamma radiation from the excited states in $^{11}\text{Na}^{22}$ has been observed in a number of experiments. Excited states of Na$^{22}$ have also been observed in the reaction $^{22}\text{Mg}^{24} (d, \alpha) ^{11}\text{Na}^{22}$ where only $T = 0$ isotopic spin states are expected to be formed. Until the recent experiments of Temmer and Heydenburg there was no evidence for the excited $T = 1$ state in Na$^{22}$ predicted to have an energy of about 0.6 Mev. One of the principal objects of the present investigation was to search for this state in $^{11}\text{Na}^{22}$.

The gamma ray spectrum observed when a 1.6 mg/cm$^2$ thick CaF$_2$ target, evaporated on a 16 mg/cm$^2$ gold radiator, was bombarded by 4.9 Mev alpha particles is shown in Figure 13. The energies of the observed gamma rays are 0.586 ± 0.004, 0.892 ± 0.005, 1.275 ± 0.008, 1.530 ± 0.10, and 2.090 ± 0.016 Mev. The three reactions which might yield gamma radiation are:
Figure 13: Photoconversion spectrum from bombarding a 1.6 mg/cm² target on 16 mg/cm² with 5 Mev alpha particles.

\[ F^{19} + \alpha \]

\[ E_\alpha = 5.0 \text{ MEV} \]

FIGURE 13

RELATIVE YIELD

10
9
8
7
6
5
4
3
2
1
0
0.3  0.5  0.7  0.9  1.1  1.3  1.5  1.7  1.9  2.1

ELECTRON ENERGY - MEV

0.586 K
0.586 L
0.892 K
1.275 K
1.275 L
1.53 K
209 K
\[ F^{19} (\alpha, \alpha') F^{19} \]
\[ F^{19} (\alpha, p) Ne^{22} \quad Q = 1.705 \text{ MeV} \]
\[ F^{19} (\alpha, n) Na^{22} \quad Q = -2.061 \text{ MeV} \]

The level schemes for Ne\(^{22}\) and Na\(^{22}\) are shown in Figure 14. The Ne\(^{22}\) levels shown are those observed by Foder through magnetic analysis of proton groups from the \(F^{19} (\alpha, p) Ne^{22}\) reaction\(^{30}\).

The Na\(^{22}\) levels are those observed by Browne and Cobb\(^{28}\) by magnetic analysis of alpha particles from the reaction Mg\(^{24}\) (d,\(\alpha\)) Na\(^{22}\), with the exception of the 666 kev level whose 73 kev cascade gamma to the 593 kev level was observed by Temmer and Heydenburg\(^{29}\). The most accurate determination of the energy of the first excited state of Ne\(^{22}\), 1.275 ± 0.0005 MeV, has been obtained by magnetic spectrometer measurements of the energy of the gamma rays from this state through the use of a Na\(^{22}\) source\(^{31}\).

The energies of the gamma rays observed in the present experiment agree very well with the known levels shown in Figure 14. The 0.586 MeV gamma ray is a ground state transition from the first excited state of Na\(^{22}\) and the 1.275 MeV gamma ray is from the first excited state of Ne\(^{22}\). The 2.090 MeV gamma ray is a cascade between the 3.35 and 1.275 MeV levels in Ne\(^{22}\). This gamma ray is thought to have either an E1 or M1 multipolarity and hence should be Doppler shifted. The Doppler corrected energy of this gamma ray is 2.075 MeV, which gives a value of 3.350 ± 0.020 MeV for the energy of the second excited state of Ne\(^{22}\).

The 0.892 and 1.530 MeV gamma rays agree well in energy with the states in Na\(^{22}\) observed by Browne and Cobb at 0.89 and 1.53 MeV\(^{28}\). The Doppler corrected energies of these gamma rays are 0.886 and 1.519 MeV. However, it is not clear that the Doppler corrections should be applied
Figure 14: Energy level diagrams of Na$^{22}$ and Ne$^{22}$. 
since the multipolarities of the gamma rays are not known. The fact that there are no strong cascades from the 1.53 Mev state indicates that a Doppler correction should probably be made for this radiation. The threshold energy of producing Na$^{22}$ in the 1.94 Mev state is 4.84 Mev. Consequently very little radiation of 1.94 Mev and no radiation of 1.99 Mev is expected, in agreement with the experimental results.

The relative intensities and the Doppler corrected energies of the observed gamma rays are listed in Table 4. No cascade gamma radiation from levels in Na$^{22}$ were observed. The intensity of the 3.35 Mev gamma radiation was obtained from a separate experiment which made use of a NaI spectrometer. No evidence was found for any gamma radiation from the 1.35, 1.46, and 1.56 Mev states in F$^{19}$ populated by the inelastic scattering of alpha particles.

Table 4

<table>
<thead>
<tr>
<th>E (Mev)</th>
<th>0.586</th>
<th>0.886</th>
<th>1.275</th>
<th>1.519</th>
<th>2.075</th>
<th>3.350</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Intensity</td>
<td>36</td>
<td>25</td>
<td>100</td>
<td>6</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

Because the L peak from the 0.586 Mev gamma ray was somewhat larger than expected, relative to the K peaks, several experiments were conducted to determine whether there could be K conversion electrons or internal conversion electrons obscured by the L peak of the 0.586 Mev gamma ray. The results of bombarding a 1.2 mg/cm$^2$ CaF$_2$ target on a 13 mg/cm$^2$ Ag backing are shown in Figure 15. The silver radiator was used so that the K and L
Figure 15: Photoconversion electron spectrum from bombarding a 1.2 mg/cm$^2$ CaF$_2$ target on 13 mg/cm$^2$ Ag with 4.9 Mev alpha particles.
conversion lines would be quite close together in energy and the L line would not obscure the K conversion line from higher energy gamma radiation. A slight peak was observed at an electron energy of about 0.660 Mev, but its shape and location were of such a nature as to suggest it was a Compton peak from the 0.886 kev level in Na$^{22}$.

In order to determine whether the peak observed at 0.660 Mev electron energy was caused by internal conversion electrons from the level at 0.666 Mev postulated by Temmer and Heydenburg$^{29}$, the internal conversion electrons obtained by bombarding a 1.5 mg/cm$^2$ CaF$_2$ target on 6.8 mg/cm$^2$ aluminum with 3.7 Mev alpha particles were observed in the spectrometer. These results are shown in Figure 16. This bombarding energy was chosen because the 73 kev gamma ray was known to have a peak in its excitation curve at this energy$^{32}$. The same type of broad peak was obtained as with the silver backing with the same electron energy indicating that it was not from external conversion when it was seen with the silver backing. The internal conversion coefficient of the 0.586 Mev gamma ray was calculated to be $(1.0 \pm 0.3) \times 10^{-4}$. This is in agreement with either E2 or M2 radiation. (See Table 5.)

The level postulated by Temmer and Heydenburg at 0.666 Mev is believed to be the $0^+$ first $T = 1$ state in Na$^{22}$, since it occurs at the energy predicted by isotopic spin considerations$^{29}$ and its lifetime of less than 0.5 millimicrosecond, as measured by Holland and Lynch$^{33}$, is compatible with this assignment. If it is a $0^+$ state and the ground state and first excited state assignments of $3^+$ and $1^+$ are correct, then the 0.666 Mev level would decay by a 80 kev M1-E2 cascade with very few direct transitions to the ground state. A 73 kev gamma ray was seen by
Figure 16: Internal conversion electron spectrum from bombarding a 1.5 mg/cm² CaF$_2$ target on 6.8 mg/cm² Al with 4.9 and 3.7 MeV alpha particles.
Table 5
Internal Conversion Coefficients of the Gamma Radiation
From F19 + α

<table>
<thead>
<tr>
<th>Eγ (Mev)</th>
<th>Experimental Internal Conversion Coefficient</th>
<th>Experimental Internal Conversion Coefficient</th>
<th>Theoretical Internal Conversion Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>.073</td>
<td>(3.98±.4) X 10^{-3}</td>
<td>3.52±.07</td>
<td>1.02±.2</td>
</tr>
<tr>
<td>.109</td>
<td>(2.52±.5) X 10^{-3}</td>
<td>1.31±.4</td>
<td>3.6±.1.1</td>
</tr>
<tr>
<td>.586</td>
<td>(1.00±.3) X 10^{-4}</td>
<td>4.16±.1.7</td>
<td>3.23±.1.3</td>
</tr>
</tbody>
</table>
Temmer and Heydenburg from the reaction \( F^{19} + \alpha \). In order to determine the multipolarity of the 73 kev gamma ray, a measurement was made of its internal conversion coefficient. Because the internal conversion coefficient of the 0.109 Mev gamma radiation from the first excited state of \( F^{19} \) had been accurately measured by Mills\(^{34} \), it was decided to re-measure this coefficient as a check on the method of measurement.

A 0.2 mg/cm\(^2\) CaF\(_2\) target evaporated on 0.2 mg/cm\(^2\) aluminum foil was used for the measurements. Because of the thinness of the target and the large amount of momentum imparted to the target nucleus by the 3.7 Mev alpha particles, it was found that some of the 0.109 Mev internal conversion electron counts were being lost because the \( F^{19} \) nucleus had recoiled from its position at the focal point of the spectrometer. This effect is negligible in the measurement of the 73 kev internal conversion electrons because of the short lifetime of this state and because the maximum momentum transfer to the \( Na^{22} \) nucleus is less because of the 2.0 Mev negative Q value of this reaction.

For this reason the following procedure was adopted. The target was bombarded with 3.7 Mev alpha particles and the 73 kev radiation was measured at 0\(^\circ\), 90\(^\circ\), and 170\(^\circ\) by means of a NaI spectrometer. It was found to deviate from isotropy by less than 10 per cent. Because the 109 kev gamma was also isotropic\(^{12} \), no correction had to be made for this effect. The 73 kev radiation at 0\(^\circ\) was accurately measured. The same target was then bombarded by 3.7 Mev protons and the 109 kev gamma radiation was measured. These curves are shown in Figure 17. The same bombarding procedure was then followed with the target in the spectrometer.
Figure 17a: Gamma ray spectrum from bombarding a .2 mg/cm² CaF₂ target on .2 mg/cm² Al with 3.7 Mev protons, taken with a 1"x1" NaI crystal.
Figure 17b: Gamma ray spectrum from bombarding a .2 mg/cm² CaF₂ target on .2 mg/cm² Al with 3.7 Mev alpha particles, taken with a 1"x1" NaI crystal.
Figure 18a: Internal conversion electron spectrum from bombarding a .2 mg/cm² CaF₂ target on .2 mg/cm² Al with 3.7 MeV α's.
Figure 18b: Internal conversion electron spectrum from bombarding a 0.2 mg/cm² CeF₂ target on 0.2 mg/cm² Al with 3.7 MeV protons.
and the internal conversion electron yields of the 73 kev and 109 kev gamma rays measured. See Figure 18 for these curves.

In order to correct for the fact that not all of the electrons in the peak are from conversion in the K-shell, but some are from L-shell conversion, a correction had to be made. Mills\textsuperscript{12} has shown that for internal conversion in the light elements in the energy range encountered here not much error is introduced by subtracting 11 per cent of the total electron yield to allow for L conversion.

The internal conversion coefficient of the 73 kev gamma radiation is $(4.0 \pm 0.4) \times 10^{-3}$ and that of the 109 kev radiation is $(2.52 \pm 0.5) \times 10^{-3}$. From Table 5 one can see that these values are in agreement with MI and EI radiation respectively. This information is compatible with assignments of $3^+$, $1^+$, and $0^+$ for the ground, first, and second excited states of Na\textsuperscript{22}, the latter state having an isotopic spin of 1.

V. Gamma Radiation From F\textsuperscript{19}++ d

Attempts had been made previously to measure the internal pair spectrum from the deuteron bombardment of F\textsuperscript{19}, but the large accidental coincidence rate due to the $\beta^-$rays from F\textsuperscript{20} had made such measurements impossible\textsuperscript{35}. It was hoped that the better time resolution obtained by use of the new 6810-A photomultipliers might now make such measurements possible. The maximum energy of these particles is 5.4 Mev. It was found, however, that when the spectrometer was set at an electron energy of 4.7 Mev, a beam of only .4 microamps on the target gave a singles counting rate of $6 \times 10^4$ counts per second. Under these conditions the accidental counting rate was so large that it would have masked a much
smaller true counting rate.

The beam pulsing technique mentioned previously was tried; the beam and counters were first turned on for one second and then off for nine seconds. Under these conditions only 10 per cent of the saturated activity in $^{20}\text{F}$ ($T_\frac{1}{2} = 11$ sec.) was obtained. This method showed considerable promise, although the slowness of obtaining information made it impractical for this reaction. Although the average beam was reduced by a factor of 3.4 the chance counts per given amount of integrated beam was reduced by a factor of 14.5. The beam was interrupted by means of a solenoid actuated tantalum shutter.

The spectrum shown in Figure 19 was obtained by introducing a diamond absorber 2.2 mm. thick between the target and a 79 mg/cm$^2$ lead converter. The target was made by evaporating 10 mg/cm$^2$ CaF$^2$ on a 13.6 mg/cm$^2$ silver foil. It was bombarded by 3.6 Mev deuterons. An additional 13 mg/cm$^2$ silver was placed between the target and the diamond in order to prevent the beam from reaching the diamond. The spectrometer was set for 3.5% resolution and the spectrum between 8 and 12 Mev was observed in this manner. Below 8 Mev the chance rate became large, in order to observe radiation down to 6 Mev, a second absorber of about 2.2 mm. of sapphire was added between the diamond and the lead converter. This spectrum is shown in Figure 20. An energy calibration was made for the first spectrum by calibrating on the 6.14 Mev line from $^6\text{Li}$ by means of the $^6\text{Li} (p, \alpha t) ^4\text{He}$ reaction. The second was calibrated by comparing with the previously observed gammas. Finally the points shown in Figure 20 indicated as $x^1s_p$ were taken at a bombarding energy of 1.8 Mev.
Figure 19: External pair spectrum from bombarding a 10 mg/cm² CaF₂ target with 3.6 MeV deuterons using a 2.2 mm diamond absorber and a 79 mg/cm² lead converter.
Fig. 19

$^{19}$F + d

DIAMOND ABSORBER
79 MG/CM$^2$ LEAD CONVERTER

$E_D = 3.6$ MEV

GAMMA RAY ENERGY MEV

From bombarding a 10 mg/cm$^2$ CaF$_2$ target using a 2.2 mm diamond absorber target.
Figure 20: External pair spectrum from bombarding a 10 mg/cm² CaF₂ target with 3.6 and 1.8 Mev deuterons using a 2.2 mm diamond absorber and a 2mm sapphire absorber and a 79 mg/cm² lead converter.
Fig. 20

F$^{19} + d$

Diamond and Sapphire Absorbers

79 mg/cm$^2$ Lead Converter

- $E_D = 3.6$ MeV
- $E_D = 1.8$ MeV

Here is a spectrum from bombarding a 10 mg/cm$^2$ CaF$_2$ target with 3.6 MeV deuterons using a 2.2 mm diamond absorber and a 2mm absorber and a 79 mg/cm$^2$ lead converter.
The following reactions are energetically possible when $^{19}F$ is bombarded with deuterons:

$^{19}F + d \rightarrow n$ $^{20}Ne \quad Q = 10.65$ Mev

$^{19}F + d \rightarrow p$ $^{20}F \quad Q = 4.37$ Mev

$^{19}F + d \rightarrow \alpha$ $^{17}O \quad Q = 10.04$ Mev

The $Q$ value of the second reaction is such that only states below 7.7 Mev may be formed. States above 4.2 Mev excitation in $^{17}O$ can break up by neutron emission and would give weak gamma emission above this level. States in $^{20}Ne$ above 6 Mev in excitation may break up by alpha particle emission to the ground state of $^{16}O$ if they have even spin and parity or odd spin and parity. All states above 12.5 Mev may break up by alpha particle emission to the first excited state $0^+_1$ state or the second excited state of $^{16}O$, a $3^-$ state.

An energy level diagram of $^{20}Ne$ is shown in Figure 25. Table 6 lists the levels observed in $^{20}Ne$ by alpha scattering from $^{16}O$, $^{36},^{37},^{38}$ by inelastic proton scattering from $^{20}Ne$, by the reaction $^{23}Na + p\rightarrow ^{20}Ne + \alpha$, and by the reaction $^{19}F + d\rightarrow ^{20}Ne$. The energies given by Schranck and O'Neil are for identification only. The gamma rays indicated are those observed in the present work and by Kruse, Bent, and Lidofsky$^{42}$ from the reactions $^{19}F + \alpha$ and $^{23}Na + p$. The states observed by alpha particle scattering emit gamma rays with negligible intensity because of their much more probable break up by alpha emission. The energies, Doppler corrected energies, assignments, and possible multipolarities of the gamma rays observed in the present experiment are listed in Table 7.

The 11.27 Mev gamma ray is most likely from a ground state transition in $^{20}Ne$ because it was also seen at a 1.56 Mev bombarding energy by
Figure 21: Energy level diagram of Ne^{20}.
<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>Energy (MeV)</th>
<th>Energy (MeV)</th>
<th>Energy (MeV)</th>
<th>Present Experiment</th>
</tr>
</thead>
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<td>0.16</td>
<td>1.63*</td>
<td>1.635*</td>
<td>1.5</td>
<td>7.26* (1+2-)</td>
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<tr>
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<td>4.26*</td>
<td>4.248*</td>
<td>4.2</td>
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<td>4.969*</td>
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<td>9.570</td>
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<tr>
<td>10.1</td>
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</table>

*Gamma radiation has been observed from states with an asterisk.
<table>
<thead>
<tr>
<th>Observed Energy (Mev)</th>
<th>Doppler Corrected Energy (Mev)</th>
<th>Relative Yield</th>
<th>Assignment</th>
<th>Multipolarity</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.18</td>
<td>6.15</td>
<td>100</td>
<td>6.14 → 0</td>
<td>E3</td>
</tr>
<tr>
<td>6.69</td>
<td>6.66</td>
<td>29</td>
<td>6.63 → 0</td>
<td></td>
</tr>
<tr>
<td>7.29</td>
<td>7.26</td>
<td>27</td>
<td>7.3 → 0</td>
<td>(M1, M2)</td>
</tr>
<tr>
<td>8.25</td>
<td>8.21</td>
<td>33</td>
<td>10.0 → 1.6</td>
<td>(M1)</td>
</tr>
<tr>
<td>9.23</td>
<td>9.19</td>
<td>38</td>
<td>9.1 → 0</td>
<td>(M1, M2)</td>
</tr>
<tr>
<td>9.98</td>
<td>9.94</td>
<td>12</td>
<td>10.0 → 0</td>
<td>(M1, M2)</td>
</tr>
<tr>
<td>10.59</td>
<td>10.55</td>
<td>32</td>
<td>12.2 → 1.6</td>
<td>(M1, M2)</td>
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<td>11.32</td>
<td>11.27</td>
<td>11</td>
<td>11.3 → 0</td>
<td>(M1, M2)</td>
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</tbody>
</table>
Terrell and Phillips. This is energetically impossible if it is a cascade between a 12.90 Mev state and the 1.63 Mev first excited state of Ne$^{20}$. The 10.55 Mev transition is undoubtedly a cascade from a state at 12.18 Mev in Ne$^{20}$ to the 1.63 Mev first excited state since it disappears at a 1.8 Mev deuteron energy. The 9.94 and 9.19 Mev transitions are probably from states in Ne$^{20}$ reported at 9.0 and 10.1 Mev by Bonner from measurements of the neutron groups from the $^1H (d, n)$ Ne$^{20}$ reaction. The 8.25 Mev radiation is probably from a cascade between the 9.94 Mev state and the 1.63 Mev state in Ne$^{20}$. The 7.26 Mev transition must be the ground state transition from the level reported at about 7.3 Mev. The 6.66 Mev transition is most likely from F$^{20}$ because there is no energy difference between known states in Ne$^{20}$ of this energy, and a 6.63 Mev gamma has been observed from F$^{20}$. The gamma could not possible be from the 6.74 Mev state in Ne$^{20}$ observed by Cameron by alpha particle scattering because it would break up by alpha emission. There are no known states around 6.15 Mev in Ne$^{20}$ or states whose cascade would give 6.15 Mev radiation. It is probable that this gamma is from the second excited state of $^0_16$ at 6.14 Mev formed by alpha emission to this state from Ne$^{20}$. This gamma should not be Doppler corrected in this case since it is an E3 transition. Further weight is given to the argument that the 6.69 and 6.18 Mev gammas are from other nuclei than Ne$^{20}$ by the fact that when the deuteron energy was reduced from 3.6 to 1.8 Mev the total gamma radiation as measured by a geiger monitor and the singles register dropped by a factor of six while the 6.69 and 6.18 Mev gammas dropped by a factor of 50. This fact indicates that the effective threshold for making these is above 1.8 Mev.
The 9.94 Mev state is probably the \( I^+ \), \( T = 1 \) analog of the ground state of \( F^{20} \). A cascade between this state and the 1.63 Mev first excited state also would be expected. The 12.18 Mev state could be either 3+ or 4-. It might be the \( T = 1 \) analog of the 1.97 Mev state in \( F^{20} \). The 11.3 Mev state must be 1+ or 2- in order to explain its high probability of decay to the ground state. It would have to be a \( T = 0 \) state if it were 2- in order for it not to cascade by E1 emission to the first excited state. If it were 1+ it could be the \( T = 1 \) analog of the 0.65 Mev first excited state in \( F^{20} \) which has been reported to have even parity and a spin of \( 1 \), \( 2 \), or \( 3 \). Any cascade between the 11.3 Mev state and the 1.63 Mev state would be close to the observed gamma of 9.94 Mev attributed to a ground state transition. The 9.19 and 7.26 Mev states by the preceding arguments would also be 1+ or 2- levels in order not to be alpha emitting and to mainly decay to the ground state.

The states postulated from the above arguments are given in Table 6. One can see that there are pairs of states with energies about 10.0, 9.0, and 7.3 Mev. One member of the pair can break up by alpha particle emission, and the other member can not because its spin and parity will not permit. It has been suggested previously that the existence of levels with approximately the same energies but different parities might result from an alpha particle model of Ne\(^{20}\) because of the tunneling motion.\(^{35}\)
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