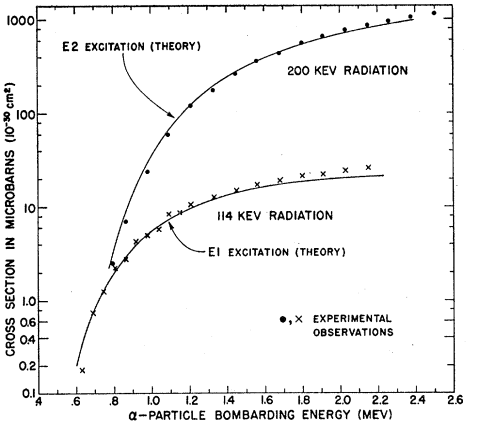

FIG. 1. Excitation of the first (114-kev) and second (200-kev) excited states of $F^{19}$ by α particles.

The excitation curves in Fig. 1 have the general character to be expected of Coulomb excitation.[2] The curves were calculated from the theories for this process developed by Mullin and Guth,[3] Ter-Martyrosian,[4] and Alder and Winther.[5] These curves were chosen to fit the data at low energy. It is not clear whether the divergence at higher energy signifies inadequacy in the theory, or whether it is the result of an increasing contribution of compound nucleus effects. From the yield of the $(\alpha,p)$ reaction we infer that the cross section for formation of a compound nucleus is comparable with the excitation cross section of the 114-kev state in the neighborhood of 1.35 Mev.

The calculations for the 200-kev state assume $E2$ excitation of a $5/2^+$ state from the ground state of $F^{19}(J=1/2^+)$. To improve the calculation near the threshold, we have replaced the parameter $\xi$ of reference 4 by

$$\xi=\frac{Z_1Z_2e}{\hbar}\left(\frac{1}{v_2}-\frac{1}{v_1}\right),$$

where $v_1$ and $v_2$ are the relative velocities of the bombarding and scattered particle. At high energy this quantity becomes identical with the expression of Alder and Winther. The absolute cross section for the excitation process is directly connected with the lifetime of the excited state. The calculated curve of Fig. 1 corresponds to a mean life $\tau=2.2\times10^{-7}$ sec, in fair agreement with the direct measurements of the lifetime by Thirion *et al.*,[6] who find $\tau\sim1\times10^{-7}$ sec. Our results support the assignment by Peterson, *et al.*[7] of $J=5/2^+$ to the second excited state of $F^{19}$.

The calculations for the 114-kev state assumes electric dipole excitation[3] of a $\frac{1}{2}^-$ state. The curve of Fig. 1 corresponds to a lifetime of $1.4\times10^{-9}$ sec for electric dipole decay of this state. The agreement with the directly observed lifetime ($\tau=1.0\pm0.2\times10^{-9}$ sec)[6] is satisfactory. It should be noted, however, that in addition to the experimental uncertainties, there is an estimated uncertainty of a factor 2 in the theoretical Coulomb excitation cross sections (and consequently in the predicted lifetimes).

Measurements of the angular distributions of the 114- and 200-kev radiations were made for a thick target at a bombarding energy of 1.84 Mev. The 114-kev radiation was isotropic within 10 percent, while for the 200-kev radiation we obtained $W(0°)/W(90°)=1.22\pm0.02$. The theory for the reaction[5] predicts 1.26 for the 200-kev radiation; however, finite lifetime effects may reduce this value.[8] The isotropy of the 114-kev radiation supports the $J=\frac{1}{2}$ assignment of Peterson *et al.*[7]

The possibility that the 114-kev state is $\frac{1}{2}^+$ can be eliminated since magnetic dipole Coulomb excitation[9] would have a cross section smaller than that observed by a factor of $v^2/c^2\approx10^{-3}$ when the magnetic dipole moment is chosen to fit the observed lifetime. In addition, the possibility that the state is $\frac{3}{2}^\pm$ is eliminated by the absence of the cascade transition[7] and by the isotropy of the angular distribution in both the α-particle excitation and the proton excitation.[7] We conclude that the first excited state of $F^{19}$ at 114 kev is $\frac{1}{2}^-$ (assuming the ground state to be $\frac{1}{2}^+$), while the second excited state at 200 kev is $5/2^+$.

The $5/2^+$ state is probably that predicted by the shell model for an odd proton in a $d_{5/2}$ state. The $\frac{1}{2}^-$ state is entirely unexpected since the shell model predicts even parities in this region from the filling of the $s_{1/2}$ and $d_{5/2}$ states. It may be related to the $\frac{1}{2}^-$ state at 3.10 Mev[10] in $F^{17}$, in fact the three lowest states of $F^{17}$ are apparently $5/2^+$, $1/2^+$, and $1/2^-$. The most obvious interpretation of the $\frac{1}{2}^-$ state is in terms of a proton hole in the $p_{1/2}$ shell. The fact that it is almost accidental that this state is not the ground state is certainly in contradiction with the usual interpretations of the shell model.

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* Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

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[7] Peterson, Barnes, Fowler, and Lauritsen, this issue [Phys. Rev. **94**, 1075 (1954)].

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# Low Excited States of $F^{19}$. IV. Angular Distributions*

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(Received March 18, 1954)

THE angular distributions[1] of inelastically scattered protons and the subsequent γ rays at resonances in $Ne^{20}$ afford one means of establishing properties of the low excited states of $F^{19}$. For this purpose the $2^-$ resonances in $Ne^{20}$ made by $p$-wave

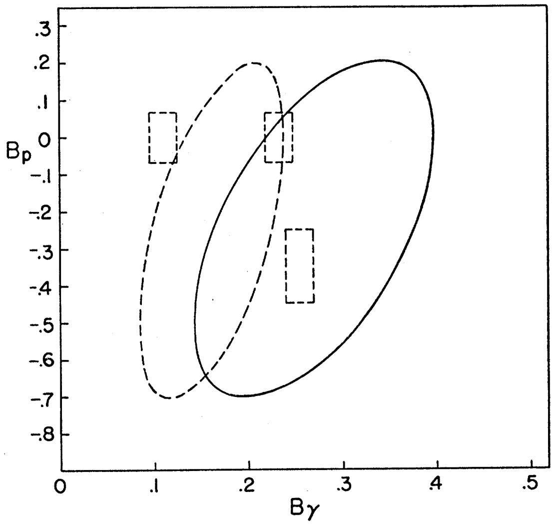

FIG. 1. The asymmetry coefficient $B_p$ of inelastically scattered protons leading to the 200-kev state of $F^{19}$ as related to the coefficient $B_\gamma$ for the angular asymmetry of the resulting ray at $2^-$ resonances in $Ne^{20}$ from $F^{19}+p$. The experimental points are plotted as dotted rectangles.

protons on $F^{19}$ in channel spin 1 are most suitable and are discussed below. Since it was not possible to measure the inelastically scattered protons leading to the 114-kev state at these resonances, we discuss only the angular distribution of protons leading to the 200-kev state and of the two $\gamma$ rays.

The protons to the $5/2^+$ state are distributed as $1+A_p\cos^2\theta = 1+B_pP_2(\cos\theta)$, where, because of the two channel spins 2 and 3 in the outgoing state, $-7/9 \leq A_p \leq 1/3$ or $-0.7 \leq B_p \leq 0.2$. The observations (tabulated below) lie within this range. A $3/2^+$ state would also be consistent with the proton distributions.

With an assignment of $1/2^-$ for the 114-kev state, the corresponding $\gamma$ ray is spherical, in agreement with observation. For the 200-kev $\gamma$ ray, we expect an angular distribution $f(\theta)=1+A_\gamma\cos^2\theta=1+B_\gamma P_2(\cos\theta)$. If the state were $3/2^+$, decaying by magnetic dipole, $A_\gamma$ would be less than or equal to zero; the fact that $A_\gamma$ is positive eliminates this possibility. For a $5/2^+$ state decaying by electric quadrupole radiation, we get $0.23 \leq A_\gamma \leq 0.75$ or $0.143 \leq B_\gamma \leq 0.4$. Before comparing with experiment, we will discuss some novel features of this problem.

The treatment of the proton spin needs some explanation. In calculating the angular distribution of the inelastically scattered protons, the proton spin is combined with that of the excited $F^{19}$ nucleus to form two channel spins: from each of these, an angular distribution is calculated and the results are the two extreme distributions, the general result being an arbitrary linear combination of the two. In calculating the distributions of the subsequent $\gamma$ rays, however, the amplitudes from the two channel spins are coherent and the general result contains a term corresponding to the interference of the two channel spins. The extreme distributions can of course be found by diagonalizing the quadratic form. It is interesting to inquire, however, if a different way of combining angular momenta will lead directly to the two extreme distributions which can be combined incoherently. It is readily seen that the appropriate combination for this purpose is the $\mathbf{l}+\mathbf{s}=\mathbf{j}$ of the outgoing proton. The $\gamma$-ray distributions for different $j$ values (here 1/2 and 3/2) of the outgoing proton are incoherent and, in fact, for $j=3/2$ we get $A_\gamma=0.23$, whereas for $j=1/2$ we get $A_\gamma=0.75$.

This result leads immediately to the formulation of a general statement as to when we may combine two angular momenta, at a certain stage of a reaction, to form a resultant which may be treated incoherently: Whenever an experiment gives equal weight to all projections of two angular momenta $j_1$ and $j_2$ which are to be combined, then we may form $\mathbf{j}_1+\mathbf{j}_2=\mathbf{J}$ and the various $J$ values can be treated incoherently for that particular experiment. For example, in observing the proton angular distribution, equal weight is given to the projections of the spins of proton and of excited $F^{19}$, whereas in observing the $\gamma$-ray distribution, equal weight is given to all directions of the proton (projections of $\mathbf{l}$) and to all projections of the proton spin. We see also when, in the excitation curve of the $\gamma$ rays from a residual nucleus, two overlapping resonances or states of the compound nucleus can show interference (a term which, as a function of excitation energy, is asymmetric about the resonance center and leads to a rapidly changing angular distribution in the neighborhood of the resonance center). Only those resonances which can lead to the residual state in question by particles of the same $j$ and $l$ can show such interference in the radiations from the residual state.

There is, of course, a correspondence between the angular distributions of inelastically scattered protons and of subsequent $\gamma$ rays at a given resonance. This is shown by the solid curve in Fig. 1, where $B_p$, the coefficient of $P_2(\cos\theta)$, is plotted against $B_\gamma$. Because of the coherence of the usual channel spins, this correspondence is in the form of an ellipse, instead of a straight line, which is bounded in the $B_p$ and $B_\gamma$ values by the numbers already computed. Taking the channel spin amplitudes as real numbers, the corresponding experimental points for $B_p$ and $B_\gamma$ should lie on the perimeter of the ellipse.

In this problem, the situation is further complicated by the long lifetime[2] of the $5/2^+$ state ($10^{-7}$ sec) which permits some precession of the nuclear spin before $\gamma$ emission. This will result in a $B_\gamma$ reduced by multiplying with some factor $\alpha<1$. In this case it does not seem possible to calculate $\alpha$ since the environment of the radiating $F^{19}$ nucleus is quite uncertain after the $p-F^{19}$ collision which will leave the atom perhaps excited and in a strange lattice position. It should be possible, by correlating sufficiently precise measurements of $B_p$ and $B_\gamma$ at different resonances, to test the conclusions given here and to find the reduction factor $\alpha$. The dotted ellipse is drawn for $\alpha=0.6$. The observations listed below are shown as rectangles in the figure and are not inconsistent with $\alpha\approx0.6$. In addition, the angular distribution of the 200-kev $\gamma$ ray as excited by Coulomb excitation under alpha-particle bombardment[3] is consistent with $\alpha$ in the range 0.6 to 0.8.

| Resonance | $A_p$ | $B_p$ | $A_\gamma$ | $B_\gamma$ |
|---|---|---|---|---|
| 873 kev | $0\ \pm0.1$ | $0\ \pm0.07$ | $0.17\pm0.02$ | $0.11\ \pm0.015$ |
| 1355 kev | $0\ \pm0.1$ | $0\ \pm0.07$ | $0.40\pm0.03$ | $0.235\pm0.015$ |
| 1381 kev | $-0.45\pm0.1$ | $-0.35\pm0.1$ | $0.44\pm0.03$ | $0.255\pm0.015$ |

* Assisted by the U. S. Office of Naval Research and the U. S. Atomic Energy Commission.

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## Short-Lived Isomeric States of $Ag^{110}$ and $In^{116}$†

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(Received March 1, 1954)

Beta and gamma radiations from the short-lived isomeric states of $Ag^{110}$ and $In^{116}$ have been investigated using a scintillation spectrometer. The detector arrangements were conventional, using RCA 5819 photomultipliers in conjunction with sodium iodide (thallium activated) or anthracene crystals for the detection of gamma or beta rays, respectively. Data were recorded photographically as dots on 35-mm film. This recording technique provides information concerning both the energy spectrum and decay rate of the sample. Details concerning the photographic dot recording method have been described elsewhere.[1]

$Ag^{110}$ was obtained by irradiating 0.001-inch silver foil in the

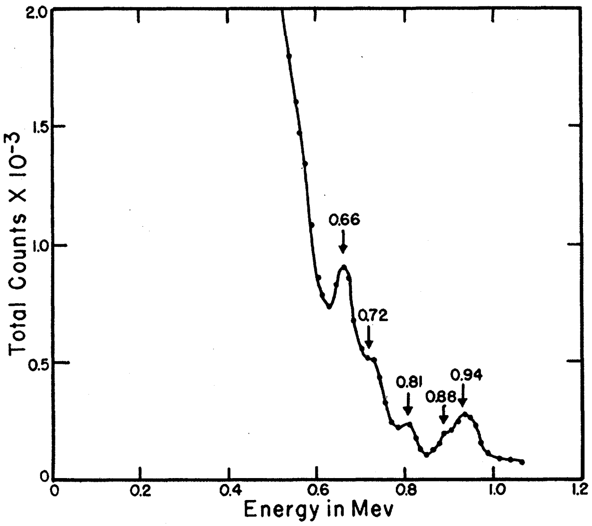

FIG. 1. Gamma spectrum of 24-second $Ag^{110}$. Energies are in Mev.