have $\frac{3}{2}^-$ ground states whose magnetic moments have been measured[7] and these are $\mu(Hg^{201}) = -0.55670$ and $\mu(Os^{189}) = +0.65596$, respectively. Hecht and Satchler[8] have attempted to fit the observed energy-level spectrum of Pt^{195} with a symmetric and an asymmetric rotator model. Although the level scheme seems to be in fair agreement with the asymmetric-rotator calculation, the model fails in its prediction of electric transition probabilities and magnetic moments. They conclude that neither a simple rotational, nor a simple vibrational model can be applied to Pt^{195}, but a more sophisticated calculation which would include strong mixtures of states might prove more successful. Clearly, there are still insufficient data to make reliable predictions on the basis of either a model or systematics.

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ACKNOWLEDGMENTS

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Properties of the State in P^{31} at 7.14 MeV*

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The $F^{19}(p,\alpha\gamma)O^{16}$ reaction has been used as the source of Doppler-broadened radiation in the study of resonance fluorescence from a level at 7.144±0.013 MeV in P^{31}. The angular distribution of the scattered radiation is consistent with a spin of either $\frac{1}{2}$ or $\frac{3}{2}$. For a spin of $\frac{3}{2}$ the quadrupole-dipole amplitude ratio δ is such that either $+0.15<\delta<+0.40$ or $-2.5>\delta>-6.5$. The mean lifetime of the ground-state transition, as determined by a self-absorption measurement, is $\tau_0 = (4.8\pm0.6\times10^{-16}$ sec for a spin of $\frac{1}{2}$, or $\tau_0 = (1.0\pm0.1)\times10^{-15}$ sec for a spin of $\frac{3}{2}$. The resonant scattering cross section is consistent with these values only if little branching to intermediate states is assumed, which is consistent with the observed pulse-height distribution.

1. INTRODUCTION

THE $F^{19}(p,\alpha\gamma)O^{16}$ reaction has been used as a source of gamma rays in the study of resonance scattering from light nuclei, and a large effect has been observed with a phosphorus scatterer. Three prominent gamma rays of energies 6.131, 6.916, and 7.115[1] MeV are emitted by the (p,α) reaction at an incident proton energy of 2.5 MeV; however, only the 6.92- and 7.12-MeV gamma rays are Doppler-broadened to a width of 130 keV. No levels in P^{31} in this energy region had been reported,[2] consequently it was not known whether the 6.92 or 7.12 gamma ray or both were giving rise to the observed resonance scattering. An estimate of the level spacing at this excitation energy in P^{31} suggested the possibility that more than one level may have been excited, and the early work[3] still left some doubt concerning this question, since there seemed to be a discrepancy between the self-absorption and scattering cross sections which could not be accounted for by branching.

To determine which gamma ray was being resonantly scattered, the experiment was repeated using a thin target and incident proton energies of 2.1 and 2.5 MeV for which the relative yields of the two gamma rays differ by a factor of 4. Furthermore, the energy of the scattered radiation was measured by a direct comparison between the pulse-height distributions of the resonantly scattered radiation from P^{31} and O^{16}. The evaluation of the scattering cross section requires a detailed knowledge of the line shape of the incident radiation, and this was measured using a Li-drifted germanium detector.

2. EXPERIMENTAL PROCEDURE

The apparatus is shown in Fig. 1, the experimental procedure being similar to that used in the study of the 7.10-MeV level in Na^{23}.[4] The initial measurements were

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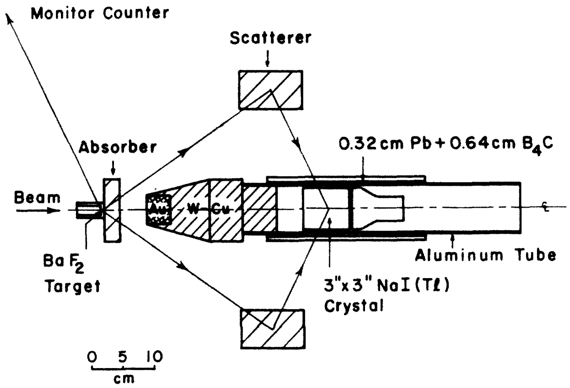

FIG. 1. Scattering and self-absorption geometries. The same geometry was used for the angular-distribution measurements, different scattering angles being obtained by moving the NaI(Tl) crystal axially.

made using thick BaF_2 targets which were prepared by pressing 99.5% pure BaF_2 powder into an aluminum holder and then covering this with a 10 mg/cm^2 tantalum foil. The foil was necessary to contain the BaF_2 which tended to evaporate under bombardment by proton beams of 5 μA. Subsequent measurements were made with targets 100- to 200-keV thick for 2.5-MeV protons, which were prepared by vacuum evaporation onto 10-mil tantalum backings.

Three different scatterers were used in these studies. These scatterers were prepared by packing powdered phosphorus into aluminum containers with $\frac{1}{32}$ in. walls. Two of these were ring scatterers with an i.d. of $12\frac{3}{4}$ in., an o.d. of $16\frac{1}{2}$ in. and widths of 1 in. and 4 in. The other scatterer was used in a "point geometry" and was $5\frac{1}{16}$ in. in diameter by $2\frac{7}{8}$ in. thick.

The phosphorus absorber was prepared in the same way as the scatterers and was 4 in. in diameter by 1 in. thick. Aluminum, which was previously shown to give no reasonance fluorescence effect,[4] was used to make the comparison absorber and scatterers. The matching of the aluminum and phosphorus absorbers for electronic absorption was checked by measuring their gamma ray attenuation directly, and was found to be within $\pm 1\%$. The effect of any residual mismatch on the self absorption measurement would be less than $\pm 0.1\%$, as the total electronic absorption was only 0.11.

TABLE I. Angular distributions of 6.14, 6.92, 7.12-MeV γ rays from $F^{19}(p,\alpha\gamma)O^{16}$ reaction with a 1.8 mg/cm^2 BaF_2 target. The coefficient a is defined by $W(\theta)=W_0(1+a\cos^2\theta)$.

Gamma ray (MeV)	Proton energy (MeV)	Coefficient a Present	Huizenga *et al.*[a]	Trail and Raboy[b]
6.14	2.1	-0.06 ± 0.3	0.19 ± 0.13	0.05
6.92		0.24 ± 0.5	0.29 ± 0.14 (6.92 and 7.12)	0.09
7.12		0.51 ± 0.1		0.44
6.14	2.5	0		
6.92		$0.1\ \pm0.1$		
7.12		$0.1\ \pm0.1$		

[a] See Ref. 9. [b] See Ref. 8.

3. GAMMA-RAY SOURCE

The $F^{19}(p,\alpha\gamma)O^{16}$ reaction has been used as a source of gamma radiation in a number of studies of resonance fluorescence.[4-6] The excitation function for incident proton energies below 2.5 MeV has been studied both by detection of the alpha particles[5] and the gamma rays.[7,8] The ratio of the yield of the 6.92-MeV gamma ray to that of the 7.12-MeV gamma ray for a thin target, is shown in Fig. 2, and is seen to be a rapidly varying function of the proton energy. A comparison of the alpha-particle and gamma-ray data indicates a significant discrepancy. In an effort to elucidate this discrepancy, the angular distributions of the gamma rays relative to the proton beam were measured with a 3×3 in. NaI(Tl) crystal, for proton energies of 2.1 and 2.5 MeV. The angular distributions were assumed to be of the form

$$W(\theta)=W_0(1+a\cos^2\theta),$$

and our results, together with those of Huizenga[9]

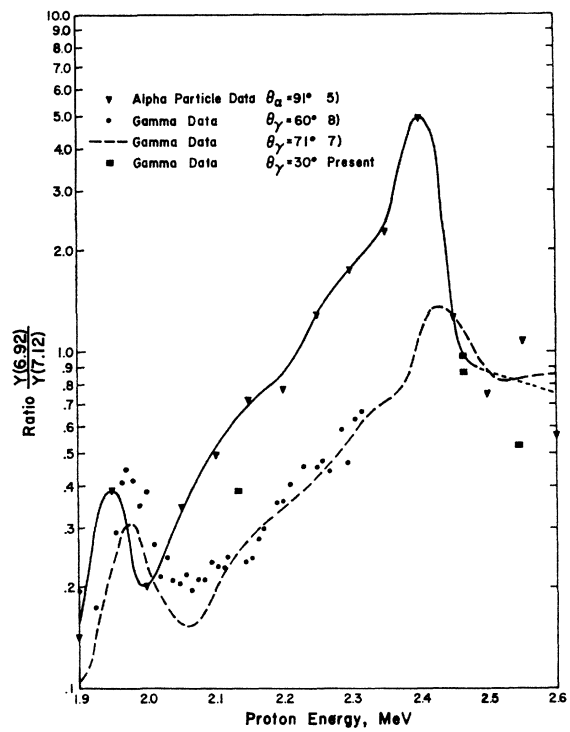

FIG. 2. The ratio of the yields of the 6.92- and 7.12-MeV gamma rays from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction as a function of proton energy.

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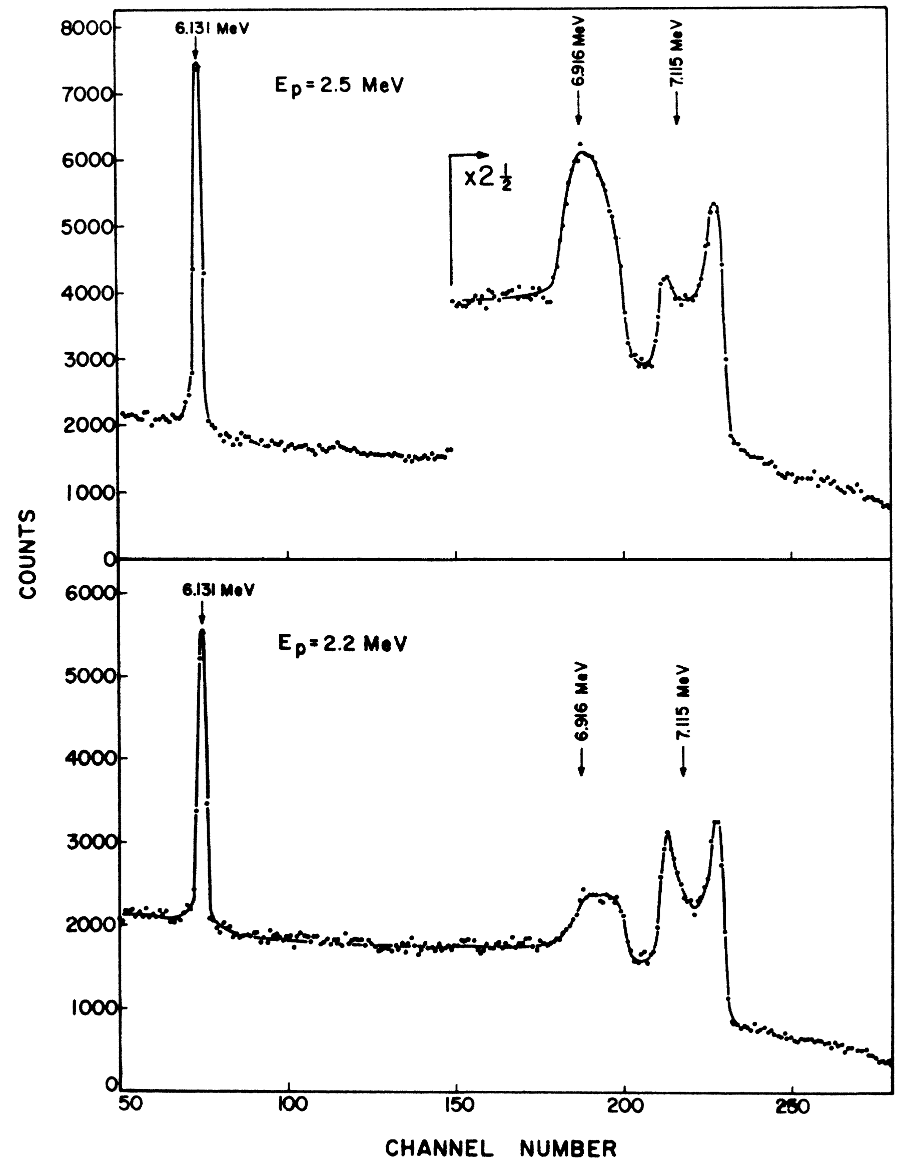

FIG. 3. Pulse-height distribution of the radiation from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction as observed in a Li-drifted germanium detector located at an angle of 30° to the proton beam. Only the two escape peaks are apparent. The arrows locate the energies of the O^{16} levels.

and Trail and Raboy[8] for a thin target, are shown in Table I.

The complex nature of the pulse-height spectra made analysis into the three component gamma rays difficult, and this was the main source of error in these measurements as well as in our initial estimates of the relative yields. The observed gamma-ray anisotropies would not account for the difference between the gamma-ray and alpha-particle yield ratios, thus leading to the conclusion that the alpha-particle angular distributions were anisotropic, which was later confirmed by measurements of the Doppler-broadened gamma-ray line shapes. The results of Clarke and Paul,[10] and Warsh[11,12] on the $F^{19}(p,\alpha_0)O^{16}$ reaction at these and higher energies show that this reaction proceeds by compound nuclear, pickup, and heavy-particle stripping reaction mechanisms, so that alpha-particle anisotropies are to be expected.

Throughout the studies of resonance fluorescence using nuclear reactions, there have always been uncertainties in the exact shape of the Doppler-broadened "micro" spectrum. Consequently, quoted lifetimes have usually been based on the results of self-absorption experiments. However, if the line shape is known, additional information, such as the ground-state

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[11] K. L. Warsh, G. M. Temmer, and H. R. Blieden, Phys. Rev. 131, 1690 (1963).

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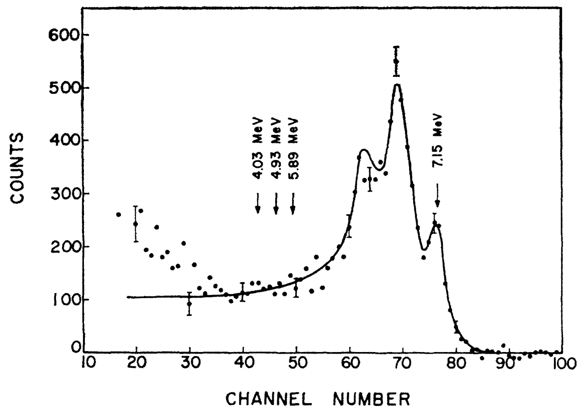

FIG. 4. Pulse-height distribution of the resonantly scattered radiation as observed in a 3-in.×3-in. NaI detector. The solid curve gives the best estimate of the distribution for a 7.15-MeV gamma ray. Also shown are the expected positions of full energies of the gamma rays that would result if branching took place to the first three excited states of P^{31}.

branching ratio, can be obtained by comparing the scattering and self absorption results. A calculation of the line shape involves a knowledge of the target thickness, excitation function, stopping powers of both protons and recoiling nuclei in the target material, the alpha-gamma angular correlations, and, except in the case of isotropic angular correlations, the angle of observation with respect to the beam direction.

To evaluate the scattering cross section, the energy of the level in P^{31} responsible for the resonant scattering must be precisely known. The simplifying assumption of isotropic angular correlations, which has been used in all previous work, and the uncertainties in the other factors involved could account for the lack of agreement between the early self absorption and scattering results.[3] The shape of the "micro" spectrum of the gamma rays from the $F^{19}(p,\alpha\gamma)O^{16}$ reaction was therefore measured directly with a Li-drifted germanium counter. The counter, which was obtained from Solid State Radiations, Inc., was 110 sq mm by 4 mm deep, and had a resolution of 5 keV (full width at half-maximum). Spectra were taken at an angle of 30° to the beam and at proton energies of 2.5 and 2.2 MeV; the target thickness was about 200 keV for 2.5-MeV protons. Figure 3 shows the results, in the region containing the second escape peaks, and it will be seen that the 6.14-, 6.92-, and 7.12-MeV lines are well resolved. The 6.14-MeV line shows no Doppler-broadening as is expected, since the lifetime of this state is long compared with the stopping time of the recoiling O^{16} nuclei. The shape of the 6.92-MeV line differs significantly from the shape of the 7.12-MeV line, which also changes appreciably with incident proton energy. The peaking of the 7.12-MeV line shape is consistent with the assumption of forward and strong backward peaking of the alpha particles. However, measurements at 90° to the beam also show peaks in the 7.12-MeV line shape; although less pronounced, thus an alpha-gamma correlation must also be involved.

4. LEVEL ENERGY

The first question that arose following the observation of resonance fluorescence in P^{31} was whether the 6.92 MeV, the 7.12 MeV, or both gamma rays were being resonantly scattered. The ratio of the intensities of the 6.92- and 7.12-MeV lines is a rapidly varying function of the proton energy, (see Fig. 2). Therefore, measurements of both the scattering and self-absorption cross sections were made at bombarding energies of 2.1 and 2.5 MeV, and the scattering cross section was also measured at 2.2 MeV. Using the average value for the number of gamma rays per unit energy interval as given by the data of Fig. 3, the ratio of the scattering cross section at 2.2 MeV to that at 2.5 MeV was 1.07 ± 0.05 assuming the 7.12-MeV radiation was responsible for the effect, and 4.2 ± 0.8 assuming the 6.92-MeV radiation; thus the resonance scattering was predominantly caused by the 7.12-MeV gamma rays. The self-absorption, if due to one gamma ray, would not change with proton energy. The measured values were $(25\pm5)\%$ and $(33\pm5)\%$ at 2.5 and 2.1 MeV, respectively, which is consistent with the assumption that only the 7.12-MeV gamma ray is being resonantly scattered. It is still possible that more than one level was being excited by the 7.12-MeV radiation; however, our measurements are consistent with the assumption that only one level is responsible.

The energy of the state was further defined by measurements of the resonance scattering as a function of the angle between the incident gamma rays and the proton beam. From the kinematics of the reaction the Doppler-spread remains constant with angle, whereas the Doppler-shift due to center-of-mass motion increases the mean energy as the angle of observation is decreased. These experiments were performed using both the ring scatterers and the point scatterer, and covered an angular range between 6° and 160° to the proton beam. No abrupt changes in the resonance scattering were observed which, therefore, limits the energy of the level to 7.075 MeV$<E_\gamma<$7.156 MeV, based on a value of 7.115 MeV[1] for the level in O^{16}.

The pulse-height spectrum for the resonantly scattered radiation from P^{31} was compared with that from O^{16}; water was used as the O^{16} scatterer. From this comparison it was determined that the energy of the P^{31} level is (7.171 ± 0.040) MeV. This combined with the limits cited above gives the energy as (7.144 ± 0.013) MeV.

5. PULSE-HEIGHT DISTRIBUTION AND BRANCHING

Figure 4 shows the pulse-height distribution obtained as the difference between that for the phosphorus scatterer, and that for the aluminum scatterer. The solid curve represents our best estimate of the pulse-height distribution for a 7.15-MeV gamma ray. Branching to the first three excited states would result in gamma rays with energies of 5.88, 4.92, and 4.02 MeV. From an analysis of the pulse-height spectrum, it was estimated that no branching occurred to the first two excited states in more than 5% of the decays and to the third excited state in more than 10% of the decays. The rise in the data above the solid curve below channel 35 was attributed to a mismatch in the P and Al scatterers, (see caption of Fig. 6).

6. ANGULAR DISTRIBUTION

The angular distribution of the scattered radiation was measured using both the large and the small ring scatterers. In each case the position of the scatterer was fixed and the angle was changed by moving the NaI crystal along the axis. Measurements were made at four angles between 90° and 150° with each scatterer, and are shown in Fig. 5. A least-squares fit to this data gives the distribution $W(\theta)=1+(-0.017\pm0.073)\ P_2$. Since the ground-state spin is $\frac{1}{2}$, this distribution will allow for either a spin of $\frac{1}{2}$ or $\frac{3}{2}$ for the 7.15-MeV state. For the spin of $\frac{3}{2}$ the amplitude ratio δ may have two ranges of values, either $+0.15<\delta<+0.40$ or $-2.5>\delta>-6.5$.

7. TRANSITION PROBABILITY

Provided that the natural width Γ of the level being studied is small compared to the thermal width Δ and as long as the percent absorption is not too large, the ratio of the resonance scattering with and without an absorber is proportional to $g\Gamma_0/\Delta$, where g is the statistical weighting factor and Γ_0 is the partial width for the ground state transition. If these conditions are not met,

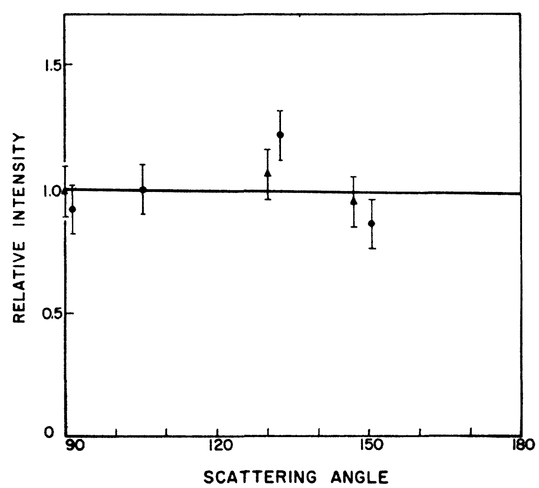

FIG. 5. The angular distribution of the resonantly scattered radiation from P^{31}.

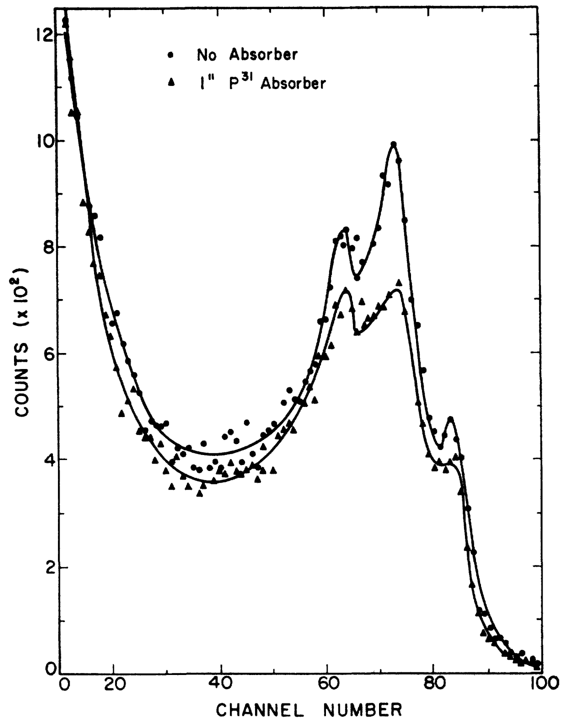

FIG. 6. Pulse-height distributions of the resonantly scattered radiation with and without a 1-in. phosphorus absorber. The distributions have been corrected for electronic effects and background by subtracting the distributions obtained with an aluminum scatterer. The rapid rise at low pulse height is due to a mismatch of the scatterers for multiple Compton scattering.

then the pure Doppler form must be replaced by the general form for the cross section.[13]

Three self-absorption measurements were carried out, one using a thick BaF_2 target and the other using a target about 1.8 mg/cm² thick, at incident proton energies of 2.1 and 2.5 MeV. A 1-in. thick absorber was used along with the large scatterer in a position such that the mean angle of the incident gamma rays relative to the proton beam was about 30°. Pulse-height spectra with and without a resonant absorber, and after correction for electronic effects and background are shown in Fig. 6. The measured reductions in counting rate were (23±2)%, (33±5)%, and (25±5)%, respectively, giving a weighted mean of (25±2)%. The calculation of $g\Gamma_0$ was first performed using the pure Doppler form for the cross section and gave $g\Gamma_0=(1.18\pm0.1)$ eV. For a 7-MeV gamma ray from P^{31}, $\Delta=9.4$ eV, and for a spin of $\frac{1}{2}$, $g=1$. Therefore, $\Gamma/\Delta=0.13$ and the use of the pure Doppler form becomes questionable. The level width was, therefore, calculated using the general form for the cross section, and the value obtained was $\Gamma_0=(1.36\pm0.16)$ eV. For a spin of $\frac{3}{2}$ the width calculated using the general form becomes $\Gamma_0=(0.63\pm0.07)$ eV.

In the scattering experiment the counting rate is proportional to $N(E_R)g\ \Gamma_0^2/\Gamma$, where $N(E_R)$ is the

[13] F. R. Metzger, Progr. Nucl. Phys. 7, 54 (1959).

number of gamma rays per unit energy interval at the resonance energy, and Γ is the total width of the level. Since it was already shown in Sec. 4 that the resonance scattering was caused by the 7.12-MeV line, we may now take the average $N(E_R)$ for the 7.12-MeV radiation relative to the total of the 6.19- and 7.12-MeV radiation in the beam from Fig. 3 and calculate $g\Gamma_0^2/\Gamma$. Two steps are involved in determining $N(E_R)$, firstly the detection efficiency of the 3-in.×3-in. NaI(Tl) crystal, used to detect the resonance fluorescence radiation, was calibrated against the monitor by placing the detector directly in the gamma-ray flux from the target. The spectrum resulting was then analyzed using the Li-drifted Ge detector data to determine the relative number of counts from each gamma ray in a specified region of the pulse-height spectrum. The width and position of the region used was selected so as to exclude any contribution from the 6.13-MeV radiation. Having done this for both the 2.2- and 2.5-MeV data, the results obtained using the pure Doppler form for the cross section were $g\Gamma_0^2/\Gamma = 1.42\pm0.10$ eV and 1.44 ± 0.20 eV, respectively. The errors have been increased by about a factor of two over the statistical error to allow for the uncertainty in the determination of $N(E_R)$. If we assume 100% branching to the ground state and a spin of $\frac{1}{2}$, the general form for the cross section gives $\Gamma_0 = 1.42\pm0.10$ eV and 1.42 ± 0.20 eV, respectively.

Assuming no branching, a comparison of the scattering and self-absorption results leads to a value for $N(E_R)/N_{av}(E)$ of 1.04 ± 0.19 for a spin of $\frac{1}{2}$, and 1.13 ± 0.20 for a spin of $\frac{3}{2}$, where $N_{av}(E)$ is the number of gamma rays per unit energy calculated assuming isotropic angular distributions. This result favors slightly the spin of $\frac{1}{2}$. The observed line shapes (see Fig. 3) lead to these values for resonance energies of 7.164 ± 0.015 MeV and 7.167 ± 0.015 MeV for spins of $\frac{1}{2}$ and $\frac{3}{2}$, respectively. The effect of the finite counter resolution on the observed line shape has not been taken into account. We therefore consider these energy values to be in good agreement with that obtained in Sec. 4.

In the above calculations it has been assumed that no branching takes place to any intermediate states. For a given $N(E_R)$, branching would lead to a larger value for Γ_0 in disagreement with the self-absorption results. On the other hand if the value of Γ_0 as obtained from the self-absorption experiment is used the introduction of branching would lead to a larger $N(E_R)$. Since this would require the level energy to be outside the value given in Sec. 4, support is given to the results of Sec. 5 which allows for little branching.

There is still a possibility that more than one level was being excited. A level with 10% of the width of the main level would essentially increase the scattering counting rate by 10% whereas it would reduce the self-absorption only about 7%. However, it would still be essential that the energy of this second level be within 31 keV of the principal level as seen in Sec. 4.

CONCLUSION

The energy of the level observed in P^{31} was measured to be 7.144 ± 0.013 MeV. The angular distribution of the scattered radiation was essentially isotropic which allows for either a spin of $\frac{1}{2}$ or $\frac{3}{2}$. For the spin of $\frac{3}{2}$ two regions of δ, the quadrupole-dipole amplitude ratio, are possible, either $+0.15<\delta<+0.40$ or $-2.5>\delta>-6.5$. From the pulse-height distribution it was observed that one could set an upper limit of 5% branching to the first excited state, 5% to the second excited state, and 10% to the third excited state. The results of the scattering experiment are consistent with the self-absorption results only if it is assumed that little branching takes place to intermediate states.

For the spin of $\frac{1}{2}$ the ground-state width becomes 1.36 ± 0.16 eV which corresponds to a mean life of $(4.8\pm0.6)\times10^{-16}$ sec. The character of this transition may then be either $E1$ or $M1$ depending on the parity. In terms of the Weisskopf estimate for these transitions, we may have either an $E1$ transition slowed down by a factor of 140 or an $M1$ transition slowed down by a factor of 5. On the basis of data accumulated for nuclei in the region $20<A<40$[14] either of these would be acceptable.

For a spin of $\frac{3}{2}$ the ground-state width becomes 0.63 ± 0.07 eV, which corresponds to a mean life of $(1.04\pm0.12)\times10^{-15}$ sec. The transition could be of either a mixed $E2$-$M1$ or $M2$-$E1$ character depending on the parity. The Weisskopf estimate for an $E2$ transition of this energy is 1.2×10^{-14} sec. Therefore, for the positive value of δ we would have an $E2$ transition of about full Weisskopf strength and for the negative value an $E2$ transition enhanced by about a factor of 8; either of these are reasonable. The Weisskopf estimate for an $M2$ transition is 3.2×10^{-13} sec. This then gives an enhancement of 40 or 300 depending on whether δ is positive or negative. Because of the lack of data on $M2$ transitions, however, very little can be said as to whether or not either of these are acceptable.

The character of a possible transition to the first $(\frac{3}{2}+)$ excited state again may be either a mixed $E2$-$M1$ transition or an $M2$-$E1$ transition for either spin, depending on the parity. The Weisskopf estimate for an $E2$ transition of 5.88 MeV is 3.3×10^{-14} sec and for an $M2$ transition is 6.6×10^{-13} sec. A branching of less than 5% to this state would, therefore, be reasonable.

Finally, it should be noted that a state in P^{31} at 7.15 ± 0.01 MeV has recently been observed in the $Si^{30}(d,n)P^{31}$ reaction,[15] in good agreement with the present results.

We would like to thank Dr. F. R. Metzger for many helpful discussions, and Dr. C. C. Trail for making his data on the $F^{19}(p,\alpha\gamma)O^{16}$ reaction available prior to publication.

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[15] B. Cujec *et al.*, Phys. Letters **15**, 266 (1965).