PHYSICAL REVIEW C VOLUME 4, NUMBER 5 NOVEMBER 1971

Spectroscopy of Some Low-Lying States in ^{69}Zn†

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(Received 24 June 1971)

The analog resonances of some low-lying states of ^{69}Zn have been investigated using the triple-angular-correlation geometry of Goldfarb and Seyler for the reaction $^{68}\text{Zn}(p, p_1'\gamma)$-$^{68}\text{Zn}^*$(1.08 MeV). Excitation functions for elastic and inelastic protons (0^+, ground state; 2^+, 1.08 MeV; 0^+, 1.66 MeV; 2^+, 1.88 MeV) have been measured at 90, 120, 130, and 160°. The following spin and parity assignments have been made for the states in ^{69}Zn: 0.835 MeV, $\frac{3}{2}^-$; 0.872 MeV, $\frac{5}{2}^+$; 1.634 MeV, $\frac{5}{2}^+$; 1.696 MeV, $\frac{1}{2}^+$; 2.262 MeV, $\frac{1}{2}^+$; 2.403 MeV, $\frac{5}{2}^+$; 2.554 MeV, $\frac{5}{2}^+$; and 2.669 MeV, $\frac{1}{2}^+$.

I. INTRODUCTION

Goldfarb and Seyler[1] have proposed a method for determining the spins of resonant states and have suggested several types of experiments where these methods might be applicable, such as isobaric analog and intermediate-structure resonances. Their method involves measurements, in a particular geometry, of proton-γ-ray angular correlations at incident particle energies corresponding to the resonances of interest. Previous studies[2,3] have been completed at the Van de Graaff Accelerator Laboratory of The Ohio State University on some excited states of ^{25}Al by the reaction $^{24}\text{Mg}(p, p_1'\gamma)^{24}\text{Mg}^*$(1.368 MeV) utilizing this method. The Goldfarb-Seyler method (GSM) was proposed only for isolated resonances, and the authors took care to warn investigators that due consideration must be given to any observed nonresonant yield, by investigating the on- and off-resonance behavior of the angular-correlation coefficients. In the $^{24}\text{Mg}+p$ system, there were relatively few states in the region of the low-lying resonances, whereas isobaric analog states in heavy nuclei are observed as resonant structures superimposed upon a sea of $T_<$ compound-nuclear states. Since the density of these $T_<$ states is normally very high, one would expect that the off-resonance angular-correlation coefficients would have a slowly varying energy dependence. This paper reports the measurement of the spins and parities of some low-lying states in ^{69}Zn by utilizing the GSM for the spin measurements on the isobaric analogs of these states in ^{69}Ga.

The region of the zinc isotopes was chosen for study, since isobaric analog resonances (IAR) have been observed previously in the zinc isotopes by several investigators. Gaarde, Wilhjelm, and Bruun[4] observed IAR in the $^{64,66,68}\text{Zn}(p, p_0)$ and (p, p_1) reactions up to $E_p = 4.2$ MeV, and extracted widths and spectroscopic factors of some low-lying levels of ^{65,67,69}Zn. Gorodetzky, Bergdolt, and Bergdolt,[5] using the reactions $^{64,66,68}\text{Zn}(p, p'\gamma)$, observed several of these resonances in the same energy range by measuring the γ-ray yield for the 2^+ to 0^+ transitions in the residual nuclei. Vourvopoulos and Fox[6] have investigated the IAR of ^{69}Zn by the (p, p_0) and (p, n) reactions on ^{68}Zn. They obtained the l_p values for the resonances investigated for $E_p = 3.9$ to 7.7 MeV. Recently, Egan *et al.*[7] investigated a previously unresolved doublet at 4.1 MeV and the doublet at 4.9 MeV, by the $^{68}\text{Zn}(p, n)$ reaction populating a number of final states in ^{68}Ga, to determine the spins, parities, and widths of these four resonances. The parent states in ^{69}Zn have been investigated by the $^{68}\text{Zn}(d, p)$ reaction for which l_n values and spectroscopic factors have been extracted. The present results for the spins and parities of the low-lying states of ^{69}Zn are compared with those of Ref. 8.

II. EXPERIMENTAL PROCEDURES

The proton beam used in this experiment was obtained from the CN Van de Graaff accelerator of The Ohio State University. Target material of isotopically enriched ^{68}Zn (98.5%) was purchased from Oak Ridge National Laboratory, Separated Isotope Division. This material was rolled into a self-supporting target[9] and was measured to be 0.63 mg/cm^2 thick by Rutherford scattering at 2.5 MeV.

Excitation curves were measured in steps of 10 or 20 keV for incident protons in the energy range 3.9–6.1 MeV. The scattered protons were observed in surface-barrier detectors placed at laboratory scattering angles of 90, 120, 130, and 160° in a 23-in.-diam scattering chamber in order to locate the prominent IAR's in elastic and inelastic channels.

Angular-correlation data were taken using a recently constructed angular-correlation apparatus that permitted operation at relatively high coincidence rates, and thus enabled us to complete this experiment in a reasonable amount of time. A solid-state detector, which was located at $90°_{\mathrm{c.m.}}$, was mounted inside a 25-cm-diam spun stainless-steel hemispherical chamber. γ rays were detected about 19 cm from the target with lead-shielded 10-cm-diam by 12.5-cm-deep NaI(Tl) detectors that were rotated in a plane perpendicular to the reaction plane. Much of the data was taken using two γ-ray detectors mounted on the same rotating table support in order to collect data more efficiently. Details of this table have been previously reported.[10]

The electronics used for the excitation functions were conventional; that used for the angular-correlation data was designed for particle and γ-ray pulse pileup rejection and measurement,[11] shown in Fig. 1. Only the integrated photopeak of the coincidence yield was used in the analysis, and this yield satisfied the following requirements:

(a) A fast-time coincidence must occur between a particle and a γ ray, typically within 0.050 μsec.

(b) The particle energy must be within a specified energy window for the reaction.

(c) The pulses from the detectors must not be followed within 2 μsec nor preceded by 1 μsec by another detector pulse.

(d) An "accidental" spectrum was taken concurrently with the same requirements as above, except the γ-ray and particle signals were displaced by 0.1 μsec. This spectrum was subtracted from the total spectrum.

With these requirements fulfilled, the subtracted photoelectric peak was integrated to obtain the coincidence yield which was then corrected for particle and γ-ray pulse pileup. In some of the later correlations, two γ-ray detectors were used simultaneously, at different angles. In this case, the γ-ray signals were clipped to a width of 0.1 μsec and only the fast coincident γ-ray signals were stretched and amplified. Although the resolution of the γ-ray signals was degraded, the pulse pileup was minimal, and no corrections were made

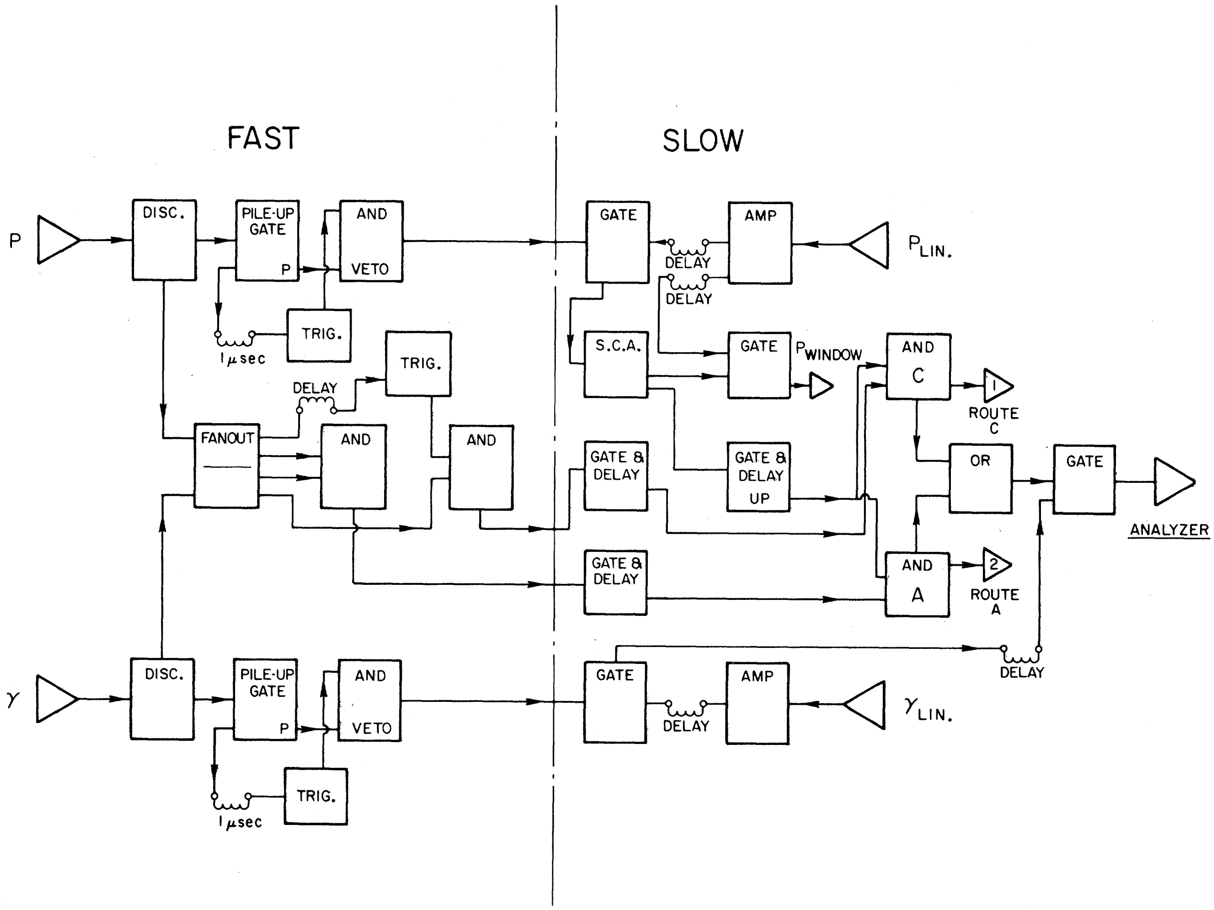

FIG. 1. Fast and slow electronics block diagram. The blocks indicate plug-in units. Arrows indicate the flow of the electronic signals that are analyzed for proper energy and pulse pileup rejection. C are the coincidence (total) signals. A are the accidental signals, UP are the unpiled-up proton signals, and P (in the pileup gate) are the piled-up signals.

for γ-ray pulse pileup.[12]

An IBM 1800 on-line computer system[13] was used as a multichannel analyzer with 512 channels for each detector subgroup. 60 to 120 μC of charge were collected for each data point of the excitation curve with a typical beam of 0.1 μA. For the correlation data, 400 to 3000 μC were collected for each angle of a correlation with a beam current of 60 to 220 μA, depending on the amount of pulse pileup. A maximum correction factor of 1.20 (that is, the product of proton pile-up and the γ-ray pileup corrections) was set as an arbitrary limit in order to determine the maximum allowed beam current. This limitation and the yield strength caused the actual time for an angle measurement to be from 40 to 200 min. A sample of total and accidental spectra is shown in Fig. 2.

Reduction of the scattering data was accomplished on line by the control program SOUTH, written by J. D. Goss and one of the authors (JRD). This program follows up to eight peaks, searches for smooth background regions for each peak, integrates the peak, and subtracts the background. SOUTH also allows the operator to choose his own background, and then recalculates the area of the peak.

The reduction of the correlation data was also accomplished on line, by the program DURAI, written by two of the authors (JRD and WSS). This program essentially stores the total and accidental spectra and scaler readings on disk, calculates the correction factors for pulse pileup and dead time, allows the operator to pick four channels for background subtraction of the photopeak, and outputs the data on cards. These cards are used as inputs to other programs used off line to analyze the angular-correlation data. Details for the data reduction and analysis have been reported previously.[10]

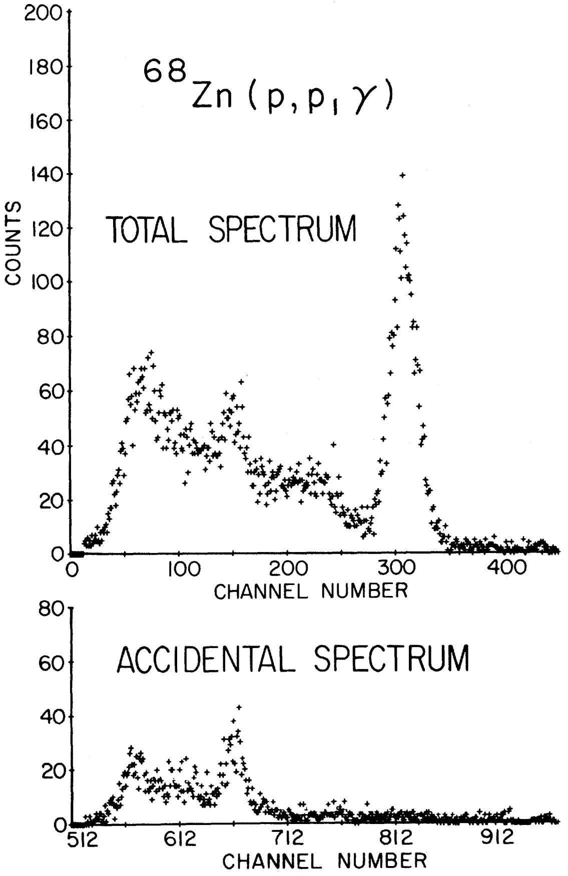

FIG. 2. Sample of total and accidental spectra. The peak of interest (1.08 MeV) is clearly seen in the total spectrum at about channel 310 and is not appreciably seen in the accidental spectrum. The peaks at channels 150 and 662 are the 0.51-MeV annihilation γ ray that results from the competing ^{68}Zn$(p,n)^{68}$Ga reaction.

III. RESULTS AND ANALYSIS

A. Proton Scattering

Excitation curves were obtained for scattering to the ground state (0^+) and several low-lying excited states of ^{68}Zn: the 1.08-MeV (2^+), 1.66-MeV (0^+), and 1.88-MeV (2^+) states. At the lower energies, the cross sections for exciting the 1.66- and 1.88-MeV states were generally too weak for observation. Gaps in the 1.08-MeV (2^+) excitation curve are due to the ^{12}C and ^{16}O impurity peaks obscuring the peaks of interest. The excitation curves are shown in Figs. 3–6.

The data points for elastic scattering at the four

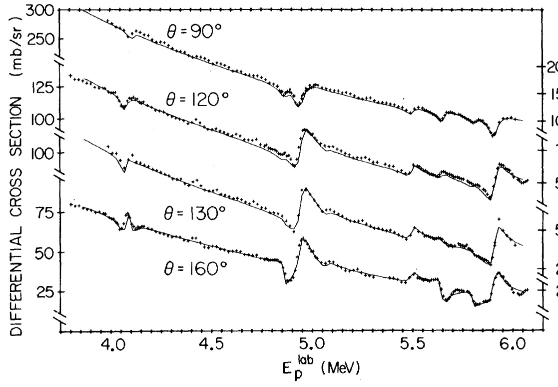

FIG. 3. ^{68}Zn(p,p_0) elastic scattering curves. The data points are represented as crosses, whose statistical uncertainty is less than the size of the points. The solid curves are the calculated yield functions as obtained from the computer code JULIUS. The parameters entered in the code are listed in Table I. The data points have been normalized to the optical-model potential calculations using the smooth region from 4.2 to 4.7 MeV.

observed angles covering the range from 3.9- to 6.1-MeV incident energy are shown in Fig. 3 as crosses. The data agree quite well with that of Vourvopoulos and Fox.[6] This yield was compared with the calculation obtained from a version of the computer code JULIUS, written by Zaidi and Darmodjo[14] using the S-matrix formalism of Weidenmuller.[15] The S matrix elements for elastic scattering from IAR may be given as [16]

$$\langle S\rangle = S_{cc}^{\mathrm{opt}} + S_{cc}^{\mathrm{res}}\,, \tag{1}$$

where S_{cc}^{opt} denotes the optical-potential scattering by the $T_<$ background states, and S_{cc}^{res} denotes the resonance scattering which is modified by the presence of $T_<$ states and depends on the microscopic structure. The off-resonance cross section was calculated, using the code JULIUS, with a set of optical-model parameters obtained from the paper by Becchetti and Greenlees.[17] Once this behavior was satisfactorily fit, parameters for Breit-Wigner resonances were introduced into JULIUS, and the program calculated the elastic cross sections. These calculations are shown in Fig. 3 as a solid curve, and the resonance and optical-model parameters are listed in Table I. The quantity Δ, as defined in Ref. 15, was used in the present case as an arbitrary phase to obtain the best visual fit to the data.

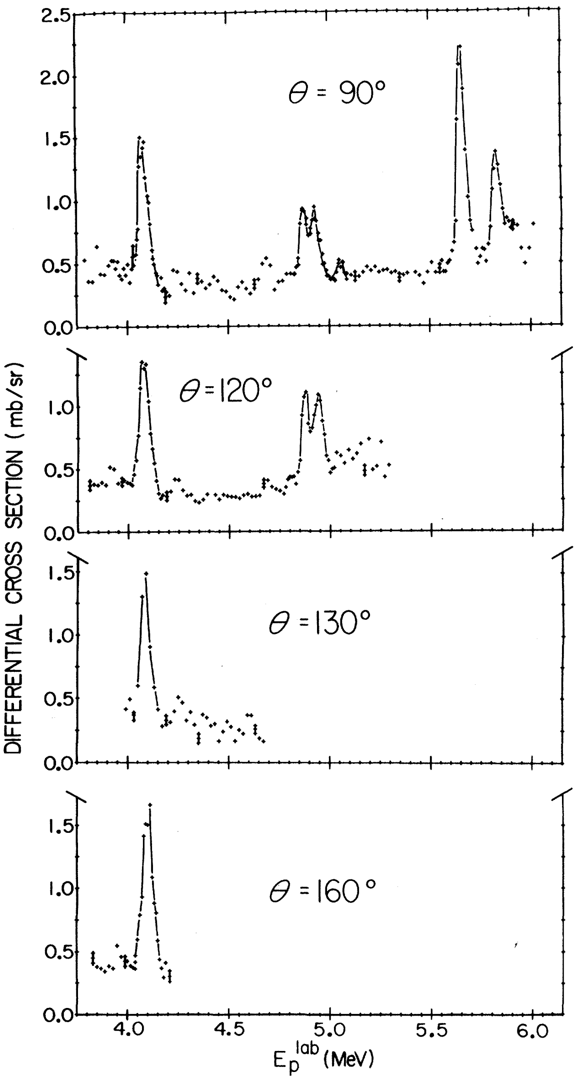

FIG. 4. ^{68}Zn$(p,p_1)^{68}$Zn* (1.08 MeV, 2^+) inelastic-yield curve. The statistical uncertainties are indicated at various points in the spectra. The solid lines are shown merely to guide the eye, and are not theoretical fits to the data. The data points have been normalized using the factors obtained from the elastic scattering data.

The spectroscopic factors, also shown in Table I, are defined as[18]:

$$S = (N+1-Z)\Gamma_p P_n\,, \tag{2}$$

where N and Z are the numbers of target neutrons and protons, Γ_p is the proton elastic scattering partial width, and P_n is the penetration factor as defined by Thompson.[18] The spectroscopic factors were obtained using our data and the results of Thompson[18] for the penetration factors. These re-

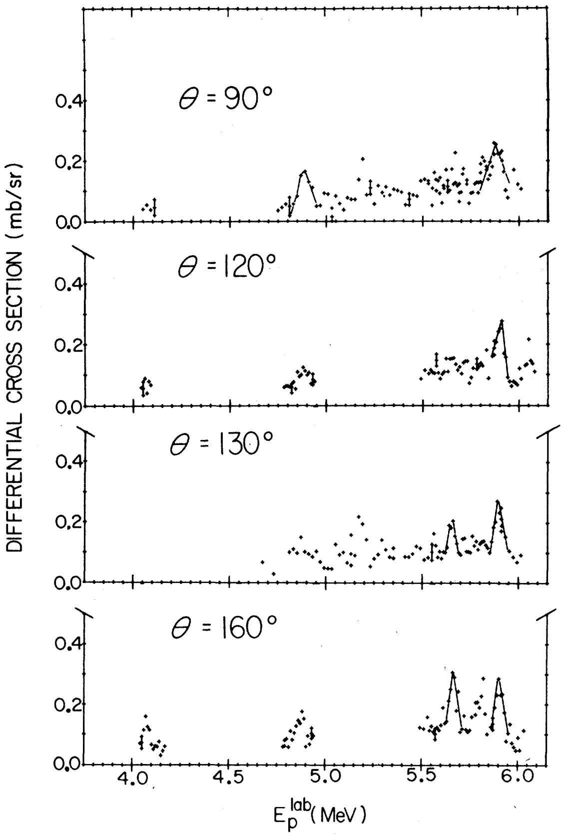

FIG. 5. ^{68}Zn$(p,p_2)^{68}$Zn* (1.66 MeV, 0^+) inelastic-yield curve. See caption for Fig. 4.

sults are compared with those found by von Ehrenstein and Schiffer[8] in the reaction ^{68}Zn(d, p)^{69}Zn. The agreement is fairly good, although the spectroscopic factors are not model independent, as pointed out by Clarkson, von Brentano, and Harney.[19]

B. Proton γ-Ray Angular Correlations

1. *General Remarks*

The geometry suggested by Goldfarb and Seyler for triple angular correlations provides a model-independent method for determining the spins of resonant states. In this geometry the z axis is defined as the out-going particle direction, and the γ ray emitted by the final state in proton scattering to the first excited state is detected in a cone about this z axis. The complexity κ of the correlation obtained by varying the γ-ray detector angle on the surface of the cone is limited by the various angular momenta involved. In particular, if the cone angle is 90°, then the correlation yield is given by

$$W(\theta_\gamma=\tfrac{1}{2}\pi,\ \phi_\gamma)=\sum_{\kappa(\mathrm{even})}A_\kappa\cos\kappa\phi_\gamma\,. \qquad (3)$$

It was shown[1] that

$$\kappa\leq\min[(2c),\ (2L)_{\max},\ (2l_1)_{\max},\ (2b-1)_{\max}], \qquad (4)$$

where c is the spin of the γ-emitting state, l_1 is the orbital angular momentum of the incoming particle, $L_{\max}$ is the multipolarity of the deexcitation

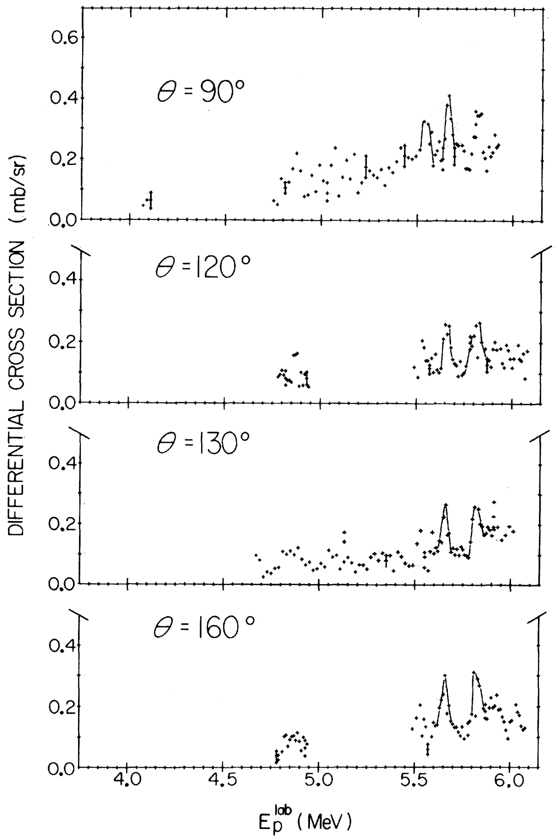

FIG. 6. ^{68}Zn(p,p_3)^{68}Zn* (1.88 MeV, 2$^+$) inelastic-yield curve. See caption for Fig. 4.

TABLE I. Elastic scattering parameters used in code JULIUS.

	Optical-model parameters (Ref. 17)		
(MeV)	(MeV)	(F)	(F)
$V_R=59.768$	$V_{so}=6.2$	$r_R=1.17$	$a_R=0.75$
$W_V=0.0$	$W_{so}=0.0$	$r_I=1.32$	$a_I=0.59$
$W_{SF}=13.312$	$V_{ER}=0.32$	$r_{so}=1.01$	$a_{so}=0.75$
	$W_{ES}=0.25$	$r_C=1.20$	

	Resonance parameters				Spectroscopic factors $(2J+1)S$		
l value	E_{res} (MeV)	Γ_p (keV)	Γ (keV)	Δ (keV)	^{68}Zn(p, p_1) (this work)	E_{ex} (MeV)	^{68}Zn(d,p) (Ref. 8)
1	4.070	2.0	30	30	0.28	0.835	0.37/0.53
2	4.105	1.1	30	−100	0.73	0.872	0.72/0.99
2	4.865	2.2	30	−40	0.55	1.634	0.45/0.61
0	4.945	20.0	60	205	0.47	1.696	0.19/0.21
(1)	5.065	2.0	30	0	0.05	1.831	0.04/0.05
0	5.498	4.0	40	50	0.08	2.262	0.03/0.03
2	5.650	4.0	30	−25	0.52	2.403	0.33/0.43
2	5.805	2.3	30	−20	0.27	2.554	(0.07)/(0.1)
0	5.910	24.0	50	140	0.43	2.669	0.15/0.16

γ ray, and b is the spin of the resonance in the compound system.

Since ^{68}Zn has a 0^+ ground state, for the yield to the 2^+ first excited state, we have $c=2$, $L_{\max}=2$, and l_1 is the orbital angular momentum of the resonance. Therefore, using this formulation, one is able to obtain the results shown in Table II for the present case.

Angular-correlation measurements were taken at and near energies corresponding to IAR. An example of angular correlations taken over one of the resonances is shown in Fig. 7. The results of the least-squares fit is shown by the solid curve, and the A_κ coefficients are indicated. The plots of the coefficients are shown in Figs. 8–10, and are discussed below for the various IAR in ^{69}Ga whose parent states were observed by von Ehrenstein and Schiffer[8] in the reaction ^{68}Zn$(d, p)^{69}$Zn.

2. 4.07- and 4.105-MeV Doublet

Figure 8 shows the results for this doublet which corresponds to the 0.835- and 0.872-MeV states in ^{69}Zn. This doublet was resolved by Egan *et al.*[7] in the ^{68}Zn(p, n) reaction. The A_2 coefficient sharply resonates at 4.07 MeV, but the A_4 coefficient shows no similar behavior there. Even though the weak state at 4.105 MeV is only indicated by the asymmetry at the high-energy side of the yield function, the A_4 coefficient shows a small peaking. The strength of this effect can be estimated by subtracting an off-resonance background from the A_4 coefficient obtained in the vicinity of the 4.105-MeV resonance. As stated before, the background is assumed to be a smoothly varying function with energy, and from the correlations investigated at 3.91, 4.03, 4.20, and 4.27 MeV, it appears to be constant in this region. Table III lists the A_4 coefficient and n, the number of standard deviations above the assumed constant background. Not only is the peak position almost 3 standard deviations above background, but the nearby values show the peaking effect.

The elastic-yield curves for the 4.07- and 4.105-MeV resonances were fitted with $l=1$ and $l=2$, respectively (where l is the orbital angular momentum of the resonance), which are consistent with the maximum $\kappa=2$ and 4 from the correlation yields. Therefore, assignments of $J^\pi=\frac{3}{2}^-$ and $\frac{5}{2}^+$ are made for the 0.835- and 0.872-MeV states in ^{69}Zn, respectively.

3. 4.865- and 4.945-MeV Doublet

Figure 9 shows the results of the angular-correlation measurements at these energies. The peaks

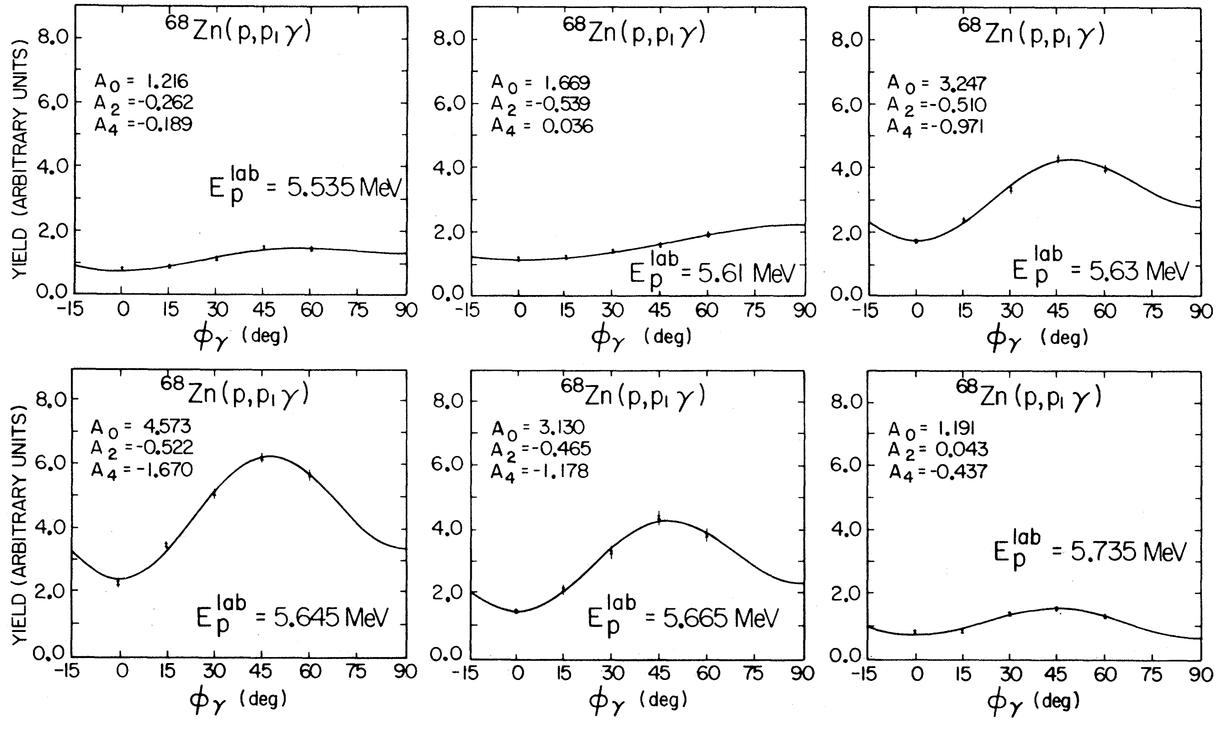

FIG. 7. Angular correlations. Six angular correlations taken over the 5.65-MeV resonance. The data points are shown with statistical uncertainties. The solid curves are the least-squares fit to the data, and the coefficients are listed as A_0, A_2, and A_4.

TABLE II. Correspondence between the complexity of the correlation function $W(\theta_\gamma=\frac{1}{2}\pi, \phi_\gamma)$ governed by κ and the spin b of the resonance in the compound system.

Maximum κ	b
0	$\frac{1}{2}$
2	$\frac{3}{2}$
4	$\geq\frac{5}{2}$

are analogs of the 1.634- and 1.696-MeV states in ^{69}Zn. Both the A_4 and A_2 coefficients peak at the 4.865-MeV resonance and then decrease to background. The coefficients show no resonance behavior for the A_2 or A_4 coefficients across the 4.945-MeV resonance. The elastic-yield curves were fitted with $l=2$ and $l=0$, respectively. Therefore, assignments of $J^\pi=\frac{5}{2}^+$ and $\frac{1}{2}^+$ were made for the 1.634- and 1.696-MeV levels in ^{69}Zn, respectively.

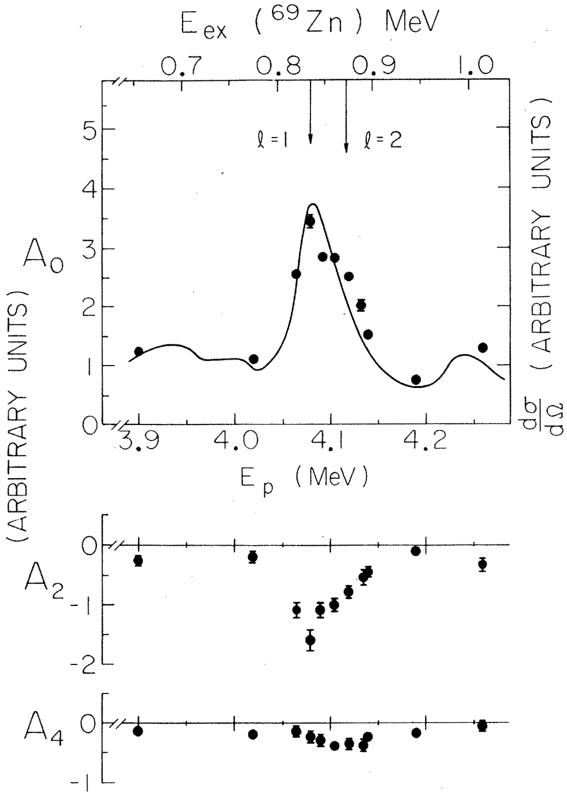

FIG. 8. The angular-correlation coefficient A_κ in the region of the 4.07- and 4.105-MeV ^{69}Ga IAR of ^{69}Zn parent states. The solid curve is a superposition of the ^{68}Zn(p,p_1) yield in arbitrary units. The coefficients are plotted on the same relative scale, and the statistical uncertainty is indicated if it is larger than the size of the data points. The bottom scales show the laboratory proton bombarding energy. The top scale shows the excitation energy of the parent states in ^{69}Zn. The arrows indicate their locations as determined in ^{68}Zn(d,p), and the l values from this reaction are shown.

TABLE III. Number of standard deviations above background for A_4 coefficient near 4.105 MeV. The notation used is

$$n(i)=[A_4(i)-B]/[\sigma_i^2(A_4)+\sigma^2(B)]^{1/2},$$

where B = background, $\langle A_4\rangle=-0.138\pm0.038$.

E_p^{lab}	A_4	$\sigma(A_4)$	n
4.09	−0.289	0.096	1.47
4.105	−0.382	0.075	2.90
4.12	−0.335	0.068	2.55
4.135	−0.376	0.111	2.02

4. 5.065-MeV Resonance

Figure 9 also shows the angular-correlation coefficients for the very weak 5.065-MeV resonance which is the analog of the 1.831-MeV state in ^{69}Zn. The A_2 and A_4 coefficients do not increase over background at the peak of the resonance, and therefore, this resonance is consistent with $J=\frac{1}{2}$. Since the l value obtained by von Ehrenstein and Schiffer[8] was $l=1$, a tentative assignment of $J^\pi=(\frac{1}{2})^-$ is made for the 1.831-MeV level in ^{69}Zn.

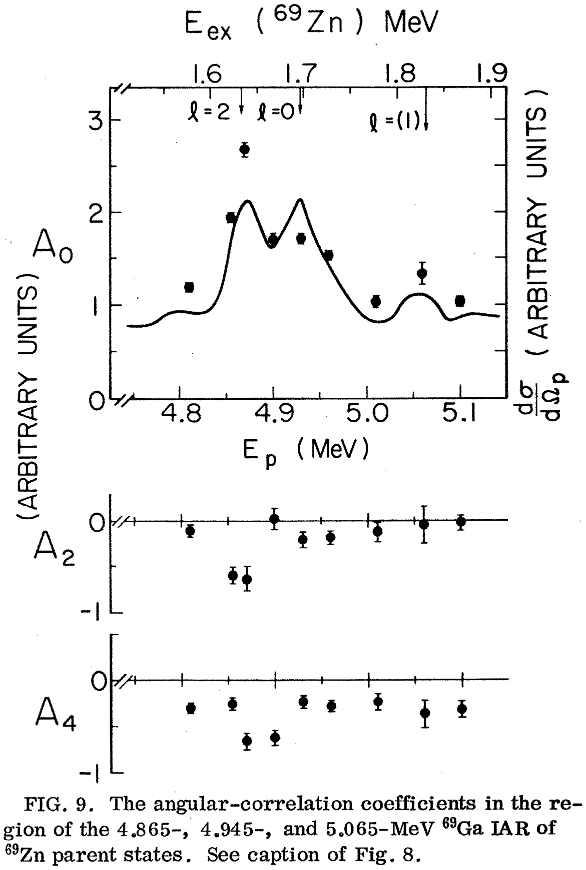

FIG. 9. The angular-correlation coefficients in the region of the 4.865-, 4.945-, and 5.065-MeV ^{69}Ga IAR of ^{69}Zn parent states. See caption of Fig. 8.

5. 5.65-MeV Resonance

Figure 10 shows the angular-correlation coefficients over the 5.65-MeV resonance which is the analog of the 2.403-MeV state in ^{69}Zn. The A_4 coefficient peaks at this resonance and the elastic scattering data were fitted with $l=2$.

Figure 5 shows that this resonance also appears in the p_2 (1.66 MeV, 0^+) channel. An angular distribution of the protons populating the 1.66-MeV (0^+) state was measured at 5.65 MeV. The angular distribution was fitted with the expression

$$W(\theta)=1+\sum_{L=2}^{6} B_L P_L(\theta),$$

where the B_L's are the coefficients of the even Legendre polynomials, $P_L(\theta)$, and have been calculated.[16] The least-squares analysis of the angular distribution is given in Table IV. Even though the B_4 is nonzero for the resonance, it does not clearly approach the theoretical value predicted for a $\frac{5}{2}$ resonance. Nevertheless, a $J^\pi=\frac{5}{2}^+$ assignment is made on the basis of the strength of the A_4 coefficient and the fits to the elastic scattering data.

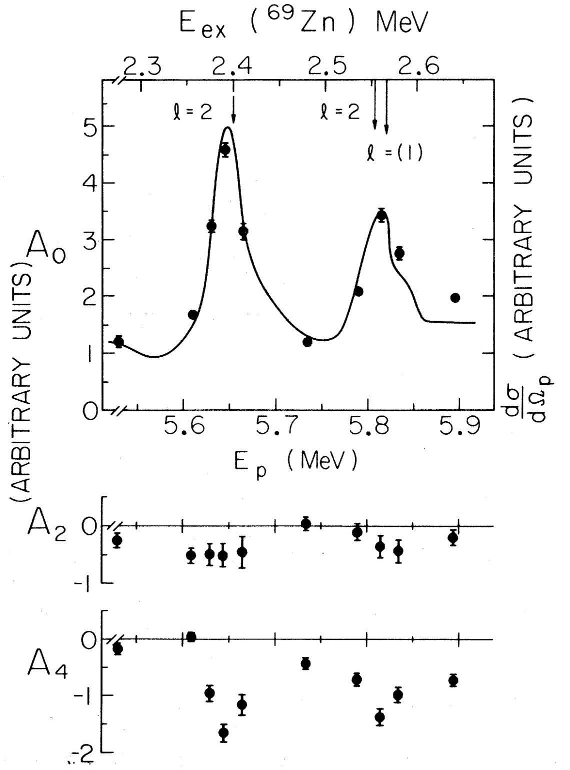

FIG. 10. The angular-correlation coefficient A_K in the region of the 5.65- and 5.805-MeV ^{69}Ga IAR of ^{69}Zn parent states. See caption of Fig. 8.

6. 5.805-MeV Resonance

The resonance observed at 5.805 MeV corresponds to a closely spaced doublet in ^{69}Zn, having components at 2.554 and 2.567 MeV. These states were assigned $l=2$ and $l=(1)$, respectively, in the ^{68}Zn(d,p) reaction.[8] The present elastic scattering results, as well as those of Vourvopoulos and Fox,[6] show definite evidence only for an $l=2$ resonance at 5.805 MeV. The A_4 coefficient in the angular correlation peaks at 5.805 MeV, also. Therefore, an assignment of $J^\pi=\frac{5}{2}^+$ is made for the 2.554-MeV level of ^{69}Zn, while no conclusion can be made regarding the 2.567-MeV level.

IV. DISCUSSION AND CONCLUSIONS

Triple angular-correlation measurements were performed to investigate various IAR in the ^{68}Zn $+p$ compound system from 3.91 to 5.90 MeV. Proton scattering to the first four states in ^{68}Zn between 3.9 and 6.1 MeV was investigated. The analysis of the scattering to the ground state provided the l-value determination, and the triple angular correlations involving the 2_1^+ state were used to determine the J value. These two measurements generally provided us with enough information for model-independent assignments of the J^π values for the parent states in ^{69}Zn listed in Table V. The results are consistent with the results obtained by von Ehrenstein and Schiffer[8] from ^{68}Zn(d,p), as well as with those from the ^{68}Zn(p,n) IAR study of Egan *et al.*[7] Since the GSM of assigning spins of resonances holds only for isolated resonances, the effect of interferences with $T_<$ states and nonresonant yield was uncertain. The fact that our results are consistent with previous studies lends greater confidence for the use of this method for the actual experimental conditions present for IAR. Also, the method has even yielded meaningful re-

TABLE IV. Angular-distribution coefficient (B_L) for inelastic protons scattering through IAR for $J_{\text{init}}=J_{\text{final}}=0^+$ and $J_{\text{IAR}}=J$.

	Theoretical coefficient (Ref. 16)		
J	B_2	B_4	B_6
$\frac{1}{2}$			
$\frac{3}{2}$	1.000		
$\frac{5}{2}$	1.142	0.857	
$\frac{7}{2}$	1.190	1.051	0.758
	Experimental values		
E_p (MeV)	B_2	B_4	B_6
5.65	0.789 ±0.039	0.146 ±0.051	0.004 ±0.066

TABLE V. Summary of results.

Energy levels of ^{69}Zn								
	Parent states			Analog resonances				
	^{68}Zn$(d,p)^{69}$Zn		^{68}Zn$+p$	^{68}Zn(p,p_0)		^{68}Zn$(p,p'\gamma)$	^{68}Zn(p,n)	Assignment
E_{ex} (MeV)	l_n (Ref. 8)	J^π (Ref. 8)	E_p (lab) (MeV)	l_p (Ref. 6)	l_p (this work)	J (this work)	J^π (Ref. 7)	J^π (this work)
0.0	1	$\frac{1}{2}^-$						
0.438	4	$\frac{9}{2}^+$						
0.531	3	$\frac{5}{2}^-$						
0.835	1	$(\frac{3}{2})^-$	4.07	2	1	$\frac{3}{2}$	$\frac{3}{2}^-, \frac{1}{2}^-$	$\frac{3}{2}^-$
0.872	2	$(\frac{5}{2})^+$	4.105		(2)	$\geq\frac{5}{2}$	$\frac{5}{2}^+$	$\frac{5}{2}^+$
1.634	2	$(\frac{5}{2})^+$	4.865	2	2	$\geq\frac{5}{2}$	$\frac{5}{2}^+$	$\frac{5}{2}^+$
1.696	0	$\frac{1}{2}^+$	4.945	0	0	$\frac{1}{2}$	$\frac{1}{2}^+$	$\frac{1}{2}^+$
1.831	1	$\frac{1}{2}^-, \frac{3}{2}^-$	5.065		(1)	$(\frac{1}{2})$		$(\frac{1}{2}^-)$
1.968	1	$\frac{1}{2}^-, \frac{3}{2}^-$						
2.262	0	$\frac{1}{2}^+$	5.498	0	0			$\frac{1}{2}^+$
2.403	2	$(\frac{5}{2})^+$	5.650	2	2	$\geq\frac{5}{2}$		$\frac{5}{2}^+$
2.554	2	$(\frac{5}{2})^+$	5.805	2	2	$\geq\frac{5}{2}$		$\frac{5}{2}^+$
2.567	(1)	$(\frac{1}{2}^-, \frac{3}{2}^-)$		...	(1)			
2.669	0	$\frac{1}{2}^+$	5.910	0	0			$\frac{1}{2}^+$

sults for the case of closely spaced doublets.

As indicated in Table V, not all of the IAR's were observed for ^{68}Zn(p, p_1) or (p, p_0) reactions. This is not entirely surprising, since the l value and spectroscopic factors indicated by von Ehrenstein and Schiffer imply quite different intensities for the various resonances, in addition to the decreased yield caused by the Coulomb-barrier penetration factor. For these reasons, the IAR of the ground state ($l = 1$), 0.438-MeV state ($l = 4$), and the 0.531-MeV state ($l = 3$), were not seen appreciably above background.

As seen in Figs. 8–10, the off-resonance values for the A_2 and A_4 coefficients of the angular correlations are slowly varying functions of energy as expected from the continuum of $T_<$ states that form the background for the IAR. This allows one to subtract a smooth background from the angular-correlation coefficients in order to obtain their variation over IAR.

The spectroscopic factors calculated using the results of Thompson[18] are accurate to about 25% (taking into account Thompson's calculations, about 15% and the extracted Γ_p, about 20%), which is not greatly different from the accuracy of the values obtained from the (d, p) stripping with which they are compared. The spectroscopic factors are a measure of the single-particle character of the resonances. Since $^{69}_{30}$Zn$_{39}$ does not have a closed neutron shell, one would not expect extreme single-particle behavior, which is in agreement with our results.

The GSM was pushed to its extreme limit when the IAR of the 1.831-MeV state was investigated; no unambiguous assignment could be made. This result was not unexpected, since the peak-to-background ratio of the ^{68}Zn(p, p_1) yield was about 1.3 to 1. On the other hand, the $\frac{5}{2}^+$ resonance at 4.86 MeV and the $\frac{1}{2}^+$ resonance at 4.945 MeV were clearly assigned for peak-to-background ratios of about 2.5 to 1. The ultimate usefulness of this method appears to be about 1.3 to 1 (peak-to-background ratio), since the IAR of the 2.797-MeV resonance in ^{67}Zn was determined with this ratio.[20] In the ^{67}Zn data, the yield strength above background was 1.7 mb/sr compared to 0.15 mb/sr for the 1.831-MeV resonance in ^{69}Zn. So it appears that the usefulness of this method is limited by the peak-to-background ratio, and by the yield strength above background for efficient spin determination.

ACKNOWLEDGMENTS

The authors wish to thank Professor R. G. Seyler for many helpful discussions, and G. K. Marshall for help in taking the data. We also wish to thank Professor W. J. Thompson for his calculations of the penetration factors P_n used in the calculation of spectroscopic factors.

†Work supported in part by the National Science Foundation.

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[1] L. J. B. Goldfarb and R. G. Seyler, Phys. Letters 28B, 15 (1968).

[2] J. R. Duray, H. J. Hausman, G. K. Marshall, J. W. D. Sinclair, and W. S. Steiner, Nucl. Phys. A136, 153 (1969).

[3] J. R. Duray, N. L. Gearhart, H. J. Hausman, J. W. D. Sinclair, and W. S. Steiner, Phys. Rev. C (to be published).

[4] C. Gaarde, P. Wilhjelm, and P. Bruun Jorgensen, Phys. Letters 22, 466 (1966).

[5] S. Gorodetsky, G. Bergdolt, and A. M. Bergdolt, J. Phys. (Paris) 29, 722 (1968).

[6] G. Vourvopoulos and J. D. Fox, Phys. Rev. 141, 1180 (1966).

[7] J. J. Egan, C. G. Dutt, M. McPherson, and F. Gabbard, Phys. Rev. C 1, 1767 (1970).

[8] D. von Ehrenstein and J. P. Schiffer, Phys. Rev. 164, 1374 (1967).

[9] Obtained from Microfoils, Argonne, Illinois.

[10] W. S. Steiner, Ph.D. dissertation, The Ohio State University, 1971 (unpublished).

[11] S. L. Blatt, J. Mahieux, and D. Kohler, Nucl. Instr. Methods 60, 221 (1968).

[12] E. M. Diener, J. F. Amann, S. L. Blatt, and P. Paul, Nucl. Instr. Methods 83, 115 (1970).

[13] The Ohio State University Van de Graaf Accelerator Laboratory Report No. VDG-007 (unpublished).

[14] S. A. A. Zaidi and S. Darmodjo, Phys. Rev. Letters 19, 1446 (1967).

[15] H. A. Weidenmüller, Nucl. Phys. A99, 269, 289 (1967).

[16] K. P. Lieb, J. J. Kent, and C. F. Moore, Phys. Rev. 175, 1482 (1968).

[17] F. D. Becchetti, Jr., and G. W. Greenlees, Phys. Rev. 182, 1190 (1969).

[18] W. J. Thompson, Nucl. Data A6, 129 (1969); W. J. Thompson, private communication.

[19] R. G. Clarkson, P. von Brentano, and H. L. Harney, Nucl. Phys. A161, 49 (1971).

[20] J. F. Morgan, N. L. Gearhart, H. J. Hausman, J. W. D. Sinclair, and W. S. Steiner, Bull. Am. Phys. Soc. 16, 626 (1971).

PHYSICAL REVIEW C VOLUME 4, NUMBER 5 NOVEMBER 1971

Doppler Shifts with Gas Backings; Mean Lives in ^{17}O, ^{25}Mg, and ^{55}Fe†

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(Received 6 July 1971)

Measurements of Doppler shifts of γ rays from nuclei recoiling in gas are described. Mean lives of the 0.87-MeV state in ^{17}O, of the 0.58- and 0.97-MeV states in ^{25}Mg, and of the 0.41-, 0.93-, 1.32-, and 1.41-MeV states in ^{55}Fe produced by (d,p) reactions were obtained from these Doppler shifts. The effect on these mean lives of a variation in the deuteron current has been investigated. Finally, the known mean lives of the 0.87-MeV state in ^{17}O and the 0.58-MeV state in ^{25}Mg were used, together with the measured Doppler shifts, to obtain information concerning the slowing down of ^{17}O and ^{25}Mg ions in krypton gas.

I. INTRODUCTION

The Doppler-shift-attenuation method has proved to be a powerful tool with which to study mean lives of excited states of nuclei. As generally used, that is with nuclei in excited states recoiling in a solid medium, the method is applicable to mean lives in the range from about 10^{-14} to 5×10^{-12} sec. Many nuclear states have mean lives from 5×10^{-12} to 10^{-9} sec, and it is of great interest to be able to make measurements in this range. The so-called "plunger," or recoil-distance method,[1,2] can be used for measurements in this range and has been extensively applied. In this paper we use another method which will allow measurements of mean lives greater than about 5×10^{-12} sec. In this method, nuclei in excited states recoil through a gas, and Doppler shifts of the γ rays emitted by the state are measured as a function of gas pressure.[3-5] We discuss some aspects of the method in detail and describe its application to the measurement of mean lives of states in ^{17}O, ^{25}Mg, and ^{55}Fe. The mean lives of the state in ^{17}O and one of the states in ^{25}Mg are well known, and our measurements on these states afford some information about the stopping power of krypton gas for ^{17}O and ^{25}Mg ions.

II. METHOD

For the work described here, the experimental Doppler-shift-attenuation factor for a particular transition is given by the equation

$$F_{\mathrm{expt}} = \frac{\langle E_\gamma(v)\rangle_\theta - E_0}{\langle E_\gamma(v_i)\rangle_\theta - E_0}. \qquad (1)$$