Large $E1$ and $M1$ Radiative Widths in Nuclei near Closed Shells

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The radiative widths, spins and parities of ten levels photoexcited by the (γ,γ') reaction at excitation around 7 MeV in ^{139}La, ^{140}Ce, ^{141}Pr, ^{142}Nd, ^{144}Nd, ^{205}Tl, and ^{209}Bi, were measured. The γ beam was produced by thermal-neutron capture in titanium, iron, cobalt, and copper. The spins of the resonance levels were obtained by angular-distribution measurements and the parities were determined by using a Compton polarimeter. These levels together with other resonance levels in $N \sim 82$ and $N \sim 126$ nuclei are discussed with regard to a possible connection to a giant $M1$ resonance.

I. INTRODUCTION

Recently, experimental evidence has been provided[1-5] as to the existence of a strong $M1$ strength in the energy range 5–10 MeV. This $M1$ strength is associated mainly with nuclei near closed shells and is believed to be due to particle-hole spin-flip configurations of the nucleons of the closed shell. Some indications for this effect have been the anomalously strong $M1$ transitions in the (n,γ) reaction on the tin isotopes and on ^{135}Ba.[1,2] Also, the results of the average resonance capture measurements[3] for the ^{117}Sn$(n,\gamma)^{118}$Sn and ^{119}Sn$(n,\gamma)^{120}$Sn reactions seem to yield a giant-resonance-like curve peaking around 8.3 MeV with a width of ~2 MeV. A similar structure observed at $E_\gamma \sim 7.8$ MeV in the inverse reactions ^{117}Sn$(\gamma,n)^{116}$Sn and ^{119}Sn$(\gamma,n)^{118}$Sn is also believed[4] to be related to the same phenomenon. Finally, direct evidence favoring an $M1$ giant resonance in ^{208}Pb was recently obtained by employing the ^{208}Pb(γ,n) reaction in the threshold photoneutron method.[5]

In the present work, the widths of 14 bound levels and two unbound levels at about 7 MeV excitation in $N \sim 82$ and $N \sim 126$ nuclei are reported and some evidence is presented for the existence of a strong $M1$ strength in the energy region below the (γ,n) threshold in these nuclei. The nuclear levels are photoexcited by the (γ,γ') technique using monochromatic γ beams produced by thermal-neutron capture in some metallic elements. Some of the present results were reported earlier either by the present authors[6-8] or by other investigators.[9-12] The radiative widths, spins, and parities of 10 levels are reported for the first time.

II. EXPERIMENTAL PROCEDURE

The γ source was obtained by thermal-neutron capture in metallic disks of one of the elements Ti, Fe, Co, and Cu. In the case of Ti, Fe, and Cu, five disks were used, each having 8 cm diam and about 2 cm thick. In the case of Co, seven disks were used of 7.5 cm diam and 3 mm thick. The disks were placed near the reactor core along a tangential beam tube of the IRR-2 reactor. Details of the experimental arrangement and the scattering system were described elsewhere.[6]

The neutron flux near the γ source is about 2×10^{13} n/cm^2 sec yielding typical γ intensities of the order of 10^8 monoenergetic photons/cm^2 sec on the target scatterer. The detectors used in these experiments were 20-, 30-, and 40-cm^3 Ge(Li) diodes; the energy resolution was around 12 keV at 7 MeV. For measuring the variation of the scattering cross section with temperature and for the nuclear self-absorption experiment a 5- × 5-in. NaI detector was used.

III. RESULTS

A. Scattering Measurements and Branching Ratios

Figure 1 shows a typical scattered radiation spectrum from a Pr target using an incident γ beam from the Co(n,γ) reaction. Besides the elastically scattered line at 6877 keV, all other lines correspond to inelastic transitions leading to low-lying levels in ^{141}Pr. The resonance scattering from Pr using Co capture γ rays was reported earlier by Pavel *et al.*[13] However, in this previous work, the energy of the elastic line was reported to be 6111 keV. Since no scattered line at this latter energy was observed here, it is possible that the reported line at 6111 keV is a spurious resonance which probably originated from a compound of chlorine in the vicinity of the γ source.

The branching ratio Γ_0/Γ between the ground-state radiation width and the total radiation width of the resonance level is obtained from the scattered spectrum after accounting for the angular distribution of the elastic and inelastic lines. It should be noted, however, that the direct determination of Γ_0/Γ from the scattered spectrum is nearly correct only for strongly scattered signals. For some weaker signals the value of Γ_0/Γ obtained from the scattered spectrum is only an upper limit because the small intensity inelastic lines expected at lower energies are masked by the steeply rising background towards low energies which is intrinsic of the present technique.

Table I shows a list of some resonance energies in $N \sim 82$ and $N \sim 126$ nuclei obtained by using capture γ rays of Fe, Ti, Co, and Cu. In the table only the strongly scattered lines are mentioned where it was possible to measure the radiative width of the resonance level.

B. Angular Distribution and Polarization Measurements

The spin and parity of the resonance level are determined by measuring the angular distribution and the polarization of the elastically scattered radiation. The polarization is measured by means of a Compton polarimeter.[6,14] Details of these measurements were described in Ref. 6. In the following we will rely heavily on the definitions and the contents of this earlier work.

Assuming dipole absorption, the angular distribution of the elastic radiation is of the form $W(\theta)=1+AP_2(\cos\theta)$. This is identical to the distribution of γ-γ cascades of the form $J_0 \rightarrow J \rightarrow J_0$ where J_0 and J are the spins of the ground and resonance levels. In order to determine J, the experimental value of A is compared with the theoretical values which correspond to the various spin sequences. It may be noted however that in some cases, ambiguities may arise in the determination of J by using this procedure because: (a) The values of A corresponding to different values of J may be close to each other and are within the experimental uncertainties; (b) the contribution of quadrupole admixtures may change the value of A. In most cases these ambiguities could be resolved either by using the results of polarization measurements as illustrated below or by considering the angular distribution of the inelastic transitions. This point is illustrated by the following two examples.

Figure 2 shows the angular distribution of the elastic lines at 6877 and 7168 keV scattered by ^{141}Pr and ^{209}Bi, respectively. The values of A were obtained by least-squares fits to the experimental distribution. In the case of ^{141}Pr, the measured value $A=0.111\pm0.023$ is in excellent agreement with the value $A=0.107$ of the cascade $\frac{5}{2}(1)\frac{7}{2}(1)\frac{5}{2}$. This apparently indicates that the transition is pure dipole and that $J=\frac{7}{2}$. However, the same A is obtained theoretically by assuming $J=\frac{5}{2}$ and a quadrupole-dipole mixing ratio $x^2=0.01$. Such a quadrupole admixture is not unreasonable because the 6877-keV transition in ^{141}Pr was found to be $M1$ (Table I). It was only by considering the angular distribution of the inelastic line leading to the 145-keV, $\frac{7}{2}$ level in ^{141}Pr that it was possible to make a conclusive spin assignment, $J=\frac{7}{2}$, to the resonance level. It may be noted that in this case the polarization measurement could not differentiate between the two possible spin values because the theoretical values[6] of the polarization P corresponding to the above two cases are:

$$P[\tfrac{5}{2}(1)\tfrac{7}{2}(1)\tfrac{5}{2}]=1.86\,, \quad P[\tfrac{5}{2}(1,2)\tfrac{5}{2}(1,2)\tfrac{5}{2}]=1.60$$

and the calculated ratios $N_\parallel/N_\perp$ obtained by assuming an asymmetry ratio, $R=1.15$, are:

$$N_\parallel/N_\perp(J=\tfrac{7}{2})=0.96\,, \quad N_\parallel/N_\perp(J=\tfrac{5}{2})=0.97$$

to be compared with a measured ratio $N_\parallel/N_\perp=0.95\pm0.03$.

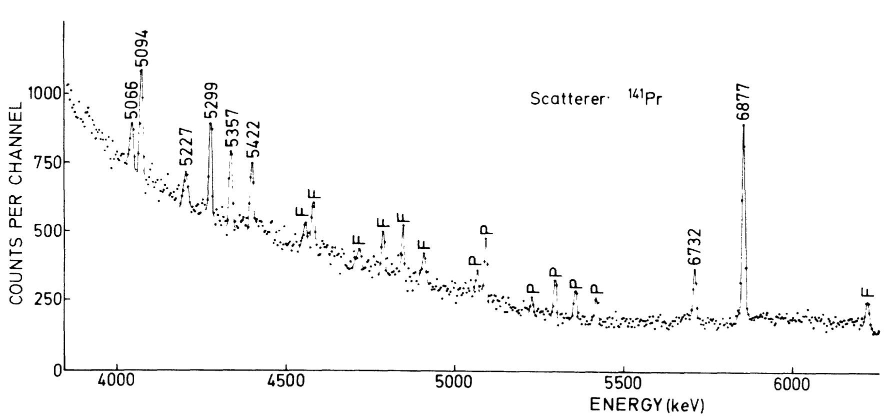

FIG. 1. Scattered γ spectrum from a Pr target at an angle of 140° measured by a 40-cm^3 Ge(Li) detector. The γ source was obtained from the Co(n,γ) reaction. γ lines denoted by P and F refer to photopeaks and first-escape peaks; other lines refer to double-escape peaks.

TABLE I. List of resonance isotopes, energies, ground-state branching ratios Γ_0/Γ, partial radiation width Γ_0, the spin and parity of the ground state $J^\pi{}_0$, and resonant levels J^π. The levels are photoexcited by capture γ rays from Ti, Fe, Co, and Cu. Only isotopes in the vicinity of $N=82$ and $N=126$ are given. Asterisks denote unbound levels.

Isotope	Energy (keV)	(n,γ) Source	$J^\pi{}_0$	J^π	Γ_0/Γ	Γ_0 (10^{-3} eV)
^{139}La	6018	Fe	$\frac{7}{2}^+$	$\frac{7}{2}^-$	0.50 ± 0.06	25 ± 8
^{139}La	6418	Ti	$\frac{7}{2}^+$	$\frac{9}{2}^-$	0.78 ± 0.08	63 ± 8
^{139}La	7637	Cu	$\frac{7}{2}^+$	$\frac{7}{2}^-$	0.28 ± 0.04	47 ± 6
^{140}Ce	5660	Co	0^+	1^-	0.95 ± 0.05	11 ± 3
^{141}Pr	6877	Co	$\frac{5}{2}^+$	$\frac{7}{2}^+$	0.20 ± 0.05	18 ± 9
^{141}Pr	7252	Cu	$\frac{5}{2}^+$	$\frac{5}{2}^-$	0.38 ± 0.04	110 ± 10
^{141}Pr	7632	Fe	$\frac{5}{2}^+$	$\frac{5}{2}^+$	0.46 ± 0.15	35 ± 10
^{141}Pr	7915	Cu	$\frac{5}{2}^+$	$\frac{5}{2}^+$	0.28 ± 0.08	2 ± 1
^{142}Nd	6877	Co	0^+	1^-	0.85 ± 0.10	275 ± 60
^{144}Nd	7915*	Cu	0^+	1^+	0.24 ± 0.06	8 ± 3
^{203}Tl	6418	Ti	$\frac{1}{2}^+$	$\frac{1}{2}$	0.26 ± 0.03	83 ± 15
^{205}Tl	7252	Cu	$\frac{1}{2}^+$	$\frac{3}{2}^+$	0.56 ± 0.06	25 ± 6
^{205}Tl	7646*	Fe	$\frac{1}{2}^+$	$\frac{1}{2}$	0.58 ± 0.06	570 ± 30
^{208}Pb	7279	Fe	0^+	1^+	1.0	780 ± 60
^{209}Bi	5603	Co	$\frac{9}{2}^-$	$\frac{11}{2}^-$	1.0	950 ± 300
^{209}Bi	7168	Ti	$\frac{9}{2}^-$	$\frac{9}{2}^+$	1.0	820 ± 40

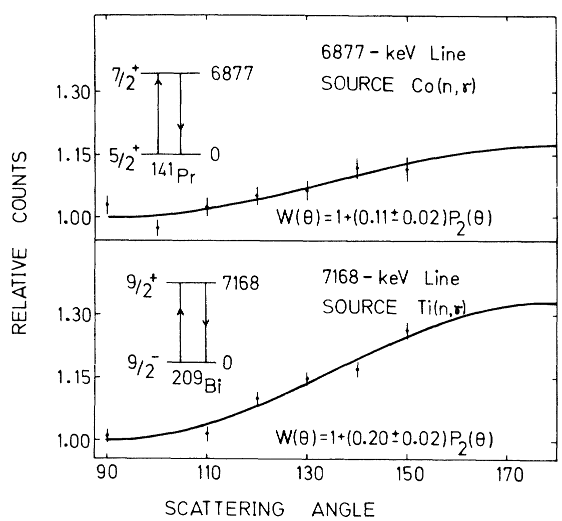

FIG. 2. Angular distribution of elastically scattered lines from ^{141}Pr and ^{209}Bi using γ sources obtained from the Co(n,γ) and Ti(n,γ) reactions, respectively. The solid lines have the form $W(\theta)=1+AP_2(\cos\theta)$ and are least-squares fits to the experimental distributions.

In the case of ^{209}Bi, the measured value, $A=0.200\pm0.023$ is also in agreement with the value $A=0.195$ of the cascade $\frac{9}{2}(1)\frac{9}{2}(1)\frac{9}{2}$. The sum-coincidence spectrum of the polarization measurement for the 7168-keV transition (Fig. 3) indicates that the corresponding transition is $E1$. Here again, the possibility exists that this value of A is obtained from a spin $J=\frac{11}{2}$ with an admixture $x^2=0.01$ of $M2/E1$. However, it may be seen from Fig. 4 (which shows a plot of P and $N_\parallel/N_\perp$ as a function of A and x) that the measured value of P is in somewhat better agreement with a spin value $J=\frac{9}{2}$ than with $J=\frac{11}{2}$. The angular distribution results show therefore that the transitions in both ^{141}Pr and ^{209}Bi are pure dipole. The measured values of spins and parities of the resonance levels obtained by this technique are listed in Table I.

C. Radiative Widths

In order to determine the ground-state radiation width Γ_0 of a resonance level, it is necessary to measure all other parameters of the level, namely J, Γ_0/Γ, and the separation energy δ between the peaks of the resonant level and the incident γ line, by performing four separate experiments. The measurement of J and Γ_0/Γ was discussed earlier. To find the remaining parameters Γ_0 and δ it is

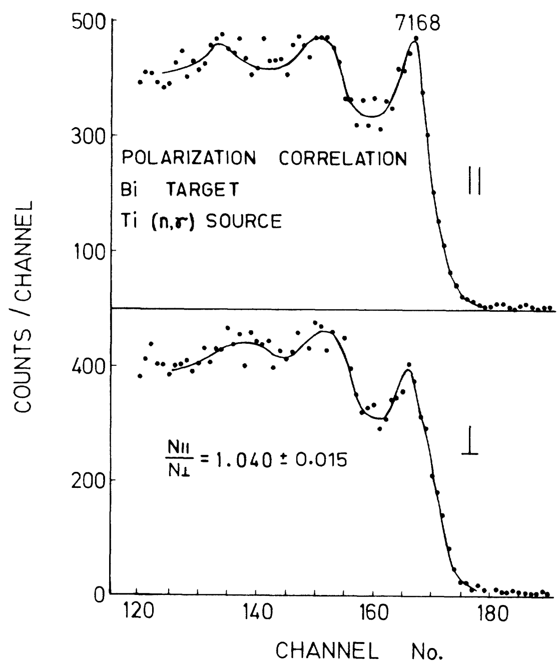

FIG. 3. Sum-coincidence spectra obtained with the NaI detectors parallel ($\parallel$) and perpendicular ($\perp$) to the resonance scattering plane. $N_\parallel$ and $N_\perp$ refer to the area under the photopeaks.

necessary to measure the temperature variation of the scattering cross section and the nuclear self-absorption.[6] For checking the consistency of the level parameters, another experiment was performed in which the effective elastic scattering cross section $\langle\sigma_r\rangle$ was measured and was compared with the calculated value of $\langle\sigma_r\rangle$ which is a function of J, δ, Γ_0, and Γ_0/Γ. For cases where no agreement was obtained it was found necessary to vary the values of Γ_0 and Γ_0/Γ within the limits of experimental uncertainties so as to get agreement between the measured and calculated values of $\langle\sigma_r\rangle$. In this process the value of Γ_0/Γ was allowed to vary below the measured value to allow for large possible errors in Γ_0/Γ caused by missing some weak inelastic lines in the scattered spectrum. This consistency check is therefore indispensible for obtaining a reliable value of Γ_0 and Γ. Results obtained without such a check or without performing the whole set of experiments may yield different values. This is the reason for the discrepancies in the values of Γ_0 for the 7168-keV level of ^{209}Bi and the 6418-keV level of ^{139}La as compared with earlier results.[10,12] It should be noted that the 7646-keV level in ^{205}Tl and the 7915-keV level in ^{144}Nd are unbound. However, in both cases owing to angular momentum restrictions, the neutron width is negligible.

IV. DISCUSSION

In an earlier work[6] it was remarked that the two measured $M1$ resonances in ^{141}Pr and in ^{208}Pb have

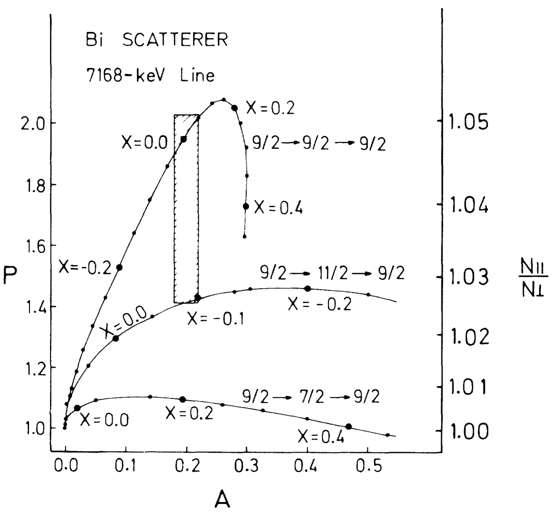

FIG. 4. A plot of the angular distribution coefficient A as a function of $P, N_{\parallel}/N_{\perp}$ and the mixing ratio x for the three possible cascades $\frac{9}{2}\rightarrow\frac{7}{2}\rightarrow\frac{9}{2}$, $\frac{9}{2}\rightarrow\frac{9}{2}\rightarrow\frac{9}{2}$, and $\frac{9}{2}\rightarrow\frac{11}{2}\rightarrow\frac{9}{2}$. The shading corresponds to the experimental values of A and P.

a ground-state radiation strength much larger than the average strength obtained from the neutron resonances. The present results provide more evidence in favor of strong $M1$ strength in several isotopes in the vicinity of $N=82$ and $N=126$. In addition a similar phenomenon was found to occur for the $E1$ strength. Table II summarizes the values of Γ_0, the character of the ground-state transitions of the resonances, and the radiation strengths[15] K_{M1} and K_{E1} defined by $K_{M1}=\Gamma_0(DE_\gamma^{\,3})^{-1}$, $K_{E1}=\Gamma_0(DE_\gamma^{\,3}A^{2/3})^{-1}$ where Γ_0 is measured in eV, E_γ (in MeV) is the transition energy, and D (in eV) is the spacing between nuclear levels of the same spin and parity as the resonance level. (Note that the $J=\frac{1}{2}$ resonances in ^{203}Tl and ^{205}Tl of Table I are not given in Table II; the scattered radiation in these two cases is not polarized and hence the character of the radiation could not be measured.) The values of D were calculated using the relation $D=D_0/(2J+1)$ where J is the spin of the resonance level and D_0 is the spacing between levels with $J=0$. The values of D_0 were taken from the table of Lynn[16] in the same or neighboring isotopes and corrections were made for the appropriate excitation energies by using a constant nuclear temperature[17] $T=0.7$ MeV. The assumption of constant-nuclear-temperature energy dependence is known to hold[17] fairly well in the region near closed shells. In order to check the values of D used in Table II, another calculation was carried out in which the relation of Lang and Le Couteur[18] was employed and the values obtained were close to within 50% to the values cited in the table. In the following we deal separately with the $E1$ and $M1$ transitions of Table II.

TABLE II. Calculated level spacings D and the ground-state radiation strength K_{E1} and K_{M1} of the resonance levels. Asterisks denote unbound levels.

Isotope	Energy (keV)	Transition	Γ_0 (10^{-3} eV)	D (eV)	K_{E1} (10^{-9}	K_{M1} MeV^{-3})
^{139}La	6018	$E1$	25	1800	2	···
^{139}La	6418	$E1$	63	870	11	···
^{139}La	7637	$E1$	47	190	21	···
^{140}Ce	5660	$E1$	11	6800	0.3	···
^{141}Pr	6877	$M1$	18	450	···	123
^{141}Pr	7252	$E1$	110	220	48	···
^{141}Pr	7632	$M1$	33	170	···	437
^{141}Pr	7915	$M1$	2	90	···	45
^{142}Nd	6877	$E1$	275	1200	26	···
^{144}Nd	7915*	$M1$	8	380	···	43
^{205}Tl	7252	$M1$	25	1200	···	51
^{208}Pb	7279	$M1$	780	25 000	···	81
^{209}Bi	5603	$M1$	950	34 000	···	160
^{209}Bi	7168	$E1$	820	4800	13	···

A. $E1$ Transitions

It is of interest to compare the ground-state radiation strength of the $E1$ resonances of Table II with the average radiation strength, $\bar{K}_{E1} = 4\times10^{-9}$ MeV^{-3} obtained from neutron resonances[19] and reported by Bollinger. For the $N\sim82$ and $N\sim126$ nuclei, the results of Table II yield $\bar{K}_{E1} = 18\times10^{-9}$ MeV^{-3}. This high value seems to be characteristic only of closed-shell nuclei because the K_{E1} value obtained by averaging on 10 $E1$ bound resonances in the mass region away from closed shells[6,20] is $\bar{K}_{E1} = 6\times10^{-9}$ MeV^{-3}.

It is possible that the strong $E1$ radiation strength found near closed shells in the present work has the same origin as the broad peaks observed by Axel *et al.*,[21] who measured the quasielastic scattering of photons in the closed-shell nuclei Sn, Zr, Pb, and Bi below the (γ, n) threshold. It is also very likely that the higher K_{E1} value is partly caused by the biased nature of the present experiment which tends to select levels of relatively high Γ_0 although this result did not show up in the value of K_{E1} in nuclei away from closed shells.

B. $M1$ Transitions

One of the most important results of Table II is the relatively high number of $M1$ resonances; out of 14 measured resonances, 7 were $M1$. In particular three of the four detected resonances in ^{141}Pr were $M1$. This situation is in contrast with the results obtained in the mass region away from closed shells where the polarizations of 10 resonances have been measured to date,[6,20] all of which were found to be $E1$.

Another interesting point is the relatively high value of the ground-state radiation strengths obtained here. The average of the seven $M1$ transitions of Table II yields $\bar{K}_{M1} = 134\times10^{-9}$ MeV^{-3} which is a factor of 7 higher than $\bar{K}_{M1} = 20\times10^{-9}$ MeV^{-3}, obtained by neutron resonances and reported by Bollinger.[19] This fact can partly be attributed to the biased nature of the (γ, γ') experiment in a similar manner to the case of the $E1$ resonances. However, the fact that a high $\bar{K}_{M1}$ value was also found on averaging on inelastic $M1$ transitions,[20] and that the $M1$ resonances were exclusively observed near closed-shell nuclei ($N\sim82$ and $N\sim126$), favors the possibility that these resonances belong to a giant $M1$ resonance which partly overlaps the energy region covered by these levels. The spin-flip-transition mechanism suggested by Mottelson[22] is perhaps responsible for the $M1$ enhancement in nuclei near closed shells. In fact, several strong $M1$ transitions were found by Bowman *et al.*,[5] in ^{208}Pb, and were interpreted as being due to spin-flip configurations of protons and neutrons near closed shells; explicit calculations by Vergados[23] yielded the entire experimental $M1$ strength. The bound $M1$ resonance at 7279 keV in ^{208}Pb (Table I) is very probably related to the low-energy tail of the giant $M1$ resonance reported in Ref. 5.

A similar explanation suggests itself for an $M1$ giant resonance for $N\sim82$ nuclei. In this case only the $1h_{9/2}1h^{-1}{}_{11/2}$ neutron spin-flip configuration is involved. In fact, an experimental indication regarding the possible existence of a giant $M1$ resonance in the 9-MeV region of La, Ce, and Pr was recently presented by Pitthan and Walcher[24] using inelastic electron scattering.

It should be pointed out that the photoexcitation process in the present work is random in nature which requires a chance overlap between one of the incident γ lines and one nuclear level in any isotope of the scattering target. Also, the energy of most of the intense γ lines from Co, Ti, Fe, and Cu are below 8 MeV and hence, the probability of overlapping a possible peaking of $M1$ strength around 9 MeV is expected to be small. Therefore, from the fact that no $M1$ resonances were detected in the present work in La or Ce, it does not necessarily follow that no $M1$ giant resonance exists in these elements.

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Two-Step Processes in Stripping Reactions*

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A formalism using a different approach has been developed for the inclusion of two-step processes in one-particle transfer reactions on deformed nuclei. Calculations for the ^{24}Mg$(d,p)^{25}$Mg and ^{182}W$(d,p)^{183}$W reactions show that the two-step processes are very important for the weakly excited and forbidden transitions; however, for the transitions that are strongly allowed in the one-step process, the effect is small. Calculations for the ^{24}Mg(d,p)-^{25}Mg $(\frac{7}{2}^+$, 1.61 MeV) and for the ^{182}W$(d,p)^{183}$W $(\frac{1}{2}^-$, g.s.) reaction show that the two-step process via inelastic scattering in the entrance channel is about equal to the two-step process via inelastic scattering in the exit channel. Good fits with the experimental data are obtained.

I. INTRODUCTION

The single-step distorted-wave Born approximation (DWBA),[1,2] where it is assumed that the transition takes place directly from the incident-deuteron channel to the exit-proton channel, has been found successful in explaining many deuteron stripping reactions. However, as has been discussed by Ascuitto and Glendenning,[3] the assumptions on which the DWBA is based might sometimes fail. One case where this may arise is when the stripping reaction takes place between states such that one of which is not the parent of the other. Another situation arises when there are strongly enhanced inelastic transitions, as for the cases of deformed nuclei. It has been suggested by several authors[3-16] that if core excitation of the target or residual nucleus is accounted for some of these difficulties may be eliminated. These processes, known as two-step (or multi-step) processes have also been found important for two-particle transfer reactions.[17] The effects of the two-step processes are that the usual selection rules found in one-step process (the usual DWBA) can be violated and also that the two-step-transition amplitudes can interfere with the one-step-transition amplitude.

The two-step processes for one-particle transfer reactions have been studied by several authors.[3-16] One method of investigation, the coupled-channel method[3-10] involves a huge computational effort. In order to minimize this effort, several authors have employed a number of approximations to calculate the effects of the two-step processes. Iano and Austern[16] have used a perturbation technique to simplify these calculations. In this work, we also make use of a perturbation method to expand the transition amplitude in terms of the deformation parameter β. But on the whole our technique is different from that of Iano and Austern. We do not make the adiabatic approximation in which the ground and excited states in each channel are considered to be degenerate. However, to simplify the calculations, we make an on-the-shell approximation for the Green's function which appears in the intermediate state.

In Sec. II, we present the general formalism of the theory. Some of the approximations used in the present work are also presented in this section. In Sec. III, we work out the specific details in order to obtain the expressions for the transition amplitudes. Selection rules obtained in the present study are discussed at the end of this section.