PHYSICAL REVIEW C VOLUME 23, NUMBER 4 APRIL 1981

Velocity dependence of the transient hyperfine field at Pd ions swiftly recoiling through magnetized Fe

A. E. Stuchbery, C. G. Ryan, and H. H. Bolotin
School of Physics, University of Melbourne, Parkville, Victoria 3052, Australia

S. H. Sie
Department of Nuclear Physics, Research School of Physical Sciences, Australian National University, Canberra, A.C.T. 2600, Australia

(Received 16 October 1980)

The velocity dependence of the transient hyperfine magnetic field manifest at nuclei of ^{108}Pd ions recoiling through magnetized Fe was investigated to a velocity higher than previously examined for the heavier nuclides. The state of interest (2_1^+) was populated by Coulomb excitation using beams of 80-MeV ^{32}S and 180-MeV ^{58}Ni ions and precessed γ-ray angular distribution measurements were carried out in coincidence with backscattered projectiles. These results, when combined with prior lower-velocity measurements for ^{106}Pd, yield a transient field velocity dependence v^p, $p=0.41\pm0.15$, for Pd isotopes over the extended velocity range $1.74\leq\langle v/v_0\rangle\leq 7.02$ ($v_0=c/137$) a result incompatible with a linear velocity dependence.

[NUCLEAR REACTIONS ^{108}Pd (^{32}S, ^{32}S$'$)^{108}Pd(2_1^+), ^{108}Pd (^{58}Ni, ^{58}Ni$'$) ^{108}Pd(2_1^+), $E_S=80$ MeV, $E_{\rm Ni}=180$ MeV, enriched target; measured $W(\theta,H,\infty)$ in polarized Fe. Deduced transient field and velocity dependence of Pd*Fe* for $v/c\leq 0.054$.]

I. INTRODUCTION

Since the discovery[1] of large *transient* magnetic hyperfine fields manifest at the nuclei of ions rapidly traversing polarized ferromagnetic materials, there have been a considerable number of experimental[2-8] and theoretical[9-11] investigations addressed to elucidating the dependence of the strength of this magnetic field on ion parameters, as well as to the understanding of the ion-solid interaction responsible for it. Although neither point appears yet to be fully resolved, it is nevertheless clear that the field strength is functionally related to both the velocity and atomic number Z of the ion and dependent on the specific ferromagnetic host only by way of its bulk magnetization, and that the strength of this transient field is quite large (of the order of 10^3 T).

At very high ion recoil velocities ($v \gg Zv_0$; $v_0=c/137$, the Bohr velocity) the ion is completely stripped of electrons, and the interaction of the bare ion with the conduction electrons in the polarized ferromagnetic host is amenable to perturbation theory treatment—the field strength velocity dependence in this case has been calculated[11] (and experimentally verified[5,12]) to vary inversely with v.

However, in the range of intermediate ion velocities ($v_0\leq v\leq Zv_0$), the situation is somewhat less clear. Dybdal *et al.*[6,7] have performed a series of elegant experiments in which they have measured the K-vacancy fractions produced as a function of v/v_0 for O, F, and Si ions slowing down in a number of ferromagnetic media. Their results showed a strong correlation between the K-vacancy fraction and the transient field strength indicating, in line with the original proposal of Borchers *et al.*[1] and revived by Eberhardt *et al.*,[10] that the main contribution to the field originates from the polarization of bound projectile electrons. Nevertheless, it is still unclear how the polarization of the ferromagnetic electrons is transferred to the bound unpaired electrons of the ion.[7] Furthermore, the velocity dependence of the field has not yet been sufficiently well established experimentally, although it has been demonstrated that for all but the lightest ions traversing polarized ferromagnetic hosts, the transient field increases as Z and as v^p, with p somewhere between ~0.5 (Ref. 8) and unity.[4]

The large magnitude of this transient field in the velocity range $v_0\leq v\leq Zv_0$ gives one an important tool for measuring the gyromagnetic ratios of rather short-lived ($\tau\geq 1$ psec) excited nuclear states; a number of such determinations have indeed been made.[13] However, despite the considerably broadened domain of short-lived nuclear states whose g factors may be determined by use of the transient field (TF), full exploitation of this hyperfine field for such measurements requires reliable experimental delineation of its dependence on the ion parameters.

The present experimental investigation was undertaken to attempt to more definitively establish the velocity dependence of the TF for $v_0 \leqslant v \leqslant Zv_0$ up to velocities considerably higher than have heretofore been examined for the heavier nuclei. To this end, we have measured the integral precession of the γ-ray angular distribution of the $2_1^+ \to 0_1^+$ transition in ^{108}Pd [$\tau_{2^+} = 34.9 \pm 2.3$ psec Ref. 14; $g = 0.36 \pm 0.03$ Ref. 15] as the swift Pd ions recoiled *through* a thin polarized Fe foil, entering the ferromagnetic host with $v/v_0 = 4.5$ and 7.38.

II. EXPERIMENTAL PROCEDURES

The nuclear state of interest was populated by Coulomb excitation using beams of 80-MeV $^{32}S^{7+}$ and 180-MeV $^{58}Ni^{12+}$ ions from the Australian National University 14UD Pelletron tandem accelerator. Targets were prepared by vacuum evaporation of ^{108}Pd (enriched to 98.88%) onto a 1 μm Fe foil (previously annealed in an H_2 atmosphere) which was backed with a thick (~20 μm) evaporated Cu layer that provided a magnetically perturbation-free environment in which the recoiling Pd ions stopped. For added mechanical support and to provide good heat conduction away from the beam spot, the three-layered target was mounted on an additional 20 μm Cu foil with an ~2 mg cm^{-2} In layer as "adhesive." The target and Fe foil thicknesses were determined to be 822 ± 36 μg cm^{-2} and 1.04 ± 0.05 μm, respectively, by Rutherford scattering of 2-MeV protons from the University of Melbourne 5U Pelletron accelerator.

Although magnetometer tests showed that 100 Oe was more than sufficient to completely saturate the Fe foil, we employed a magnetizing field of 300 Oe. The triple-layered target was placed between the pole tips of a diminutive electromagnet which provided this field, whose direction, normal to the beam, was automatically reversed periodically to minimize systematic errors.

The triple-layered, thin Fe foil experimental technique used to measure the precession of the γ-ray angular distribution has been described in detail elsewhere.[13] Two 50-cm^3 Ge(Li) detectors placed 5 cm from the target at ±70° to the beam direction recorded the 434-keV $2_1^+ \to 0_1^+$ transition γ ray in coincidence with beam ions backscattered into an annular surface-barrier detector subtending the angular range 162°–176°. The coincidence requirement resulted in events recorded for ^{108}Pd ions which recoiled in forward cones of half-angles <4° and <3° with average initial velocities of $v/c =$ 3.0% and 5.4%, respectively. The trajectories of both the incident and backscattered projectile ions were shielded from the field of the electromagnet to reduce beam-bending effects to negligible proportion ($\leqslant 0.076$ and $\leqslant 0.064$ mrad for the ^{32}S and ^{58}Ni ions, respectively). These beam-bending magnitudes for each of these ion projectiles were calculated using our measurements of the fringing field as a function of distance from the Fe foil upstream of the target along the beam trajectory, with the soft iron shielding cone in place. This field was found to decrease markedly with increasing distance from the foil. These calculated values represent upper limits, as the effect of the field on backscattered ions, which can be readily shown to reduce the overall beam-bending effect, was not taken into account.

III. ADDITIONAL EXPERIMENTAL CONSIDERATIONS

For the present case, where the mean lives of all relevant states are long compared with the transit time of the Pd ions through the Fe foil (see below), the measured ratio of the $2_1^+ \to 0_1^+ \gamma$ rays registered in a given detector at θ_γ with polarizing field up (↑) and down (↓) is expressed as

$$\frac{N\uparrow}{N\downarrow} = \frac{1+\phi R}{1-\phi R}, \tag{1}$$

where

$$R = \left(\frac{g_2 \left.\frac{dW_{20}}{d\theta}\right|_{\theta_\gamma} + g_4 \eta_{42} \left.\frac{dW_{42}}{d\theta}\right|_{\theta_\gamma} + g_{2'} \eta_{2'2} \left.\frac{dW_{2'2}}{d\theta}\right|_{\theta_\gamma} + \cdots}{\langle W_{\text{fed}} \rangle (1 + \eta_{42} + \eta_{2'2} + \cdots)} \right)$$

and $\phi \equiv \Delta\theta/g = -(\mu_N/\hbar) \int_0^T B_{TF} dt$, T is the transit time of the Pd ions through the Fe foil, μ_N is the nuclear magneton, g_i is the g factor for the nuclear state of spin J_i, η_{i2} is the ratio of direct population of the state J_i to that of the 2_1^+ state (scaled by the decay branching ratio of the $J_i \to 2_1^+$ transition), and

$$\langle W_{\text{fed}} \rangle = \left. \frac{(W_{20} + \eta_{42} W_{42} + \eta_{2'2} W_{2'2} + \cdots)}{(1 + \eta_{42} + \eta_{2'2} + \cdots)} \right|_{\theta_\gamma},$$

with W_{20} being the angular distribution for the $2_1^+ \to 0_1^+$ transition without feeding contribution, and W_{i2} being the angular distribution for the $2_1^+ \to 0_1^+$ transition when the 2_1^+ state is fed from the level J_i by the unobserved $J_i \to 2_1^+$ transition. For the case where the g factors of all states are equal, expression (1) reduces to the more familiar form

$$\frac{N\uparrow}{N\downarrow} = \frac{1+Sg\phi}{1-Sg\phi},$$

where

$$S = \frac{1}{\langle W_{\text{fed}} \rangle} \left. \frac{d\langle W_{\text{fed}} \rangle}{d\theta} \right|_{\theta_\gamma}.$$

Of course, when $\eta_{i2} \to 0$, $\langle W_{\text{fed}} \rangle \to W_{20}$.

Among other criteria which helped dictate our choice of both ^{108}Pd and the experimental particulars, that of minimal feeding of the 2_1^+ state was also satisfied. Even so, population of levels higher in excitation energy than the 2_1^+ state, while quite small, was not altogether negligible, particularly for excitation by 180-MeV ^{58}Ni projectiles; Eq. (1) was therefore used to extract the experimental precessions $(\Delta\theta/g)$. The population parameters n_{i2} and the various pertinent angular distributions W_{i2} and W_{20} were calculated using the multiple Coulomb excitation computer code of Winther and de Boer[16] with matrix elements from Ref. 14.

The only states higher in excitation energy than that of the 2_1^+ level in ^{108}Pd which were discernibly populated (albeit quite weakly) in our experimental investigation were the $2'$, 4_1^+, and 0_2^+ levels. Our calculated values for $\eta_{2'2}$, η_{42}, $\eta_{0'2}$, and the angular distributions $W_{2'2}$, W_{42}, and W_{20} which are required in order to extract the experimental precessions using Eq. (1) are presented in Table I. As can be seen, the magnitudes of all terms in Eq. (1) which reflect feeding corrections are quite small; for this reason the extracted precessions proved insensitive to any reasonable values assumed for the g factors of these feeding states.

In the present study, the full unperturbed angular distributions were not measured; these were calculated using the same program employed to evaluate the pertinent statistical tensors. As a check on the calculated angular distributions, the values of S, and any attendant attenuation of the angular distributions in the Fe-Cu environment, the ratios $[W(70°)-W(66°)]/[W(70°)+W(66°)]$ were measured; these ratios were in agreement with their calculated values [i.e., for 180-MeV ^{58}Ni—measured: 0.104 ± 0.010, calculated: 0.095 ± 0.005; for 80-MeV ^{32}S—measured: 0.122 ± 0.010, calculated: 0.122 ± 0.006 (the uncertainties in the calculated ratios reflect those of the matrix elements[14] used)]. Althought the yields at these two angles did not differ greatly, the agreement between the measured and calculated ratios proved sufficiently good, expecially in light of the statistical uncertainties associated with our measured values of ϕ and the degree of concurrence of our lower-velocity measurement with prior results for ^{106}Pd at virtually the same velocity (see below), to justify confident use of the calculated value of R [Eq. (1)].

IV. RESULTS

Table II summarizes the experimental particulars and results of the present investigation, as well as of the similar precession measurements of earlier workers for ^{106}Pd recoiling through thin magnetized Fe foils at lower velocities. In the next to last column of Table II are displayed the time-averaged transient fields (B_{TF}), $\langle B\rangle = (1/T_{\mathrm{Fe}})(\Delta\theta/g)(\hbar/\mu_N)$, experienced by the nuclei of the Pd ions over their transit times T_{Fe}, through the Fe foils. The average velocity $\langle v/v_0\rangle$ of the ions traversing the foil of thickness L is given by $(L/T_{Fe})(1/v_0)$.

The energy losses of the recoiling ^{106,108}Pd ions traversing the Fe foil and their transit times T_{Fe} through it (presented in Table II) were calculated from the stopping power tables of Zeigler[18]; these differ for ^{106}Pd from those calculated by the previous authors using the Northcliff and Schilling[19] tabulation. We have recalculated these parameters for the experimental particulars which were reported by these prior workers for their lower-velocity ^{106}Pd measurements using the Zeigler[18] set. We find that although the latter stopping powers calculations yield consistently lower (10–20%) energies for the ions upon emergence from the Fe foils than do the former, both sets of stopping powers nevertheless provided virtually the same (within <2%) calculated transit times and, consequently, the same values of $\langle v/v_0\rangle$, and calculated values of ϕ (Ref. 20)—the pertinent and most relevant quantities required. This serves to demonstrate that for ions traversing thin ferromagnetic foils at $v/c \geq 1\%$, the significant calculated

TABLE I. Calculated[a] gamma-ray angular distribution and level population parameters[b] relevant to extraction of measured precessions for ^{108}Pd.

Levels populated		80-MeV ^{32}S			180-MeV ^{58}Ni	
(J_i^π)	η_{i2}	$W_{i2}(\theta)\|_{\theta=70°}$	$(dW_{i2}/d\theta)\|_{\theta=70°}$	η_{i2}	$W_{i2}(\theta)\|_{\theta=70°}$	$(dW_{i2}/d\theta)\|_{\theta=70°}$
2_1^+	1.00	0.79	−3.08	1.00	0.79	−3.12
$2'$	0.04	1.03	−0.37	0.15	1.03	−0.38
4_1^+	0.07	0.85	−0.98	0.38	0.85	−0.99
0_2^+	0.01	1.00	0.00	0.05	1.00	0.00

[a] Calculated using multiple Coulomb excitation code (Ref. 16) with matrix elements of Ref. 14.

[b] See text, Sec. III, for definition of parameters.

values pertinent to these precession measurements are rather insensitive to which of these specific sets of stopping powers are employed.

The present ^{108}Pd results listed in the last columns of Table II are experimental; the findings for ^{106}Pd and ^{108}Pd have not been normalized to each other in any way.

The best fit to the Pd precession data was sought for a transient field of the form

$$B(v,z)=a(v/v_0)^p Z^q \mu_B N_p\ , \qquad (2)$$

where μ_B and N_p, are respectively, the Bohr magneton and the density of polarized electrons in the saturated Fe foil. The value of $\mu_B N_p$ is 1752 G for an Fe foil magnetized to saturation, as was the case in the present work and reported to be so in those prior investigations for ^{106}Pd which are listed in Table II. χ^2 fitting all data (both ^{106}Pd and ^{108}Pd) to expression (2) gave best fit parameters $aZ^q = 5645 \pm 919$ and $p = 0.41 \pm 0.15$ with χ^2 per degree of freedom $\chi_\nu^2 = 0.4$ ($\nu = 5$).

Shu *et al.*[8] combined almost all previous "thin target" data reported for a wide range of nuclides in a "universal" fit Eq. (2); they found $a = 96.7 \pm 1.6$, $p = 0.45 \pm 0.18$, and $q = 1.1 \pm 0.2$. Based upon a value of $q = 1.0$, and using $Z(46)$ of Pd, we find for the combined ^{106,108}Pd data $a = 123 \pm 20$, which in not significantly different from that obtained by Shu *et al.*[8]

The value of a should, if the form of Eq. (2) is valid, be a universal constant characteristic of the *strength* of the transient field, independent of the particular ferromagnetic employed, the ion velocities, and other specifics which relate to any given measurement. That the present value for a and the value obtained by Shu *et al.*[8] are not closer in magnitude than found should, we believe, not be particularly stressed. Our value for a results from the ^{106,108}Pd data alone; theirs reflects the value of q which resulted from a univeral fit[8] to a broader body of experimental data over a wide range of Z values and for a variety of experimental conditions and particulars which may have pertained; some of these data incorporated in this universal fit were taken from specifically applicable thin-target measurements, while for others Shu *et al.*[8] interpolated "thin-target results" from data recorded under thick ferromagnetic foil experimental conditions. Thus, considering the foregoing and the sensitivity for $Z = 46$ to the uncertainty reported[8] for its exponent q, the near concurrence of our value of a and theirs could, equally well, be interpreted as evidence of confirmation of the form presumed for the transient field [Eq. (2)] and the universality and constancy of its characteristic value a.

The nonlinear velocity dependence of the transient field for Pd is exposed in Fig. 1, where the

TABLE II. Experimental particulars and results for Pd in thin magnetized Fe.

Nucleus	E_i (MeV)[a]	E_0 (MeV)[a]	$(v/v_0)_i$[a]	$(v/v_0)_0$[a]	$\langle v/v_0\rangle$	L (μm)[b]	$T_{\rm Fe}$ (fsec)[c]	Measured $\Delta\theta/g$ (mrad)	$\langle B\rangle$ (kT)	$a_{\rm LIN}$[d]
	47.4	18.7	4.24	2.66	3.50	1.73	226	18.3 ± 2.2[e]	1.69 ± 0.20	59.8 ± 7.8
^{106}Pd	42.0	15.5	4.00	2.42	3.24	1.73	244	20.8 ± 3.2[e]	1.78 ± 0.27	68.0 ± 10.9
$\tau = 16.3 \pm 0.9$ psec[h]	45.9	21.2	4.18	2.83	3.55	1.46	188	16.3 ± 2.4[f]	1.81 ± 0.27	63.0 ± 9.8
$g = 0.40 \pm 0.02$[f]	17.3	3.9	2.56	1.21	1.97	1.46	339	21.0 ± 2.3[f]	1.29 ± 0.14	81.4 ± 9.7
	11.6	4.3	2.10	1.27	1.74	0.89	234	16.0 ± 5.1[f]	1.43 ± 0.46	101.9 ± 32.7
^{108}Pd										
$\tau = 34.9 \pm 2.3$ psec[h]	146.0	116.6	7.38	6.57	7.02	1.04	68 ± 3	5.6 ± 2.0[g]	1.71 ± 0.62	31.5 ± 11.4
$g = 0.36 \pm 0.03$[e]	46.1	27.5	4.15	3.19	3.68	1.04	129 ± 6	10.5 ± 1.5[g]	1.70 ± 0.24	59.5 ± 9.1

[a] Energies of Pd ions: E_i entering Fe foil; E_0 leaving Fe foil. Similarly for $(v/v_0)_i$ and $(v/v_0)_0$. See text for basis of calculation of E_0, $(v/v_0)_0$.

[b] Thickness of Fe foil.

[c] Transit time of Pd ion in Fe foil.

[d] These values of $a_{\rm LIN}$ were obtained assuming $Z^{1.0}$.

[e] Reference 15.

[f] Reference 17.

[g] Results of present investigation.

[h] Reference 14.

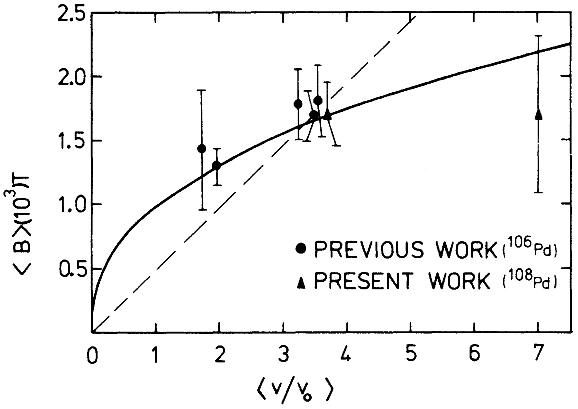

FIG. 1. Experimentally derived average transient field $\langle B \rangle$ experienced at the nuclei of Pd ions recoiling through thin, saturated Fe foils with average velocities $\langle v/v_0 \rangle$. The solid curve reflects our best fit parametrization of these data using the transient field form of Eq. (2) (with a linear Z dependence); see Table II. The dashed straight line corresponds to the best fit to these data assuming a linear velocity dependence [Eq. (3)] and a linear Z dependence.

experimentally inferred values of $\langle B \rangle$ are plotted as a function of $\langle v/v_0 \rangle$; the solid line is based on our best fit parametrization to these data.

The nonlinear dependence found and displayed in Fig. 1 for the transient field manifest at the nuclei of Pd ions rapidly traversing thin Fe foils is perhaps even more evident if one assumes a *linear* velocity dependence for this field, i.e.,

$$B = a_{\mathrm{LIN}}(v/v_0)\, Z^q \mu_B N_p \, . \tag{3}$$

The best fit to the combined data presuming this linear velocity dependence [Eq. (3)] yielded $\chi^2_\nu = 3.2$ ($\nu = 6$); it is also presented in Fig. 1 (dashed line). Were the transient field of this form, a_{LIN} should be constant, which is characteristic of this linear dependence. However, the data displayed in Fig. 2, in which the experimentally derived values of a_{LIN} (given in Table II) are presented as a function of $\langle v/v_0 \rangle$ for Pd, show that a_{LIN} is far from constant, decreasing markedly with increasing $\langle v/v_0 \rangle$.

V. CONCLUSIONS

We conclude from the combined data for ^{106,108}Pd ions recoiling through thin, magnetized Fe foils over the broadened velocity range encompassed by the present investigation, $1.74 \leq \langle v/v_0 \rangle \leq 7.02$, that these results are consistent with a $v^{0.41 \pm 0.15}$ dependence for the transient field, and are inconsistent with a linear velocity dependence for it. Moreover, our results indicate that the velocity dependence obtained by Shu *et al.*[8] appears to remain applicable for ion velocities up to approximately twice that previously studied for the heavier nuclides. It would be of signal import if the ion-solid interaction suggested by Dybdal *et al.*[6,7] as the mechanism which gives rise to the transient field manifest at nuclei of ions in this velocity range were shown to lead to a specific velocity-dependence and Z dependence which could be compared with experiment.

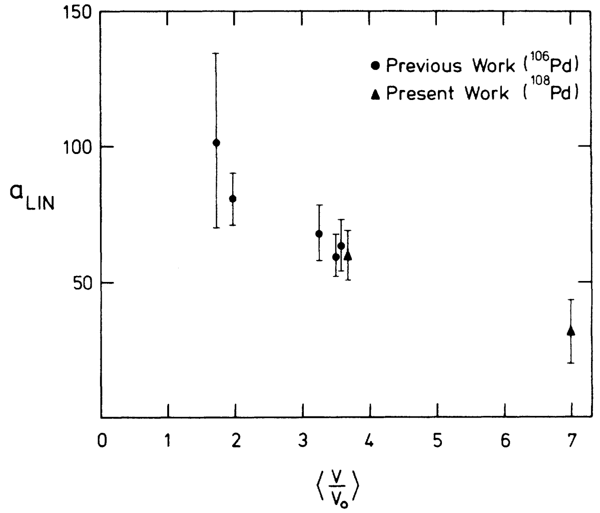

FIG. 2. Plot derived from measured $(\Delta\theta/g)$ values reported earlier for ^{106}Pd and in the present work (^{108}Pd) and a presumed linear velocity dependence of the TF, for which a constant value of a_{LIN} as a function of $\langle v/v_0 \rangle$ should pertain (see text). The present ^{108}Pd measurement at $\langle v/v_0 \rangle = 3.68$ is seen to be in excellent agreement with those reported for ^{106}Pd at $\langle v/v_0 \rangle$ values of 3.50 and 3.55, while the extension to the higher velocity $\langle v/v_0 \rangle = 7.02$ in the present investigation (^{108}Pd) clearly makes the presumption of a linear velocity dependence untenable.

ACKNOWLEDGMENTS

The authors with to acknowledge the benefit of fruitful discussions with Dr. N. Benczer-Koller, Dr. R. Kalish, and Dr. M. Hass, the aid of N.K.B. Shu provided by discussions with him and the magnetometer measurements he performed on our behalf, the help of D. Conley in particular facets of the experimental runs, and the cooperation of the staff of the 14UD Pelletron tandem at the Australian National University. This work was supported in part by the Australian Research Grants Committee.

[1] R. R. Borchers, B. Herskind, J. D. Bronson, L. Grodzins, R. Kalish, and D. E. Murnick, Phys. Rev. Lett. 20, 424 (1968).

[2] M. Hass, J. M. Brennan, H. T. King, and T. K. Saylor, Phys. Rev. C 14, 2119 (1976).

[3] R. Kalish, J. L. Eberhardt, and K. Dybdal, Phys. Lett. 70B, 31 (1977).

[4] G. van Middlekoop, Hyperfine Interact. 4, 238 (1978), and references cited therein.

[5] K. Dybdal, J. L. Eberhardt, and N. Rud, Hyperfine Interact. 7, 29 (1979).

[6] K. Dybdal, J. L. Eberhardt, and N. Rud, Phys. Rev. Lett. 42, 592 (1979).

[7] K. Dybdal, J. S. Forster, and N. Rud, Nucl. Instrum. Methods 170, 233 (1980).

[8] N. K. B. Shu, D. Melnick, J. M. Brennan, W. Semmler, and N. Benczer-Koller, Phys. Rev. C 21, 1828 (1980), and references cited therein.

[9] J. Lindhard and A. Winther, Nucl. Phys. A166, 413 (1971).

[10] J. L. Eberhardt, R. E. Horstman, P. C. Zalm, H. A. Doubt, and G. van Middlekoop, Hyperfine Interact. 3, 195 (1977).

[11] J. Sak and J. Bruno, Phys. Rev. B 18, 3437 (1978); J. Bruno and J. Sak, Phys. Lett. 68A, 463 (1978); Phys. Rev. B 19, 3427 (1979).

[12] J. M. Brennan, N. Benczer-Koller, M. Hass, W. J. Kossler, J. Lindemuth, A. T. Fiory, D. E. Murnick, R. P. Minnich, W. K. Lankford, and C. E. Stronach, Phys. Rev. B 18, 3430 (1978).

[13] N. Benczer-Koller, M. Hass, and J. Sak, in *Annual Review of Nuclear and Particle Sciences*, edited by J. D. Jackson, H. E. Gove, and R. F. Schwitters (Annual Reviews, Palo Alto, 1980), Vol. 30.

[14] R. L. Robinson, F. K. McGowan, P. H. Stelson, W. T. Milner, and R. O. Sayers, Nucl. Phys. A124, 553 (1969).

[15] J. M. Brennan, M. Hass, N. K. B. Shu, and N. Benczer-Koller, Phys. Rev. C 21, 574 (1980).

[16] A. Winther and J. de Boer, *Coulomb Excitation,* edited by K. Alder and A. Winther (Academic, New York, 1966), p. 303.

[17] H. T. King and D. L. Clark, Bull. Am. Phys. Soc. 23, 961 (1978).

[18] J. F. Zeigler, Appl. Phys. Lett. 31, 544 (1977).

[19] L. C. Northcliff and R. F. Schilling, Nucl. Data Tables A7, 233 (1970).

[20] N. K. B. Shu (private communication).