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Magnetic moments of 2_1^+ states of even-even Pd, Cd, and Ba isotopes

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The magnetic moments of 2_1^+ states of $^{102-110}$Pd, $^{106-116}$Cd, and $^{130-136}$Ba have been measured by the dynamic field technique. The resulting magnetic moments are compared to the predictions of the vibrational model and to the interacting boson model.

[NUCLEAR REACTIONS $^{102-110}$Pd(^{32}S, ^{32}S′)$^{102-110}$Pd(2_1^+), $^{106-116}$Cd(^{32}S, ^{32}S′) $^{106-116}$Cd(2_1^+), $^{130-136}$Ba(^{32}S, ^{32}S′) $^{130-136}$Ba(2_1^+) $E_S \sim 72$-80 MeV, enriched targets; measured $W(\theta, H, \infty)$ through polarized iron; deduced $g(2_1^+)$.]

INTRODUCTION

The Pd, Cd, and Ba nuclei exhibit general collective properties. Theoretical calculations based on the vibrational model and on the interacting boson model[1] have been made and the present experiment was undertaken in order to test these predictions. The magnetic moments of the first excited 2^+ states of the stable even $^{102-110}$Pd, $^{106-116}$Cd, and $^{130-136}$Ba isotopes were systematically measured using the dynamic field technique.[2-4] The ^{102}Pd and ^{106,108}Cd moments have been measured here for the first time.

Recent experiments on ions traversing thin iron foils have established the existence of a dynamic magnetic field which acts on fast ions during their traversal through the iron. Although the exact dependence of the dynamic field on the velocity and charge of the moving ion is not yet well known, it has been demonstrated that the field is very large and increases both with the atomic number and with the velocity of the ion in the region $0.02 < v/Zv_0 \ll 1$ where $v_0 = e^2/\hbar$ is the Bohr velocity, and Z is the atomic number of the ion. The dynamic field is of the order of 10^7 G and hence can give rise to measurable interactions with nuclear states with lifetimes as short as picoseconds. The general features of the dynamic field have been determined from experiments on a variety of excited nuclei[5-7] whose magnetic moments were measured by independent methods. The variation of the observed magnetic field with velocity and atomic number of the moving ion has been parametrized by a number of authors.[6,7] The resulting expressions for the dynamic field have then been interpolated or extrapolated to obtain the value of the dynamic field acting on ions of nuclear species with unknown magnetic moments, and in several instances magnetic moments have been determined. Because of the possible atomic structure effects on the dynamic field, such interpolations, or especially extrapolations of the field far from actual measurements, might be susceptible to systematic corrections and should be used with caution.

In the cases of Pd and Cd isotopes, there exist two isotopes, ^{106}Pd and ^{110}Cd, for which the magnetic moments of 2_1^+ states have been accurately determined in experiments on radioactive sources placed in known external magnetic fields.[8,9] The magnetic moments of the 2_1^+ states of the even Pd and Cd isotopes can therefore be measured relative to those of ^{106}Pd and ^{110}Cd, respectively. In addition, the interaction between the known moments and the dynamic field yields an unambiguous calibration of the field.

Most of the moments of the 2_1^+ states in the Pd and Cd isotopes have been measured previously by ion implantation perturbed angular correlations techniques[10] (IMPAC); however, these results are subject to severe systematic uncertainties arising from the dependence of the data on the static hyperfine field, on the lifetimes of the states, and on the need for accurate knowledge of low energy stopping powers. On the other hand, the present measurement which uses the "thin foil" technique is free of these difficulties.

No calibration of the dynamic fields exists for the Ba isotopes and hence the absolute magnitude of the magnetic moment cannot be determined absolutely, but may be obtained by interpolation of whatever general expression is chosen for the dynamic field. Under the experimental conditions used in the present experiment, the interpolation procedure yields the same value (within 5%) for the Ba magnetic moments for different parametrizations of the dynamic field.

EXPERIMENTAL TECHNIQUE AND RESULTS

The details of the technique have been described frequently in previous publications.[4,5] The essential feature lies in the use of a triple-layered target (Fig. 1) consisting of a layer of the isotope

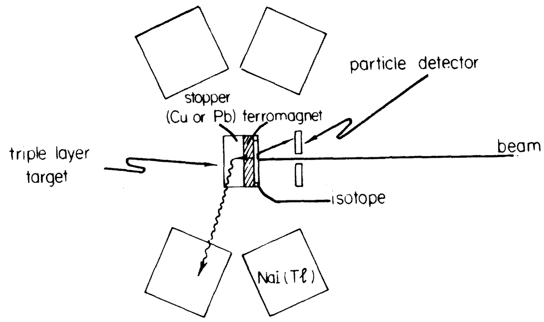

FIG. 1. Schematic of the experimental arrangement (not to scale) displaying the triple layer target and the particle and γ-ray detectors. The recoiling ions traverse the ferromagnetic foil and stop in the interaction-free Cu or Pb backing.

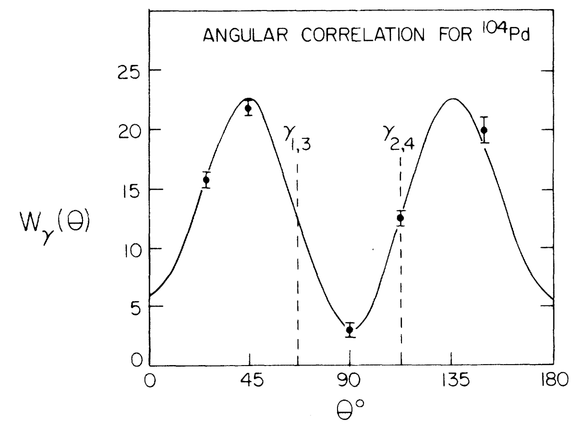

FIG. 2. Typical particle-γ angular correlation. The four NaI(Tl) detectors are placed at angles $\theta = \pm 67.5°$ and $\pm 112.5°$.

under study evaporated on a *thin* layer of iron (about 1.2 to 1.6 mg/cm^2) which the moving ion will traverse before stopping in the last backing layer of copper in which it suffers no further magnetic interactions. The duration of the interaction is given by the time the ion spends in the iron foil. This time is adequately calculated from a knowledge of the stopping power at high velocities ($v/c \gg 0.01$) about which there is no controversy. No radiation damage affects the interaction since the beam stops in the copper backing.

The nuclei are Coulomb excited by heavy ions, in particular, sulfur beams of 72 to 80 MeV from the Rutgers-Bell tandem accelerator. The backscattered sulfur ions are detected in an annular surface barrier detector and coincidences are required between decay gamma rays and the sulfur ions. Four 12.7×12.7 cm NaI(Tl) detectors are placed at $\theta = \pm 67.5°$ and $\pm 112.5°$, the angles at which the slope of the gamma-ray angular correlation $W(\theta)$ corresponding to the $m=0$, $2^+ \rightarrow 0^+$ transition is large $[|S| = (1/W)(dW/d\theta) = 3.00 \pm 0.09]$ (Fig. 2). A small aligning external magnetic field of 300 G was used to magnetize the iron foils. The iron foils were always annealed and their absolute magnetization was measured in a double coil in-

TABLE I. Summary of the experimental precession angles $\Delta\theta$ observed for the Pd and Cd isotopes, data relevant to the analysis of the precession angles, and resulting g factors. $E_{\rm in}$, $E_{\rm out}$, $(v/v_0)_{\rm in}$, and $(v/v_0)_{\rm out}$ are the energies and velocities of the moving ions as they enter and leave the ferromagnetic foil. L is the thickness of this foil and T is the time spent by the ion in the foil.

Isotope	L (mg/cm^2)	$E_{\rm in}$ (MeV)	$E_{\rm out}$ (MeV)	$(v/v_0)_{\rm in}$	$(v/v_0)_{\rm out}$	Time (psec)	$\Delta\theta$ (mrad)	g factor
^{102}Pd	1.35	48.5	22.4	4.36	2.97	0.217	−6.8±1.1	0.41 ±0.04
^{102}Pd	1.35	42.9	19.0	4.10	2.73	0.233	−9.0±1.3	
^{104}Pd	1.20	47.3	24.2	4.27	3.05	0.193	−7.3±0.9	0.46 ±0.04
^{104}Pd	1.32	42.5	19.3	4.04	2.73	0.230	−9.1±1.2	
^{106}Pd	1.36	47.4	22.1	4.23	2.89	0.225	−7.3±0.8	0.398±0.021
^{106}Pd	1.36	42.0	18.9	3.98	2.66	0.242	−8.3±1.2	
^{108}Pd	1.33	43.7	20.4	4.02	2.74	0.232	−5.8±0.9	0.36 ±0.03
^{108}Pd	1.35	40.2	17.9	3.86	2.58	0.250	−7.5±0.8	
^{110}Pd	1.42	46.1	20.8	4.09	2.75	0.245	−5.8±0.7	0.31 ±0.03
^{110}Pd	1.42	41.0	17.7	3.86	2.54	0.262	−5.6±0.9	
^{106}Cd	1.6	46.1	17.4	4.17	2.57	0.282	−13.4±2.5	0.40 ±0.10
^{106}Cd	1.6	40.6	14.5	3.91	2.34	0.305	−10.6±2.6	
^{108}Cd	1.6	46.0	17.6	4.13	2.56	0.285	−10.4±1.9	0.34 ±0.09
^{110}Cd	2.0	45.0	12.8	4.05	2.16	0.390	−11.7±2.0	0.285±0.055
^{110}Cd	1.6	44.9	17.2	4.04	2.51	0.290	−7.5±2.0	
^{112}Cd	1.6	44.4	17.2	3.98	2.48	0.294	−9.6±1.8	0.32 ±0.08
^{114}Cd	1.6	44.7	17.6	3.96	2.48	0.295	−8.8±1.4	0.29 ±0.07
^{116}Cd	1.6	43.1	16.9	3.86	2.41	0.303	−9.0±1.4	0.30 ±0.07

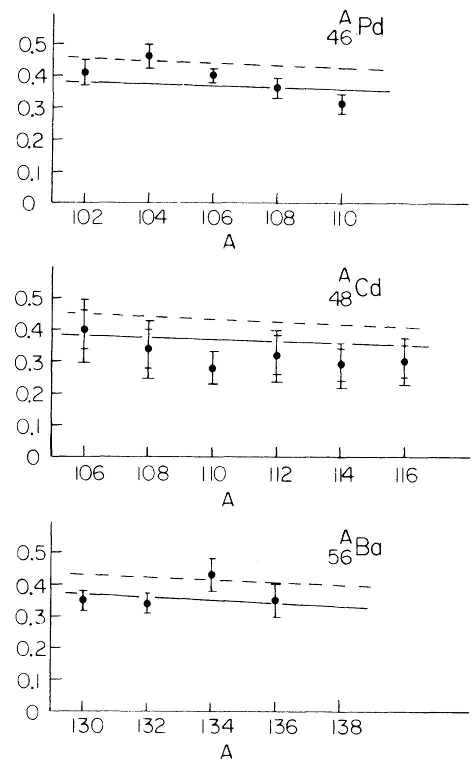

FIG. 3. g factors of Pd, Cd, and Ba isotopes. The error bar represents the absolute error resulting from the combination of the experimental statistical errors and the error in the calibration point. The smaller error bars shown on the data for the Cd isotopes indicate just the statistical errors in the experiments. The dotted line corresponds to $g = Z/A$ as predicted by the collective model. The solid line includes the contribution arising from different pairing between protons and neutrons.

duction magnetometer. The effect of the stray magnetic field on incoming and scattered beam (beam-bending effect) was measured; the gamma-ray angular correlation was found to precess by 0.09 ± 0.06 mrad, which was subtracted from the measured precession. The dynamic field was calibrated using the measurements on the 2_1^+ levels of ^{106}Pd and ^{110}Cd whose magnetic moments were independently determined[8,9]:

$$g(^{106}\mathrm{Pd}) = 0.398 \pm 0.021$$

and

$$g(^{110}\mathrm{Cd}) = 0.285 \pm 0.055 \ .$$

The initial and final energies and velocities of the ion traversing the magnetic layer of thickness L, the time the ion spends in this layer, the measured precession angles, and the deduced g factors are listed in Table I. The g factors are plotted in Fig. 3. For the Cd isotopes the error on the calibrating moment is appreciable so that two error bars are presented. The larger includes the error on ^{110}Cd and indicates the accuracy in the determination of the absolute magnitude of the moments. The smaller expresses the error on the measured precession angle only and indicates the error on the relative values of the moments.

Since, as discussed above, there is no calibration value from the Ba isotopes, a parametrization of the dynamic field has to be invoked in order to obtain an absolute scale for the measurement of g factors. An often-used parametrization is the linear velocity expression[2,3,5]

$$B(v, Z) = aZ^{P_z}(v/v_0)\mu_B N_p \ ,$$

where v is the ion's velocity, μ_B is the Bohr magneton, N_p the volume density of polarized elec-

TABLE II. Summary of data and g factors of the Ba isotopes.

Isotope	L (mg/cm^2)	E_{in} (MeV)	E_{out} (MeV)	$\left(\frac{v}{v_0}\right)_{in}$	$\left(\frac{v}{v_0}\right)_{out}$	Time (psec)	$\Delta\theta$ (mrad)	g factor	
^{130}Ba	1.64	36.88	11.88	3.38	1.93	0.372	-14.1 ± 0.1	0.35 ± 0.03 [a]	0.35 ± 0.03 [b]
^{132}Ba	1.64	36.29	11.79	3.33	1.91	0.375	-13.3 ± 0.2	0.34 ± 0.03 [a]	0.34 ± 0.03 [b]
^{132}Ba	1.64	36.60	11.90	3.34	1.91	0.375	-13.8 ± 0.3		
^{134}Ba	1.74	36.39	10.89	3.31	1.82	0.409	-18.1 ± 0.2	0.43 ± 0.05 [a]	0.43 ± 0.05 [b]
									0.41 ± 0.06 [c]
^{136}Ba	1.77	34.39	9.79	3.19	1.71	0.435	-12.1 ± 0.04	0.34 ± 0.05 [a]	0.35 ± 0.05 [b]
^{136}Ba	1.77	34.39	10.26	3.24	1.75	0.428	-14.8 ± 0.02		

[a] $B(v, Z) = 97\,Z^{1.1}(v/v_0)^{0.45}\mu_B N_p$.
[b] $B(v, Z) = 12\,Z^{1.5}(v/v_0)\mu_B N_p$.
[c] Reference 11, $B(v, Z) = 63Z\,(1 + Z/84)^{2.5}(v/v_0)\,\mu_B N_p$.

trons, $\mu_B N_p = 1752$ for an iron foil magnetized to saturation, and a is a free parameter. The best fit to the early data yields $a = 12$ and $P_s = 1.5$. However, several recent experiments[6] have shown that the linear parametrization may not be adequate and a much better fit is obtained with

$$B(v, Z) = a(v/v_0)^{0.45} Z^{1.1} \mu_B N_p ,$$

with $a = 97$.

Nevertheless, since calibration points for the Pd, Cd, and Sm isotopes are close to the Ba region, the results for the Ba isotopes obtained by interpolation are barely affected by the choice of the two different parametrizations. Table II presents the results obtained for Ba based on both of the parametrizations presented here. In a recent experiment, Eberhardt and Dybdal[11] established that a linear dynamic field best fits the ^{134}Ba data. They obtain a magnetic moment for ^{134}Ba in agreement with the present result. We would like to caution that in case of a measurement on ions with Z or v well outside those used for the calibration experiments, the absolute value of a measured magnetic moment could be affected much more by the choice of parametrization.

DISCUSSION

The most obvious feature of the set of magnetic moments is that they are nearly constant, a clear manifestation of the collective nature of the states. The large variations from one isotope to another found for iron and nickel isotopes are not present. In first approximation, the g factor of a purely collective state should be equal to Z/A (dashed line in Fig. 3); the measurements fall consistently below this value. Greiner[12] derived a correction to the simple Z/A prediction based on the Nilsson and Prior[13] suggestion that the pairing force between protons is greater than that between neutrons, thus allowing for a larger neutron deformation. In this formalism

$$g = Z/A(1 - \tfrac{4}{3} f) ,$$

where

$$f = \frac{N}{A}\left(\frac{\beta_0(n)}{\beta_0(p)} - 1\right)$$

and $\beta_0(n)$ and $\beta_0(p)$ are the deformation parameters for neutrons and protons, respectively. These can be related to the strength of the pairing forces G_n and G_p for neutrons and protons by

$$\frac{\beta_0(n)}{\beta_0(p)} = \left(\frac{G_p}{G_n}\right)^{1/2} = 1.20 .$$

The solid line in Fig. 3 is the prediction based on the above consideration. The agreement with the data is better, particularly for the Cd isotopes, but the data are still below the calculated values. In addition, the data for ^{104}Pd through ^{110}Pd show a trend which decreases more rapidly than either calculation. ^{102}Pd is an exception to the trend which may be related to closure of the $d_{5/2}$ subshell at 56 neutrons. The ratios of the energies of the second 2^+ state to that of the first range between 2.4 and 2.1 for the $^{104-110}$Pd isotopes, as in most vibrational nuclei, but are equal to 2.8 for ^{102}Pd, indicating a more single-particle nature for this nucleus.

An alternative framework within which these results can be discussed is the interacting boson model of Arima and Iachello.[1] In this model a unified description of collective nuclear properties is attempted in terms of a system of interacting bosons. In the first approximation, the g factors of the 2^+ excited states of even-even vibrational nuclei can be written in terms of the number N_ν or N_π or neutron or proton bosons:

$$g = A + B_\nu N_\nu + B_\pi N_\pi .$$

In the case of Pd there is a clear indication that the g factors change with neutron number and a coefficient $B_\nu = -0.025$ can be extracted from the data.

The g factors of the Cd isotopes could be fit either with a constant or with a term decreasing linearly with the neutron number as found for the Pd isotopes. The combined data yields $A = 0.42$, $B_\nu = -0.025$, and $B_\pi = 0.05$ where the boson numbers are counted from the closed shell at 50.

The Ba g factors, on the other hand, are approximately constant across the whole range of isotopes, but could also be fit with a term increasing linearly with neutron number. Considerably higher accuracy is required for careful comparison with theory. This is especially true if one tries to test the second order term in the interacting boson model which relates the g factors to the number of bosons and to the quadrupole moments of the corresponding levels.

However, even within the present accuracy, systematic measurements in neighboring isotopes like $_{44}$Ru and $_{52}$Te could provide a basis for testing the interacting boson model predictions in this mass region. Experiments to this effect are now in progress.

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