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INELASTIC SCATTERING OF 30 MeV POLARIZED PROTONS FROM ^{112}Cd

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Résumé. — Les sections efficaces différentielles et pouvoirs d'analyse des diffusions élastique et inélastiques de protons polarisés de 30 MeV sur ^{112}Cd ont été mesurés. L'interprétation des excitations des états à deux phonons a été faite dans le cadre du formalisme des équations couplées. Un bon accord avec les sections efficaces et pouvoirs d'analyse mesurés des premiers niveaux excités 2_1^+ (0,617 MeV) et 2_2^+ (1,31 MeV) a été obtenu en supposant que les développements choisis sur la base un phonon et deux phonons pour leurs fonctions d'onde sont orthogonaux et un mélange d'état à deux phonons pour le premier 2_1^+.

Abstract. — Differential cross-sections and analysing powers for elastic and inelastic scattering of 30 MeV polarized protons from ^{112}Cd have been measured. The coupled-channel formalism is used to interpret the excitation of the two-phonon states. A good fit to the observed cross-sections and analysing powers for the excitation of the first 2_1^+ (0.617 MeV) and the second 2_2^+ (1.31 MeV) states is obtained if the expansions of their wave functions in terms of the one-phonon and two-phonon basis functions are assumed to be orthogonal and if some admixture of the two-phonon component is assumed in the 2_1^+ state wave function.

1. **Introduction.** — We have measured the differential cross-sections and analysing powers for the elastic and inelastic scattering of 30 MeV polarized protons from ^{112}Cd. The elastic scattering was analysed by an optical-model potential, and the excitations of the first collective 2^+ and 3^- states were compared to the predictions of the coupled-channel formalism. With analysing powers data in addition, our interest was therefore to study and interpret conveniently the excitations of the two collective quadrupole states 2_1^+ and 2_2^+. In the analysis of 13 MeV inelastic scattering cross-sections the 2_1^+ state (0.617 MeV) has been assumed to be a pure one-phonon state, while the 2_2^+ state (1.31 MeV) has been assumed to have a small admixture of the one-phonon state [1]. These authors have obtained a rather good agreement between cross-sections data and calculated curves. In our analysis using the CC calculations, two assumptions have been made for the two states 2_1^+ and 2_2^+ : the orthogonality of the expansions of their wave functions in terms of the one-phonon and two-phonon basis functions and the strong admixture of the two-phonon component in the 2_1^+ state wave function.

2. **Experimental method.** — The data were obtained at an energy of 30 MeV with the polarized proton beam of the Grenoble cyclotron. Since the new analysing magnet [2] recently installed was used, an overall resolution of 80 to 100 keV (FWHM) was obtained for most of the data. Up to 1 nA of energy analysed polarized protons were delivered on the target, with a polarization close to 70 % which was measured with a carbon polarimeter. The carbon polarimeter consists of a thin foil of graphite, introduced into the incident beam during one minute for every twenty minutes interval, and of two Si(Li) detectors of 5 mm thickness located at 60° on each side of the beam L (left) and R (right). The analysing power for elastic scattering of 30 MeV protons by ^{12}C at this angle is $A_0 = 0.57 \pm 0.01$. The sign of the polarization was reversed every 0.2 s. We measured the polarization of the beam for the two spin orientations ↑ (up) and ↓ (down) using the following relation :

$$p\uparrow = \frac{1}{A_0}\,\frac{2\,\mathrm{L}\!\uparrow \mathrm{R}\!\uparrow - (\mathrm{L}\!\downarrow \mathrm{R}\!\uparrow + \mathrm{L}\!\uparrow \mathrm{R}\!\downarrow)}{\mathrm{L}\!\downarrow \mathrm{R}\!\uparrow - \mathrm{R}\!\downarrow \mathrm{L}\!\uparrow}$$

$$p\downarrow = \frac{1}{A_0}\,\frac{2\,\mathrm{L}\!\downarrow \mathrm{R}\!\downarrow - (\mathrm{L}\!\uparrow \mathrm{R}\!\downarrow + \mathrm{L}\!\downarrow \mathrm{R}\!\uparrow)}{\mathrm{L}\!\uparrow \mathrm{R}\!\downarrow - \mathrm{R}\!\uparrow \mathrm{L}\!\downarrow}.$$

If the polarized source was well adjusted, we would find $p\uparrow = -p\downarrow$. (This was generally the case.) Enriched target of 1 mg/cm^2 thickness obtained from

ORNL was used. The measurements were made using two telescopes comprising ΔE surface barrier detectors of 700 μ thickness and E Si(Li) detectors 5 mm thick all cooled to − 25 °C by a thermoelectric device. The treatment of signals coming from the two detectors of each telescope was realized so that only coincidence events were registered. We eliminated therefore the alpha-particle groups of 33 MeV maximum energy, which were completely stopped in the first detector ΔE.

The value of the analysing power A for the studied reaction is given by

$$A = \frac{N\uparrow - N\downarrow}{p\downarrow N\uparrow - p\uparrow N\downarrow} \quad \text{for the right detector R}$$

$$A = \frac{N\uparrow - N\downarrow}{p\uparrow N\downarrow - p\downarrow N\uparrow} \quad \text{for the left detector L}.$$

To obtain absolute values of differential cross-sections, we used a beam monitor consisting of two Si(Li) detectors placed at 30° on each side of the beam and slightly above the reaction plane. The beam monitor gave a counting rate which is proportional to $C/\cos\theta_{\text{target}}$, where C is the charge obtained from the integration of the Faraday cup current and θ_{target} is the angle between the normal to the target and the incident beam direction. The good resolution achieved permitted analysing powers for several low-lying states such as the 2_1^+, 2_2^+ and 3^- to be extracted.

3. **Optical-model analysis.** — The optical-model potential used in this analysis is local and has the usual form :

$$U(r) = -V_0(e^x+1)^{-1} - i(W_V - 4W_D\,d/dx')(e^{x'}+1)^{-1} + (\hbar/m_\pi c)^2 V_{LS}\,\boldsymbol{\sigma}.\mathbf{L}r^{-1}(d/dr)(e^{x_s}+1)^{-1}$$

where

$$x = (r - r_0 A^{1/3})/a_0$$
$$x' = (r - r_I A^{1/3})/a_I$$
$$x_s = (r - r_{LS} A^{1/3})/a_{LS}$$

to which is added the Coulomb potential from a uniformly charged sphere of radius 1.17 $A^{1/3}$ F. The optical-model parameters were determined from an analysis of the elastic cross-section and analysing power together, data taken concurrently with the inelastic data. The optimum parameters were determined by use of automatic search routines MAGALI [3] which minimized the quantity χ_t^2 which is the sum of χ_σ^2 and χ_p^2

$$\chi_\sigma^2 = \sum_{i=1}^{N} \{ (\sigma_{th}(\theta_i) - \sigma_{exp}(\theta_i))/\Delta\sigma_{exp}(\theta_i) \}^2$$

$$\chi_p^2 = \sum_{i=1}^{N} \{ (P_{th}(\theta_i) - P_{exp}(\theta_i))/\Delta P_{exp}(\theta_i) \}^2$$

where $\sigma_{exp}(\theta_i)$ is the measured, and $\sigma_{th}(\theta_i)$ the calculated differential cross-section at angle θ_i, while $\Delta\sigma_{exp}$ is the error associated with σ_{exp} ; $P_{exp}(\theta_i)$ is the measured, and $P_{th}(\theta_i)$ the calculated polarization at angle θ_i, while ΔP_{exp} is the error associated with P_{exp}.

Errors on the cross-sections were uniformly set at ± 5 %, the errors on the polarization were statistical. The best results of the analysis are given in table I. The value of $\chi_t^2/2N$ is smaller than 7. The fits with the data using the potentials of table I are shown on figure 1. No volume absorption was needed to reproduce the data.

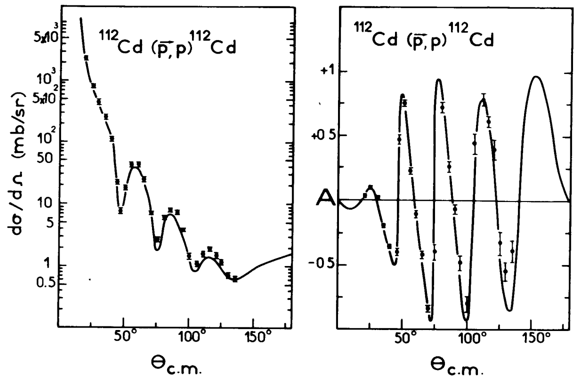

FIG. 1. — Elastic scattering cross-section and analysing power and optical-model predictions with the parameters of table I.

4. **Coupled-channel calculations.** — It has been known that the pure harmonic vibrational model does not explain completely the proton inelastic scattering cross-sections from several states in ^{112}Cd like the second 2_2^+ at 1.31 MeV in this nucleus [1]. Although good fits to the data were obtained by adding to the basically two-phonon state 2_2^+ some admixture of a one-phonon state, several problems in this nucleus still remain to be investigated. In particular, recently, it has been suggested (1) that a strong two-phonon admixture should be added also to the one-phonon wave function of the first 2_1^+ at 0.617 MeV in ^{112}Cd to describe successfully this state. The data taken at the Grenoble cyclotron were analysed with the program ECIS 74 [4] by coupling the 0^+, 2_1^+, 2_2^+ and 3^- (E_x = 1.97 MeV) states using the vibrational model. The two states 2_1^+ and 2_2^+ of which the expansions of the wave functions in terms of the one-phonon and two-phonon basis functions are assumed to be orthogonal, may be represented by, following the notation of Raynal [5]

$$| 2_1^+ \rangle = \sin\varphi\,| 2-\text{ph} \rangle + \cos\varphi\,| 1-\text{ph} \rangle$$
$$| 2_2^+ \rangle = \cos\varphi\,| 2-\text{ph} \rangle - \sin\varphi\,| 1-\text{ph} \rangle$$

or, following the notation of Tamura [6]

$$| 2_1^+ \rangle = -(\beta''_{02}/\tilde\beta_2)\,| 2-\text{ph} \rangle + (\beta_{22}/\beta_2)\,| 1-\text{ph} \rangle$$
$$| 2_2^+ \rangle = (\beta_{22}/\beta_2)\,| 2-\text{ph} \rangle + (\beta''_{02}/\tilde\beta_2)\,| 1-\text{ph} \rangle$$

where $\tilde\beta_2 \equiv \beta_{2_2^+}$ and $\beta_2 \equiv \beta_{2_1^+}$.

(1) Shute, G. G. and Fagan, M. J., private communication.

TABLE I

Optical-model parameters

V_0 (MeV)	r_0 (F)	a_0 (F)	W_V (MeV)	W_D (MeV)	r_I (F)	a_I (F)	V_{LS} (MeV)	r_{LS} (F)	a_{LS} (F)
49.74	1.18	0.81	0	15.08	1.28	0.53	5.89	1.09	0.47

TABLE II

Optical-model and deformation parameters used in the coupled-channel calculations

V_0 (MeV)	r_0 (F)	a_0 (F)	W_V (MeV)	W_D (MeV)	r_I (F)	a_I (F)	V_{LS} (MeV)	r_{LS} (F)	a_{LS} (F)	r_C (F)	β_2	$\tilde{\beta}_2$	β_3
50.34	1.20	0.66	0	11.08	1.25	0.56	5.70	1.10	0.64	1.17	0.242	0.058	0.140

In view of the determination of the value for the admixture of one-phonon and two-phonon components for each state, and therefore the deformation parameters β_l, we have analysed simultaneously the differential cross-sections and analysing powers using the CC calculations. The optical-model parameters used as initial values for the optical-model search procedure were taken from table I. The interaction potential arises from the deformation of the Coulomb potential, the complex central potential and the spin-orbit potential. The deformed spin-orbit potential was of the full Thomas form [7]. The best results obtained from the search procedure over the optical-model parameters as well as the admixture components, and therefore the deformation parameters, show that we have to consider an equal admixture (50 %), i.e. $\varphi = -45°$, for each component. These results are presented in figure 2 and the corresponding parameters listed in table II. As can be seen in this figure, good agreement is obtained for the measured cross-sections and analysing powers. The χ^2 values vary rapidly with φ, calculations indicate that χ^2 increases at the rate of about 2 % per degree for $\varphi \simeq -45°$.

5. **Conclusions.** — The experimental cross-sections and analysing powers reported here for the 0^+, 2_1^+, 2_2^+ and 3^- levels were analysed simultaneously in the coupled-channel formalism by coupling them together and using the vibrational model. The best agreement between experimental data and theoretical curves has shown firstly that the data could be analysed correctly assuming the orthogonality of the expansions of the wave functions for the two states 2_1^+ ($E_x = 0.617$ MeV) and 2_2^+ ($E_x = 1.31$ MeV), in terms of the one-phonon and two-phonon basis functions, and secondly a strong two-phonon admixture (50 %) for the 2_1^+ state which has been considered up to now as a pure one-phonon state [1]. This proposed strong two-phonon admixture in the first 2_1^+ in ^{112}Cd is however in agreement with a theoretical suggestion made recently ([1]).

Acknowledgments. — We would like to thank Dr. J. Raynal for using his coupled-channel code ECIS 74 and for his constant interest in this work.

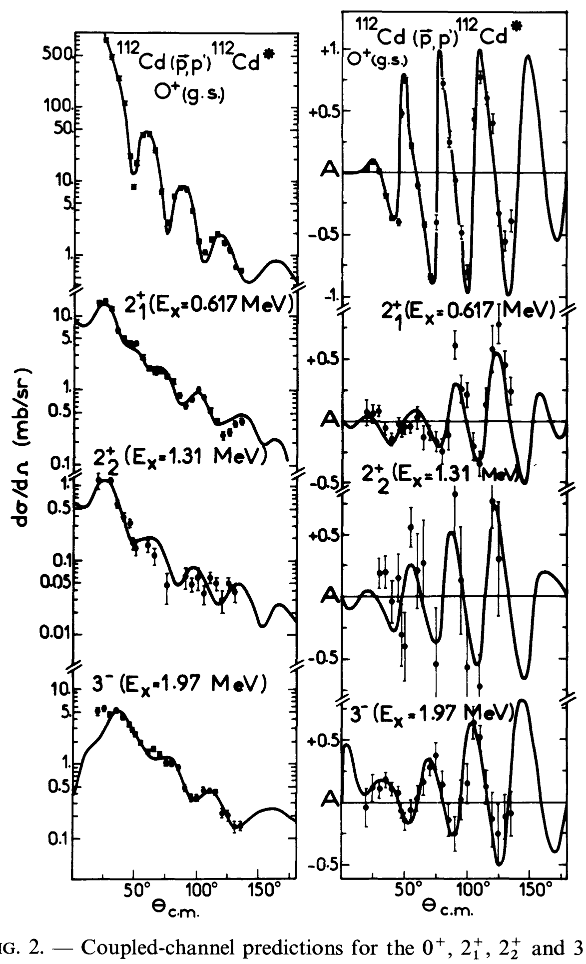

FIG. 2. — Coupled-channel predictions for the 0^+, 2_1^+, 2_2^+ and 3^- states with the parameters of table II.

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