POLARIZATION STUDY OF AN ISOBARIC ANALOG STATE IN ^{91}Nb†

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Double-scattering techniques have been used to measure the polarization of protons elastically scattered by ^{90}Zr for proton energies between 6.6 and 7.1 MeV. This region contains a resonance previously identified as an isobaric analog state[1] in the compound nucleus ^{91}Nb. The state in ^{91}Zr which is a member of the same isobaric multiplet occurs at an excitation energy of 2.06 MeV and has been observed by Cohen and Chubinsky.[2] They report the angular distribution of the (d,p) reaction leading to this state to be characteristic of an $l=2$ orbital angular momentum for the added neutron. With this experimental information and shell-model calculations, Cohen and Chubinsky made the spin and parity assignment of $\frac{3}{2}^+$ to the ^{91}Zr level.

The recent observation of j-dependent effects in (d,p) stripping[3] has increased interest in the study of ^{90}Zr$(d,p)^{91}$Zr. Using the tentative assignment of $d_{3/2}$ for the 2.06-MeV level and $d_{5/2}$ for the ground state of ^{91}Zr, a spin dependence was observed. This j-dependent effect in the (d,p) reaction was also observed in similar states in Zr^{93} and Zr^{95} and shown to have a consistent behavior. The polarization study near the analog state in ^{91}Nb has provided a direct, model-independent determination of the spin of the isobaric multiplet.

Measurements. – For all the polarization measurements, the protons were first elastically scattered by a self-supporting, enriched (98.6%) ^{90}Zr target and then elastically scattered at a mean angle of 50° by a thick (≃8.7 mg/cm^2) carbon analyzing target.

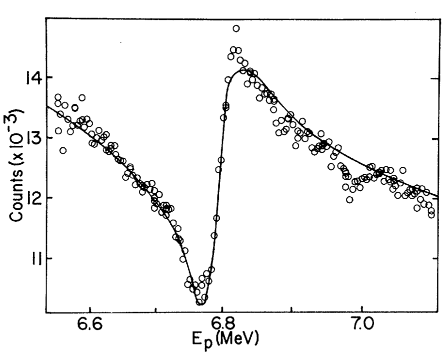

FIG. 1. Elastic-scattering differential cross section measured as a function of energy at 92.4° in the laboratory system. The solid line represents a least-squares fit to the data.

In the proton-energy region 5.4 to 6.4 MeV, the magnitude of the polarization produced in p-^{12}C elastic scattering at 50° (lab) is large and a slowly varying function of both energy and angle. Therefore, it is convenient, and in certain instances highly advantageous, to use a thick carbon target and rather poor geometry in the second scattering. This was done to measure the polarizations reported here. The effective polarization produced in the second scattering was measured as a function of the energy of the protons incident on the second target for proton energies in the afore-mentioned region. A polyethelene absorber was used to reduce the energy of the singly scattered protons to a value within this interval.

The angular spread in the first scattering angle was less than ±0.7°, so that effects on the measured asymmetries due to the finite geometry used were negligible. The laboratory and data-processing techniques used to measure the data and calculate the asymmetries reduced all sources of instrumental error to negligible proportions. The effect of the 1.4% contaminant in the zirconium target is negligible compared to the statistical errors. Contaminants in the second target produce no effect on the measured polarizations since in the calibration of the second scattering device, the polarization measured was that due to the total contents of the second target. Therefore, no corrections were necessary to the measured polarizations.

The elastic-scattering differential cross section was measured as a function of energy at the laboratory angles 172.4°, 152.4°, 122.4°, and 92.4° to complement the polarization measurements. A fit to the 92.4° data is shown in Fig. 1. The resonance parameters obtained are listed in Table I. The spin assignment is based solely on the polarization measurements and calculations.

Preliminary calculations had shown that near the $l=2$ resonance the magnitude of the polar-

Table I. Level parameters for the $l = 2$ resonance.

$E^{\text{c.m.}}$ (MeV)	Γ_p (keV)	Γ (keV)	l	J^π
6.71	18	54	2	$\frac{3}{2}^+$

izations would be largest at angles near 60° and 140°. Therefore, the polarization was measured as a function of energy in the region of the resonance at these laboratory angles. These data are shown in Fig. 2. The solid curve was calculated assuming $J^\pi = \frac{3}{2}^+$, and the dashed curve was calculated assuming $J^\pi = \frac{5}{2}^+$. The resonance parameters used were obtained from the differential cross-section fit.

Two angular distributions of the polarization were measured near the resonance, one at a proton energy below the resonance energy and one above. These angular distributions are shown in Fig. 3. The curves were obtained from calculations based on the assumption that the level was characterized by $J^\pi = \frac{3}{2}^+$.

The two polarization angular distributions were fitted using the University of Wisconsin computer program SCRAM-5.[4] The results of the SCRAM analysis confirm the assignment of $\frac{3}{2}^+$ to this level.

Analysis.—The 92.4° elastic-scattering data were fit using a least-squares fitting code SNOW[5] for the general scattering problem. The resulting resonance parameters were then used to calculate the polarization shown by the curves in Figs. 2 and 3 using the expressions below.

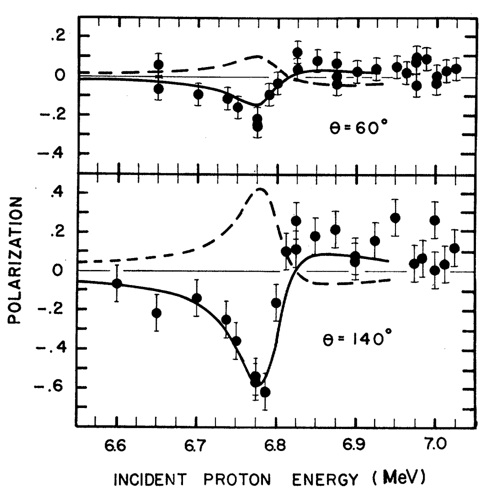

FIG. 2. Elastic-scattering polarization measured as a function of energy at 60° and 140° in the laboratory system. The solid curve represents a calculated prediction assuming the state to be $\frac{3}{2}^+$ while the dashed curve assumes the state to be $\frac{5}{2}^+$.

For elastic scattering of protons by spin-zero nuclei, the differential elastic-scattering cross section and polarization can be expressed in terms of the coherent and incoherent scattering amplitudes, A and B, respectively, in the following manner:

$$d\sigma/dr = A^*A + B^*B,$$

and

$$P = (A^*B + B^*A)/(A^*A + B^*B).$$

The amplitudes A and B can be expressed as

$$A = -(\eta/2k)csc^2(\theta/2)\exp[i\eta\ln\{csc^2(\theta/2)\}] + \frac{i}{2k}\sum_{L,J}(J+\tfrac{1}{2})T_{L,J}P_l^{\,0}(\cos\theta),$$

and

$$B = \frac{1}{2k}\sum_{L,J}(-1)^{L+J+\frac{1}{2}}T_{L,J}P_l^{\,1}(\cos\theta).$$

Here,

$$T_{L,J} = \exp(2i\omega_L) - U_{L,J};$$

$$U_{L,J} = \exp(2i\omega_L) \times \left\{\exp(2i\xi_L) + \exp(2i\varphi_L)\frac{i\Gamma_L^{\,P}}{(E_J - E) - \frac{1}{2}i\Gamma_L}\right\};$$

$$\omega_L \equiv \text{Coulomb phase} = 0 \text{ for } L = 0, \quad = \sum_{t=1}^{L}\tan^{-1}(\eta/t);$$

ξ_L = optical phase, in general complex;

φ_L = background resonance phase, real [when $\text{Im}(\xi_L) = 0$, then $\xi_L = \varphi_L$]

$$= 4.98 Z_I Z_T (M/E)^{1/2},$$

$$k^2 = 4.78ME \times 10^{-3}\ (\text{b}^{-1}),$$

$$M = \frac{M_I M_T}{M_I + M_T}\ (\text{amu}),$$

$$E = \frac{M_I}{M_I + M_T}E_{\text{lab}}\ (\text{keV}).$$

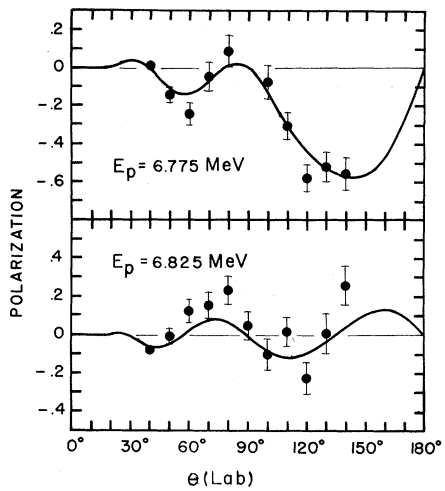

FIG. 3. Elastic-scattering polarization measured as a function of angle at 6.70 and 6.75 MeV in the center-of-mass system. The solid curve represents a calculated prediction assuming the state to be $\frac{3}{2}^+$.

Conclusions.—The polarization study made on this $d_{3/2}$ isobaric analog resonance has conclusively established the spin of the level. Similar studies on additional analog resonances in the future will serve as valuable determination of the spin of nuclear states.

An analysis of polarization and differential elastic-scattering cross-section measurements determines the total width, elastic partial width, resonance energy, and various phase parameters. The preliminary fits to the data (with the imaginary part of the optical phase set to zero) exhibit small inconsistencies. The origin of these difficulties are at present attributed to the lack of a set of reliable optical phases. Although these problems are a cause of concern, the effect is actually small since the resonance energy is more than 2 MeV below the Coulomb barrier.

We wish to emphasize the simple analysis necessary to determine the spin of a level using polarization techniques compared to the more formidable, still to be explained, j-dependent effects of (d,p) stripping.

It is pleasing to find the shell-model calculations used by Cohen to be correct. This may add some confidence to such calculations for heavy nuclei. It will add some assurance to the j-dependent (d,p) studies, which can be applied to cases where isobaric analog states cannot be studied as elastic-scattering resonances.

The spin assignment to this level could have been made with only about 25% of the polarization data actually measured. It is estimated that had the magnitude of the polarization effect been smaller by a factor of 3, it would still have been possible to make a definite spin assignment in this case. Therefore, it appears likely that polarization measurements may be very useful and practical for the study of levels in even heavier nuclei.

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