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MEDIUM-ENERGY PROTON SCATTERING FROM ^{58}Ni .
EXPERIMENTAL RESULTS AND COUPLED-CHANNEL CALCULATIONS

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ABSTRACT

Angular distributions have been obtained for the differential cross-section in 178 MeV elastic proton scattering from ^{58}Ni , as well as inelastic scattering from the states at 1.45 MeV (2^+) and 4.47 MeV (3^-). For elastic scattering and for scattering from the 2^+ state also the polarization was measured. Together with the corresponding results at 1 GeV these experimental data were analyzed in coupled-channel calculations using the partial-wave approach and with a deformed spin-orbit potential of the full Thomas form.

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1. INTRODUCTION

The inelastic scattering of 150-200 MeV protons is well described by the extended optical model using the distorted wave Born approximation (DWBA). The spin-dependence is very strong in this energy region, and it has been found^{1,2)} that it is impossible to reproduce the experimental data, not only for the polarization but also for the differential cross-section in the inelastic scattering without a deformed spin-orbit potential of the full Thomas form³⁾.

In this report we present angular distributions for the differential cross-section in 178 MeV elastic proton scattering from ^{58}Ni , as well as inelastic scattering from the states at 1.45 MeV (2^+) and 4.47 MeV (3^-). For elastic scattering and for scattering from the 2^+ state the polarization also was measured. The experimental data were analysed in coupled-channel calculations using the partial-wave approach and with a deformed spin-orbit potential of the full Thomas form. The purpose of this analysis was to investigate to what extent the effects of coupled-channels are important in the case of ^{58}Ni .

In order to obtain a comparison with the region around 1 GeV we have also analysed the corresponding data obtained by the Saclay group at 1047 MeV⁴⁾. For the higher energy, calculations were previously made, for instance in the partial wave approach using DWBA⁵⁾ and in the Glauber approximation^{6,7)} including spin-dependence. In the latter case Fäldt et al.⁷⁾ found that the influence of the spin-dependent amplitude was most pronounced in the maxima of the angular distributions of the differential cross-sections, and that the effect increased gradually with increasing momentum transfer.

2. EXPERIMENTAL DETAILS

The 178 MeV data were obtained using the external proton beam from the synchrocyclotron at the Gustaf Werner Institute, Uppsala. An 80 mg/cm² thick target of ^{58}Ni enriched to 99% was used.

The scattered protons were momentum-analysed in a magnetic spectrometer and detected by a 16-channel hodoscope. The polarization measurements were made by

means of a polarimeter with carbon as the second scatterer. Details of the experimental set-up are given, for example, in Ref. 8.

The total energy resolution including energy spread in the beam and straggling in the target was found to be of the order of 270 keV (FWHM), and the scattering angle of the protons was determined to $\pm 0.05^\circ$.

Angular distributions were evaluated by fitting standard peaks on a constant background in the energy spectra of scattered protons. In order to evaluate the 3^- level at 4.47 MeV, the contribution from the 4^+ level at 4.75 MeV had to be taken into account. The fitting was performed using the CERN MINUIT⁹⁾ fitting package. Details of the data handling for the polarization are given in Ref. 8.

Absolute values of the differential cross-section were obtained by using a ^{12}C target, for which the 4.4 MeV level at $\theta_{\text{lab}} = 17.5^\circ$ is assumed to be known accurately. The absolute error in the differential cross-section turns out to be of the order of 10% when the errors in the calibration procedure and target thickness are considered.

3. EXPERIMENTAL RESULTS AND PRELIMINARY DISCUSSION

The results for the differential cross-section in the elastic scattering and in the inelastic scattering from the 2^+ state at 1.45 MeV and the 3^- state at 4.47 MeV are shown in Fig. 1 (filled circles). The results for the polarization in the elastic scattering and in the inelastic scattering from the 2^+ state are shown, for example, in Fig. 6.

The differential cross-section at 1 GeV for the elastic and inelastic scattering from ^{58}Ni has been measured at Saclay⁴⁾. Since no polarization data are available at this energy, we decided to investigate whether the very accurate data obtained for the elastic scattering of 800 MeV protons¹⁰⁾ could be used instead. A comparison was made between the results obtained at the two energies, 800 MeV and 1 GeV¹¹⁾ for ^{12}C and ^{208}Pb . Owing to the large amount of data at 800 MeV, only some representative errors are shown in Fig. 2. The angular scale refers to

1 GeV, and the 800 MeV data have been transformed so that the experimental points are plotted for the same momentum transfer. As seen, the polarization is somewhat smaller at 1 GeV. The difference in shape looks very similar to what one would expect from effects of different finite angular resolution. For these reasons we thought it possible to use the polarization data obtained at 800 MeV in the analysis of 1 GeV data after multiplying the amplitudes by 0.8.

In Fig. 1 our results for the differential cross-section are compared with those obtained at 1047 MeV (unfilled circles). In this figure the differential cross-sections divided by the squared wave number k^2 have been plotted versus the momentum transfer. It is seen that this normalization, which is predicted by Fraunhofer diffraction theory, is quite well borne out by the experimental results. It is also seen that, in general, the angular distributions show much stronger oscillations for 1047 MeV protons. In two earlier reports the same comparison was made for ^{208}Pb and ^{12}C ^{2,12}). In the case of ^{208}Pb the angular distributions were found to be very similar at the two energies, and the results for the elastic as well as for the inelastic scattering were very well reproduced by Fraunhofer diffraction theory. In the case of ^{12}C the angular distributions differed even more than noted here for ^{58}Ni .

The fact that the angular distributions obtained with 1 GeV protons are strongly oscillating in the scattering from light as well as heavy nuclei, while 185 MeV protons give diffractive angular distributions only for very heavy nuclei, indicates that 1 GeV protons are more strongly absorbed in the scattering from nuclei. The observation that the polarization has a much larger amplitude at 178 MeV than at 1 GeV implies that the differential cross-sections for spin-up and spin-down protons differ much more at 178 MeV. With the aid of the differential cross-section for an unpolarized beam σ_0 , and the polarization P calculated with the potential U_1 (see below), which reproduces the experimental results at 178 MeV rather well, the differential cross-sections for spin-up and spin-down protons were calculated from $\sigma_0(1 + P)/2$ and $\sigma_0(1 - P)/2$, respectively. The results are

shown in Fig. 3, together with the differential cross-section calculated without spin-orbit potentials, and one observes that the angular distributions are quite different. For spin-down protons the angular distribution is characteristic of that for a strongly absorbed particle with strong oscillations, while the angular distribution for spin-up protons has less structure. Thus the spin dependence might be described as giving one strong and one weak absorption channel. This is further illustrated in Fig. 4 where the absorption coefficients obtained with the potential U1 are found to be much larger for spin-down protons.

In the small-angle region where the angular distribution at 178 MeV has little structure for the inelastic scattering, it can be seen in Fig. 3 that, to a large extent, this is caused by the fact that the angular distributions for spin-up and spin-down protons oscillate out of phase. For large angles, however, it is seen that there are strong in-phase oscillations resulting in deep minima in the angular distribution.

In fact, such a behaviour has been observed in inelastic scattering of 185 MeV protons¹³⁾ from the 2^+ states in ^{28}Si and ^{32}S where, after a relatively unstructured distribution, suddenly a deep minimum occurs at about 70° .

For 1 GeV protons the absorption coefficients obtained with the potential S1 (see below) were found to be rather insensitive to spin effects. In Fig. 5 the absorption coefficients, calculated without spin dependence, are plotted as a function of the impact parameter. It is clearly seen that even in this case there is a weaker absorption at 178 MeV than at the higher energy.

4. ANALYSIS

The calculations were performed by using the code ECIS¹⁴⁾ in which coupled-channel calculations may be made with a deformed spin-orbit potential of the full Thomas form. In this code, calculations in the vibrational model are possible to first or second order. The first-order calculation provides results which are very similar to those obtained in DWBA, whereas the second-order calculations provide the results of a full coupled-channel calculation.

Since the code is non-relativistic, corrections have to be included because of the relativistic kinematics. According to ref. 15 these may be taken into account by calculating the wave number from the relativistic centre-of-mass momentum and by multiplying the potential strengths by γ_{rel} which is defined by

$$\gamma_{\text{rel}} = \frac{k^2}{E^2 - m_1^2} \times \frac{E}{\mu}, \quad (1)$$

where E is the total energy in the centre-of-mass system, m_1 is the mass of the incoming particle, and μ is the reduced mass.

Some authors⁵⁾ replace the reduced mass, $m_1 \times m_2 / (m_1 + m_2)$, by the reduced energy, $E_1 \times E_2 / (E_1 + E_2)$, instead of multiplying the potential depths by γ_{rel} . These two corrections are, however, very similar. The values of γ_{rel} at 178 and 1047 MeV are 1.182 and 2.049, while the ratio between the reduced energy and the reduced mass at the two energies are 1.179 and 2.022, respectively.

In earlier calculations, only the central potentials have been corrected with γ_{rel} , whereas in the present case also the depths of the spin-orbit potentials were corrected.

As in earlier analyses of the inelastic scattering, equal deformation lengths $\beta_L R$ were used for each potential instead of equal deformation parameters β_L .

Owing to the uncertainty in the elastic polarization and the lack of polarization data for the inelastic scattering at 1 GeV, the imaginary part of the spin-orbit potential was omitted in this case.

5. RESULTS AND DISCUSSION

The calculations were started by searching for an optical model potential which reproduces the elastic scattering without introducing coupled channels.

Also the reaction cross-section was included in the χ^2 -fitting procedure. The values adopted in the calculations were the same as for ^{56}Fe at 180 MeV, $662 \pm 19 \text{ mb}^{16)}$, and at 1 GeV a value of 717 mb was extrapolated from Ref. 17.

The resulting potentials are found in Table 1 and are denoted by U1 for the 178 MeV data and S1 for the 1047 MeV data. The resulting angular distributions for elastic scattering are shown in Figs. 6a and 7a as dot-dash curves. It can be seen that the optical model calculation gives an excellent fit to the 178 MeV data, whereas for the 1 GeV case the calculation overestimates the amplitude of the last two maxima.

The results from the first- and second-order calculations are shown as dashed and solid curves in Figs. 6 and 7. The first-order calculation is seen to give very similar results to those of the optical model calculations for the elastic scattering at 178 MeV, whereas for 1 GeV the agreement with the experimental results is considerably improved for the last two maxima. The second-order calculation is seen to suppress considerably the elastic cross-section at higher angles at both energies.

For the inelastic scattering to the 2^+ and 3^- levels the situation is somewhat different. In that case there is no significant difference between a first- and a second-order calculation, especially not for 178 MeV. The fits to the 178 MeV inelastic data are very good, and a reasonable fit was also obtained for the 2^+ level in the 1 GeV case. It is somewhat surprising to see the rather poor fit for the 3^- level at 1 GeV where the position of the second maximum is not reproduced. The deformation lengths used, $\beta_2 R = 0.805$ for the 2^+ level and $\beta_3 R = 0.674$ for the 3^- level, cannot be directly compared to other results since most analyses have been performed with equal deformation parameters. The fact that we reproduce the magnitudes at both energies with equal deformation lengths but quite different deformation parameters (see Table 1) supports the use of equal deformation lengths.

As seen in Table 2 the calculated reaction cross-sections agree very well with the experimental ones. They are quite similar in the optical model calculation and the first-order calculation, whereas in the second-order calculation the value is increased by about 2%, which can partly be explained by the fact that the imaginary potential has not been decreased as it should, when inelastic channels are treated explicitly.

Since the search for a potential in a coupled-channel calculation would consume too much computer time, we tried to find a more reliable potential in the following way. For each experimental angular setting the ratio between the differential cross-section in the optical model calculation and in the coupled-channel calculation was obtained. Then the experimental data for the differential cross-sections were multiplied by this ratio and an optical search was performed for this new set of data. The resulting potentials are denoted by U2 and S2 in Table 1, and it can be seen that the values of the parameters are modified only slightly. Also the volume integrals of the real central potential (JU_c/A) and of the complex central potential (JW_c/A) are changed by only a few per cent. Since the mean square radius is considered to be the best defined quantity in optical model calculations, it is interesting to note that this quantity decreases at both energies when the effects of coupled channels are taken into account and that the reason for this is the decrease in the diffuseness. The difference between the mean square radii of the real potential at the different energies is surprisingly large and, as seen in Table 1, this is due to the fact that the radius as well as the diffuseness have smaller values at 1 GeV.

The angular distributions obtained for the elastic scattering are shown in Figs. 8 and 9 by solid curves. As seen, the second-order calculations now give excellent fits to the 178 MeV data, and for the 3^- level the magnitude of the differential cross-section for large angles is considerably better reproduced. For the 1 GeV data the quality of the fits is almost the same as for potential S1.

The dash-dot lines and the dashed lines in Figs. 8 and 9 show the effect of excluding the deformation in the spin-orbit potential and of omitting the spin dependence altogether. As can be seen, at 178 MeV there is a drastic effect of excluding the deformed spin-orbit potential for the inelastic levels, not only for the polarization but also for the differential cross-section. In addition, it is seen that the exclusion of the deformed spin-orbit interaction also affects the differential cross-section in the elastic scattering. A comparison with Fig. 6a shows that the effects of coupled channels become much smaller in this case.

The spin-orbit distortion effects are seen to be important for the 2^+ as well as for the 3^- level at 178 MeV. We also observe that without any spin-dependence the angular distributions for the differential cross-section become strongly diffractive, as expected from the discussion in Section 3. The spin dependence for the elastic as well as for the inelastic scattering is found to be much weaker at 1 GeV. It must be remembered, however, that the strength of the spin-orbit potential is rather uncertain, since, lacking data for the polarization at 1 GeV, we have been forced to include the data obtained at 800 MeV. Furthermore the spin dependence may have been suppressed because of the omission of the imaginary spin-orbit potential, which is very important in analyses of 178 MeV data. Even if it is possible that with other parameters for the spin-orbit potential the rather poor fits to the inelastic scattering would have been improved, it seems more reasonable to assume that the small values of the mean square radius for the real central potential obtained at 1 GeV is the main reason why the minima and maxima in the angular distributions for the inelastic scattering appear at too large angles. Such an effect was also noticed by Fäldt and Osland⁷⁾ who had to increase the radius previously obtained in an analysis of elastic scattering by about 5% in order to get a reasonable agreement between experimental and calculated values for the positions of the maxima in the case of the 2^+ state at 1.45 MeV.

6. CONCLUDING REMARKS

The effect of including coupled channels in a calculation of intermediate energy proton scattering has been studied at two energies, 178 and 1047 MeV, where experimental data exist for elastic as well as for a few cases of inelastic scattering from ^{58}Ni . For both energies the inclusion of coupled channels changes the elastic angular distribution considerably in that the cross-section decreases, and the effect becomes relatively larger as the scattering angle increases. For inelastic scattering, however, the effects of including coupled channels are quite modest. Consequently, the validity of DWBA is retained provided that the optical potential used is obtained from a coupled-channel calculation which reproduces the elastic scattering.

The importance of spin-dependent effects at the lower energy has been quite clearly demonstrated in different ways. Perhaps the most striking illustration is given by Fig. 4, where the different behaviour of the angular distributions for spin-up and spin-down protons is shown to be due to the difference in absorption.

At the higher energy the spin-dependence is much weaker, but it can be noticed that for elastic scattering the main effect is seen on the diffraction maxima which are enhanced more and more as the scattering angle increases. This observation is in agreement with the results of Fäldt and Hulthage⁷⁾ in their analysis of elastic proton-nucleus scattering at 1 GeV.

The comparisons which were made between the absorption coefficients obtained without spin dependence at the two energies showed that there is a stronger absorption at 1 GeV. Since in addition the strong spin dependence at 178 MeV was found to decrease the absorption, it seems clear that the lower energy protons are better probes of the interior of nuclei.

Regarding the deformed spin-orbit term, its great importance at the lower energy is clearly seen in the present work, confirming earlier results^{1,2)}. For the 1 GeV analysis the effect of this form is quite negligible in the case of the differential cross-sections. This is true for both elastic and inelastic scattering from ^{58}Ni . On the other hand, large differences were seen in the polarization of protons scattered inelastically, pointing to the need for experimental data.

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Table 1

Best fit optical model parameters obtained for the $p + {}^{58}\text{Ni}$ elastic scattering data. The potentials U1 and S1 give the best fits for the elastic scattering in optical model calculations at 178 and 1047 MeV, respectively. The potentials U2 and S2 give the best fits in coupled-channel calculations. All potential depths are in MeV and all radial parameters in fm. The deformation parameters β_L are those for the real central potential.

Pot.	U	r_1	a_1	W	r_2	a_2	V_{so}	W_{so}	r_{so}	a_{so}	β_2	β_3
U1	10.96	1.338	0.591	16.57	1.112	0.711	2.49	-2.14	1.012	0.610	0.156	0.130
U2	10.87	1.339	0.548	16.56	1.094	0.728	2.38	-2.02	1.029	0.572	0.156	0.130
S1	-38.74	1.067	0.482	40.09	1.126	0.554	0.82		1.009	0.781	0.195	0.163
S2	-37.00	1.077	0.444	42.15	1.118	0.531	0.82		1.001	0.741	0.193	0.162

	$\beta_2 R$	$\beta_3 R$	JU_c/A	JW_c/A	$\langle r^2 \rangle^{\frac{1}{2}}_{\text{real}}$	$\langle r^2 \rangle^{\frac{1}{2}}_{\text{imag}}$
U1	0.805	0.674	124.0	121.1	4.57	4.26
U2	0.805	0.674	121.3	117.3	4.50	4.25
S1	0.805	0.674	223.6	277.9	3.67	3.95
S2	0.805	0.674	215.3	283.4	3.63	3.89

Table 2

Calculated reaction cross-sections in mb with the four potentials in Table 1. The experimental value at 178 MeV is from Ref. 16. The value at 1047 MeV has been extrapolated from the results of Ref. 17.

	O.M.	1 st order	2 nd order	Exp.
U1	663.9	664.3	674.6	662 ± 19
U2	651.9	652.4	662.7	
S1	727.1	726.4	740.7	717
S2	716.3	715.4	730.3	

Figure captions

- Fig. 1 : Experimental differential cross-sections obtained at 178 MeV (filled circles) and 1047 MeV (unfilled circles) divided by the squared wave number.
- Fig. 2 : Polarizations in the elastic scattering of protons from ^{12}C and ^{208}Pb , obtained at 796 MeV (filled circles) and 1047 MeV (unfilled circles) plotted versus the centre-of-mass scattering angle. The angular scale refers to 1047 MeV; the data at the lower energy have been adjusted to correspond to the momentum transfer of the higher-energy data.
- Fig. 3 : The differential cross-section for protons with spin-up (solid curves) and with spin-down (dashed curves) calculated with potential U1 in Table 1. The dash-dot curves have been calculated without spin dependence.
- Fig. 4 : Absorption coefficients for partial waves with $j = \ell - \frac{1}{2}$ (solid curve) and $j = \ell + \frac{1}{2}$ (dashed curve) obtained in an optical model calculation with potential U1 in Table 1. The dash-dot curve has been calculated without spin dependence.
- Fig. 5 : Absorption coefficients obtained at 178 MeV and 1047 MeV (no spin dependence) plotted versus the same impact parameter.
- Fig. 6 : Angular distributions for the differential cross-section and the polarization for 178 MeV protons in
- a) the elastic scattering,
 - b) the inelastic scattering from the 2^+ level at 1.45 MeV in ^{58}Ni ,
 - c) the inelastic scattering from the 3^- level at 4.47 MeV in ^{58}Ni .
- The dash-dot curves are obtained from optical-model calculations, the dashed curves from a first-order and the solid curves from a second-order ECIS calculation, using the potential U1 of Table 1.

Fig. 7 : Same as Fig. 6 for 1047 MeV protons and using the potential S1 of Table 1.

Fig. 8 : Angular distributions for the differential cross-section and the polarization for 178 MeV protons in

a) the elastic scattering,

b) the inelastic scattering from the 2^+ level at 1.45 MeV in ^{58}Ni ,

c) the inelastic scattering from the 3^- level at 4.47 MeV in ^{58}Ni .

The solid curves are obtained from second-order ECIS calculations with potential U2 in Table 1. The dash-dot curves illustrate the effect of excluding the deformed spin-orbit interaction, whereas for the dashed curves the spin dependence has been totally removed.

Fig. 9 : Same as Fig. 8 for 1047 MeV protons and using the potential S2 of Table 1.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6 (a)

Fig. 6 (b)

Fig. 6 (c)

Fig. 7 (a)

Fig. 7 (b)

Fig. 7 (c)

Fig. 8 (a)

Fig. 8 (b)

Fig. 8 (c)

Fig. 9 (a)

Fig. 9 (b)

Fig. 9 (c)