Dirac Phenomenological Analyses of Polarized Proton Inelastic Scattering from ^{34}S Nucleus

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Abstract: *Polarized Proton inelastic scatterings from ^{34}S nucleus are analyzed using the optical potential model and the first order rotational collective model in Dirac coupled channel formalism. It is shown that the theoretical results of the Dirac calculations reproduce the experimental data very well, showing better agreements with the experimental data than those obtained in the nonrelativistic calculations, especially for the spin analyzing power data. The Dirac equations are reduced to the second-order differential equations in order to obtain the Schroedinger equivalent effective central and spin-orbit optical potentials, and the surface-peaked phenomena are observed at the imaginary effective central potentials for the scatterings from ^{34}S. The obtained deformation parameters of Dirac phenomenological calculations are found to agree pretty well with those of the nonrelativistic calculations using the same Woods-Saxon potential shape.*

Keywords: *Dirac analyses, Coupled channel calculation, Optical potential model, Proton inelastic scattering, Collective model*

1. INTRODUCTION

Relativistic Dirac analyses are known to be remarkably successful in treating nuclear reactions. Considerable progress has been made by using approximate relativistic descriptions [1-3], even though complete relativistic descriptions of nuclear matter and finite nuclei using a relativistic quantum field theory are not available. Because relativistic Dirac analysis of intermediate energy proton-nucleus elastic scatterings have proven to be very successful for the spherically symmetric nuclei and a few deformed nuclei [3-6], the relativistic Dirac approaches have been expanded to the inelastic scatterings and have shown significant improvements compared to the conventional nonrelativistic approaches [7-9].

In this work we performed a relativistic Dirac phenomenological coupled channel calculations for the intermediate energy, 650 MeV, polarized proton inelastic scatterings from an axially-symmetric nucleus ^{34}S and compared the results with the experimental data and those of nonrelativistic calculations. The optical potential model [3] is used and the Woods-Saxon shape is used for the geometry of the optical potentials. The scalar-vector (S-V) model for the optical potentials is employed, where only Lorentz-covariant scalar and time-like vector potentials are included in the calculation. The first order rotational collective model is employed in order to accommodate the collective motion of the low-lying excited states of the ground state rotational band in the nucleus. The complicated Dirac coupled channel equations are solved phenomenologically to calculate the differential cross-sections and analyzing powers by using a computer program called ECIS [10], which employs the sequential iteration method. The Dirac equations are reduced to the Schroedinger-like second-order differential equations by considering the upper component of the Dirac wave function in order to obtain the effective central and spin-orbit optical potentials. The obtained effective potentials for the ^{34}S nucleus are analyzed and compared with those of nonrelativistic calculations. The calculated results for the deformation parameters for the low-lying excited states of the ground state rotational band in the nucleus are compared with those obtained in the nonrelativistic calculations.

2. THEORY AND RESULTS

Dirac coupled channel analyses are performed phenomenologically for the 650 MeV proton inelastic scatterings from ^{34}S nucleus, using the optical potential model and the first order collective rotational model. Because the ^{34}S nucleus is a spin-0 nucleus, only scalar, time-like vector and tensor optical potentials survive [1, 11], as in spherically symmetric nuclei [12]; hence, the relevant Dirac equation for the proton elastic scattering from the nucleus is given as

$$[\alpha \cdot p + \beta(m + U_S) - (E - U_V^0 - V_C) + i\alpha \cdot \hat{r}\beta U_T]\Psi(r) = 0.$$

Here, U_S is a scalar potential, $U_V{}^0$ is a time-like vector potential, U_T is a tensor potential, and V_C is the Coulomb potential. The scalar and the time-like vector potentials are used as direct potentials in the calculation. Tensor potentials are always present due to the interaction of the anomalous magnetic moment of the projectile with the charge distribution of the target. However, tensor potentials are neglected in this calculation because they have been found to be always very small compared to scalar or vector potentials [8]. The scalar and time-like vector optical potentials are complex and it is assumed that the potentials have Fermi distribution as they are assumed to follow the distribution of nuclear density. The Woods-Saxon shape is used for the geometry of the Dirac optical potentials. In the first order rotational model of ECIS, the deformation of the radius of the optical potential is given using the Legendre polynomial expansion method; with β_λ being a deformation parameter, R_0 the radius at equilibrium, and λ the multipolarity. The shape of the deformed transition potential is assumed to follow the shape of the deformed nuclear densities. The transition potentials can be obtained by assuming that they are proportional to the first-order derivatives of the diagonal potentials. It is true that pseudo-scalar and axial-vector potentials may also be present in the equation when we consider inelastic scattering, depending on the model assumed. In the collective model approach used in this work, we assume that we can obtain appropriate transition potentials by deforming the direct potentials that describe the elastic channel fairly well [12]. In order to compare the calculated results with those of the nonrelativistic calculations, we reduce the Dirac equation to a Schroedinger-like second-order differential equation by considering the upper component of the Dirac wave function to obtain the effective central and spin-orbit optical potentials [4]. The experimental data for the differential cross sections and analyzing powers are obtained from [13] for the 650 MeV polarized proton inelastic scatterings from the deformed nucleus, ^{34}S.

As a first step, 12 parameters of the diagonal scalar and vector potentials in Woods-Saxon shapes are determined to reproduce the experimental elastic scattering data by using a sequential iteration method. The Dirac equations are phenomenologically solved to obtain the best fitting optical potential parameters to the experimental data by using the minimum chi-square (χ^2) method. The calculated optical potential parameters of the Woods-Saxon shape for the 650 MeV proton elastic scatterings from the ^{34}S nucleus are shown in **Table 1.** The real parts of the scalar potentials and the imaginary parts of the vector potentials turn out to be large and negative, and that the imaginary parts of the scalar potentials and the real parts of the vector potentials turn out to be large and positive, showing the same pattern as in the spherically symmetric nuclei [4, 5].

Table 1: *The optical potential parameters of Woods-Saxon shape obtained in the relativistic Dirac phenomenological calculations for the 650 MeV polarized proton elastic scatterings from ^{34}S nucleus.*

potential	strength (MeV)	radius (fm)	diffusiveness (fm)
scalar real	-170.1	3.518	0.759
scalar imaginary	204.6	2.426	0.895
vector real	105.5	3.449	0.786
vector imaginary	-126.9	3.019	0.742

As a next step, all of the optical potential-parameters and deformation parameters are searched by including the lowest-lying excited state of the ground state rotational band, the 2^+ state (2.127MeV), in addition to the ground state in the calculation, using the 12 parameters for the direct optical potentials obtained in the elastic scattering calculations. Usually, we searched for the two deformation parameters, β_S and β_V, per each excited state by assuming the real and imaginary deformation parameters are the same for the excited state in our previous publications [8, 9]. However, we set β_S and β_V are the same in this work and searched for only one deformation parameter, β_2, in order to have the same number of parameters with those in the nonrelativistic calculations. The optical potential parameters obtained by fitting the elastic scattering data in the elastic scattering calculation are varied because the channel coupling of the excited states to the ground state should be included in the inelastic scattering calculation.

The results of the coupled channel calculations for the ground and the 2^+ excited state in the ground state rotational band are shown in the **Figures 1 and 2** and it is shown that relativistic Dirac coupled channel calculation using an optical potential model could describe the low-lying excited states of the ground state rotational band for 650 MeV polarized proton inelastic scatterings from the ^{34}S nucleus very well. It is shown that the theoretical results of the Dirac calculations reproduce the experimental data better than those of nonrelativistic calculations, especially for the spin analyzing power (A_y) data. We use the same computer program ECIS [10] for the nonrelativistic calculations.

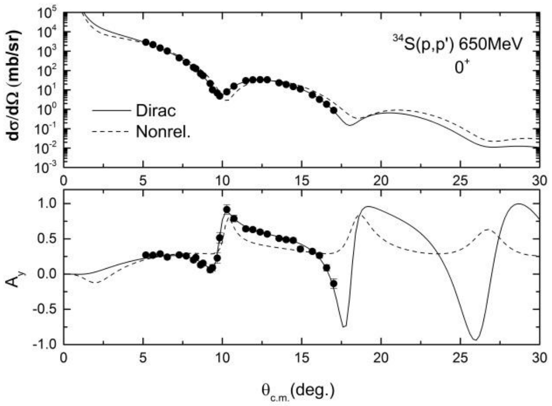

Figure 1: *Comparison of the results of Dirac coupled channel calculations with the ground state experimental data of 650 MeV polarized proton inelastic scatterings from ^{34}S nucleus and those of nonrelativistic calculations.*

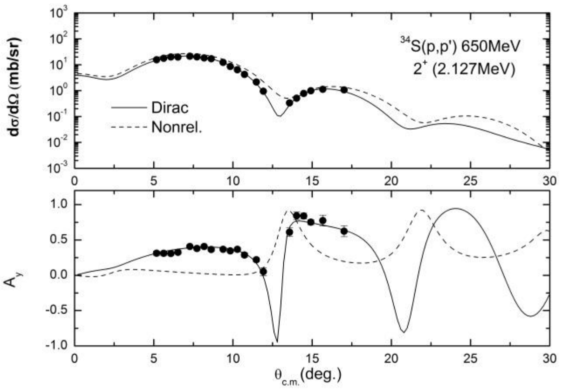

Figure 2: *Comparison of the results of Dirac coupled channel calculations with the 2+ state experimental data of 650 MeV polarized proton inelastic scatterings from ^{34}S nucleus and those of non relativistic calculations.*

In **Table 2 and 3**, we show the optical potential parameters of Woods-Saxon shape and the deformation parameters for the 2^+ excited state of the ^{34}S nucleus obtained in the relativistic Dirac phenomenological calculations and those obtained in the nonrelativistic calculations for the 650 MeV proton inelastic scatterings from ^{34}S nucleus. It is observed that the deformation parameters obtained in the Dirac phenomenological coupled channel calculation for the 2^+ state excitations of the ^{34}S nucleus show pretty good agreement with those obtained in the nonrelativistic calculation using the same Woods-Saxon potential shape for the geometries of the optical potentials, even though the theoretical bases are quite different.

Table 2: *The optical potential parameters of Woods-Saxon shape and the deformation parameter obtained in the relativistic Dirac phenomenological calculations for the 650 MeV proton inelastic scatterings from ^{34}S nucleus*

potential	strength (MeV)	radius (fm)	diffusiveness (fm)	deformation parameter(β_2)
scalar real	-133.9	3.776	0.611	0.243
scalar imaginary	59.46	2.010	0.608	
vector real	95.56	3.595	0.695	
vector imaginary	-56.25	3.211	0.567	

Table 3: *The optical potential parameters of Woods-Saxon shape and the deformation parameter obtained in the nonrelativistic calculations for the 650 MeV proton inelastic scatterings from ^{34}S nucleus.*

potential	strength (MeV)	radius (fm)	diffusiveness (fm)	deformation parameter(β_2)
central real	3.988	4.357	0.401	0.284
central imaginary	37.02	3.357	0.497	
spin-orbit real	0.499	2.867	0.624	
spin-orbit imaginary	-1.73	3.360	0.635	

In **Figure 3**, we compared the effective central and spin-orbit potentials of the ^{34}S nucleus with several other deformed nuclei. Surface-peaked phenomena are clearly observed for the imaginary parts of the effective central potentials (CI) at ^{34}S, while the surface-peaked phenomena are not clearly observed for the real parts of the central potentials (CR). The surface-peaked phenomena are observed at the real parts of the effective central potentials for the scatterings from the deformed nucleus ^{28}Si [14]. The surface-peaked phenomena are clearly shown at the effective spin-orbit potentials, and the effective spin-orbit potential strengths turned out to be about the same order with those obtained from nonrelativistic calculations, as shown in **Table 3**, even though the signs are the opposites. It is noted that the surface-peaked phenomena never appear at the conventional nonrelativistic approaches because they use the Woods-Saxon shapes for both the central and spin-orbit potentials. It should be noted that one of the merits of the relativistic approach based on the Dirac equation instead of using the nonrelativistic approach based on the Schroedinger equation is that the spin-orbit potential appears naturally in the Dirac approach when the Dirac equation is reduced to a Schroedinger-like second-order differential equation, while the spin-orbit potential should be inserted by hand in the conventional nonrelativistic Schroedinger approach.

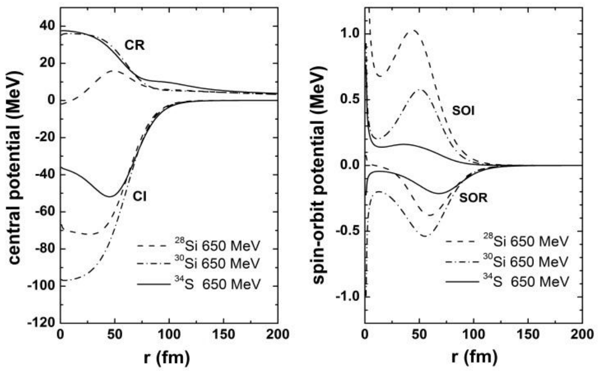

Figure 3: *Comparison of the effective central and spin-orbit potentials of ^{34}S with those of several other deformed nuclei. CR and CI represent central real and imaginary potentials, and SOR and SOI represent spin-orbit real and imaginary optical potentials, respectively.*

3. CONCLUSIONS

Relativistic Dirac coupled channel analyses using an optical potential model are performed for the 650MeV polarized proton inelastic scatterings from ^{34}S nucleus. The optical potential parameters for the axially-symmetric nucleus are obtained phenomenologically using scalar-vector potential model. It is shown that the theoretical results of the relativistic Dirac calculations reproduce the experimental data very well, showing better agreements with the data than those obtained in the nonrelativistic calculations, especially for the spin analyzing power (A_y) data. The effective central and spin-orbit potentials are obtained by reducing Dirac equations to the Schroedinger-like second-order differential equations, and the surface-peaked phenomena are observed at the imaginary effective central potentials for the scattering from ^{34}S. The first-order rotational collective models are used to describe the low-lying excited states of the ground state rotational bands in the nucleus, and the obtained deformation parameters are analyzed. The deformation parameters for the 2^+ state excitation of the ground state rotational band are also compared with those of nonrelativistic calculations, and the deformation parameters obtained in the Dirac phenomenological calculations are found to agree pretty well with those of the nonrelativistic calculations using the same Woods-Saxon potential shape.

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