Separation of direct and compound nuclear contributions in inelastic α scattering

H. Ortner, W. Eyrich, A. Hofmann, and U. Scheib
Physikalisches Institut der Universität Erlangen-Nürnberg, Erlangen, Federal Republic of Germany
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A method for separating direct and compound nuclear reaction contributions to inelastic α scattering on spin 0 targets is proposed. It is based on the characteristic behavior of the parameters of the α-γ angular correlation function in a distorted-wave Born approximation and a Hauser-Feshbach model treatment. The method is applied to the reaction $^{28}Si(\alpha,\alpha'\gamma)$.

[NUCLEAR REACTIONS ^{28}Si $(\alpha,\alpha'\gamma)$, $E_{\alpha}=10$, 16.5 MeV. Measured differential cross sections and angular correlations. Determined direct and compound nuclear contributions.]

I. INTRODUCTION

In nuclear reactions at intermediate incident energies direct (DI) and compound nuclear (CN) reaction mechanisms are usually present simultaneously. A simple method to determine the relative amount of the direct reaction contribution is provided by the Ericson model,[1,2] in which, however, the number of effectively contributing channels has to be introduced as a model-dependent parameter. A method to separate the two contributions, in which this model dependence is avoided, is to analyze energy averaged cross section data together with analyzing power data.[3] For α scattering this method is of course not applicable. We propose another largely model independent method[4,14–16] to separate DI and CN contributions which is suitable especially for inelastic α scattering. As in the case of scattering of particles with spin, we need information about polarization or alignment of any of the reaction particles. An easy way to get alignment and polarization of the residual nucleus is the measurement of the

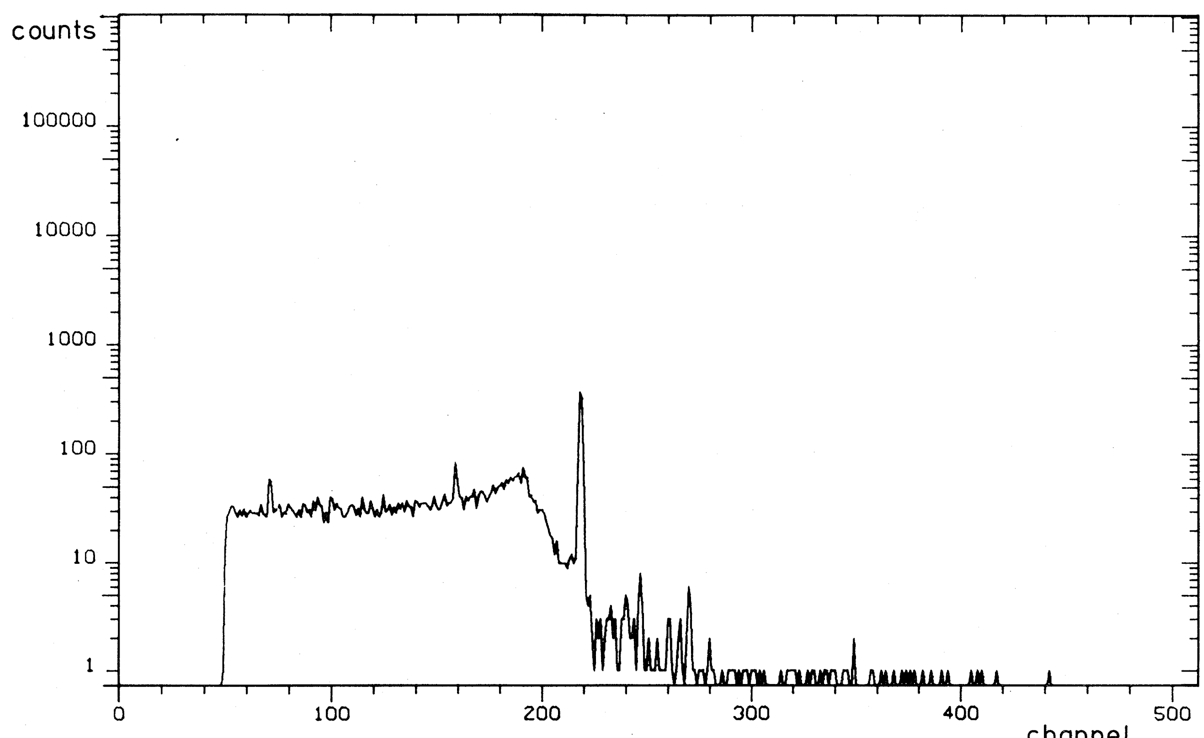

FIG. 1. γ spectrum of the reaction $^{28}Si(\alpha,\alpha'\gamma)$ taken in coincidence to the α particles scattered from the first excited state of ^{28}Si.

particle-γ angular correlation between the scattered particle and the deexcitation γ ray. As CN and DI reactions lead to completely different angular correlation data, one can disentangle the strength of their contributions by comparing the data with theoretical predictions.

As an example we measured the differential cross section and the γ-angular correlation of the inelastic α scattering leading to the first 2^+ state in ^{28}Si. The analysis of the data was performed in the framework of distorted wave Born approximation (DWBA) and Hauser-Feshbach (HF) calculations.

II. EXPERIMENT

The experiment was performed at the Erlangen tandem accelerator with incident energies of 10 and 16.5 MeV. The targets, self-supporting disks of natural silicon, had thicknesses of 8 and 21 μm, respectively. These thicknesses lead to an averaging of the beam energy in the target of about 1 to 1.5 MeV for both beam energies.

A special scattering chamber was used to measure particle-γ angular correlations.[5] Thin walls of aluminum of constant thickness provided good penetration of the γ rays. Eight silicon surface barrier detectors were used for the detection of the scattered α particles. The thickness of the detectors was chosen to stop the α particles. Lighter particles from competing reactions like $^{28}\mathrm{Si}(\alpha,p)^{31}\mathrm{P}$ suffered only a small energy loss in the detectors; hence we did not need particle identification.

For the detection of the γ rays we used two Ge-Li detectors placed in the reaction plane. The efficiency of these detectors was only 15% of a 3×3 inch NaI detector, but the better resolution and the better gain stability justify this choice. In Fig. 1 a typical spectrum of γ quanta coincident to the inelastically scattered α particles is shown. It is dominated by the total absorption peak of the interesting 1.79 MeV ($2^+\to0^+$) transition in ^{28}Si. For the analysis of the data we used only this total absorption peak. The absolute efficiency of the Ge-Li detectors in this peak was measured with the aid of standard γ sources. A standard fast slow technique was used for the electronics. The data were stored in a PDP 11/40 computer on magtape event by event. This list-mode technique has the advantage that electronic gain shifts during the experimental runs of about eight hours can be adjusted afterwards by setting appropriate windows on the data. The differential cross sections and the angular correlation data were measured with the same equipment in order to avoid problems with the norm of absolute data.

III. THEORY

The usual way to describe energy averaged cross-section data in the presence of DI and CN contributions is to add both parts incoherently. This procedure is justified by the fact that interference terms in the density matrix cancel if the energy interval is large enough to average over a sufficient number of statistical fluctuations in the excitation function. We use the same argument not only for the diagonal elements of the density matrix but also for the off-diagonal elements. Decomposing the reaction amplitudes X_M for the inelastic scattering of a spin 0 projectile on a spin 0 target, where M denotes the magnetic substates of the excited target state, into $X_M = X_M^{\mathrm{DI}} + X_M^{\mathrm{fl}}$ with $\langle X_M^{\mathrm{fl}} \rangle = 0$, one obtains for the density matrix $\rho_{MM'} = X_M X_{M'}^*$:

$$\langle \rho_{MM'} \rangle = X_M^{\mathrm{DI}} X_{M'}^{\mathrm{DI}*} + \langle X_M^{\mathrm{fl}} X_{M'}^{\mathrm{fl}*} \rangle = \rho_{MM'}^{\mathrm{DI}} + \rho_{MM'}^{\mathrm{CN}} . \tag{1}$$

The density matrix elements $\rho_{MM'}^{\mathrm{DI}}$ and $\rho_{MM'}^{\mathrm{CN}}$ can be calculated in the framework of DWBA and HF. We have done this using the codes DWUCK (Ref. 6) and DWKS (Ref. 7) for the DWBA calculations. The HF calculations were performed with the code SABINE.[8] In this code the sum over the transmission coefficients $\sum T_{ij}(E)$ in the HF formula is replaced by the well-known expression[9]

$$\sum T_{ij}(E) = N(2J+1)\exp[-J(J+1)/2\sigma^2] ,$$

where the factor N is 2π times the quotient of the mean level width and the mean level spacing of the compound-nucleus states for the lowest J value to be formed, and σ is the "spin cutoff parameter."

The inplane angular correlation function for the inelastic scattering of α particles on 0^+ targets to the first excited 2^+ state and subsequent γ decay into the ground state has the following general form (the Z axis is perpendicular to the reaction plane[10]):

$$W\left[\vartheta_\gamma = \frac{\pi}{2}, \varphi_\gamma\right] = A + C \sin^2 2(\varphi_\varphi - \varphi_2) \tag{2}$$

with

$$A = \frac{1}{\mathrm{tr}\,\rho_{MM'}} \tfrac{5}{4}(\rho_{22} + \rho_{-2-2} - 2\,|\rho_{2-2}|) ,$$

$$C = \frac{5}{\mathrm{tr}\,\rho_{MM'}} |\rho_{2-2}| ,$$

and

$$4\varphi_2 = \arctan \frac{\mathrm{Im}\,\rho_{-22}}{\mathrm{Re}\,\rho_{-22}} .$$

Inserting now for the density matrix elements in Eq. (2) the matrix elements summed according to Eq. (1) we can calculate theoretical angular correlation functions in the presence of DI and CN contributions.

IV. DISCUSSION

First we will discuss the differential cross sections. Here we used the usual method to extract the optical model parameters from the elastic scattering data just by adding DI and CN contributions.[11] The lower part of Fig. 2 shows the result of a fit to the data with an incident energy of 10 MeV. The 16.5 MeV data behave quite similarly. With the optical model parameters so extracted, a DWBA and HF calculation was performed. In the upper part of Fig. 2 the comparison of these calculations with the inelastic cross section for the 10 MeV data is shown. As can be seen, even the HF calculation alone (dashed curve) would be sufficient to describe the experiment. On the other hand, inserting realistic β_2 values in the DWBA calculation and adding the HF calculation with a suitably reduced factor N, one can get equally good agreement. But there is a wide range for β_2 and N which gives good fits to the inelastic scattering cross section. In all calculations we used the value $\sigma = 2.6$ for the spin cutoff parameter, which turned out to enter not too sensitively.

In Fig. 3 calculations for the correlation parameters A, C, and φ_2 are shown and compared with the experimental data. In the calculations remarkable differences for both types of the contributions appear. Whereas the parameter A is nearly 0 for the direct part, it has a value near 0.7 for the CN part. For the parameter C the contrary holds. It nearly

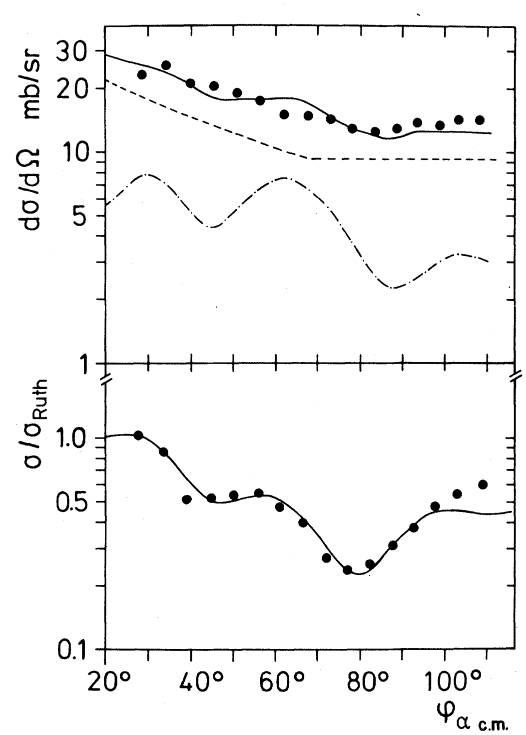

FIG. 2. Lower part: differential cross section of the elastic α scattering on ^{28}Si at $E_\alpha = 10$ MeV. The curve represents an optical model fit. Upper part: experimental and calculated differential cross section for the inelastic α scattering on ^{28}Si at $E_\alpha = 10$ MeV. Dashed-dotted curve: DWBA calculation; dashed curve: Hauser-Feshbach calculation; full curve: sum of both contributions.

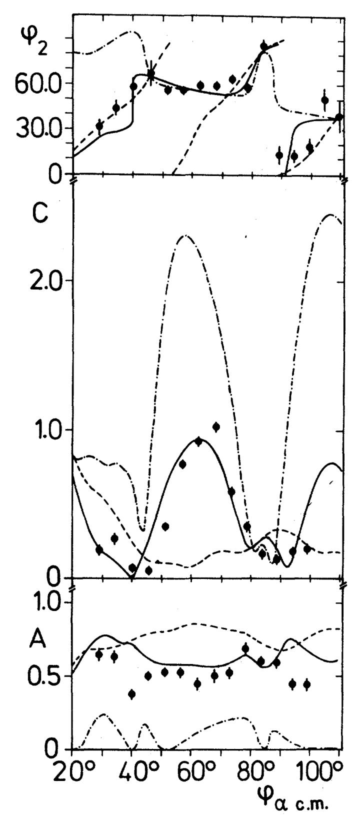

FIG. 3. Experimental and calculated angular correlation parameters φ_2 (upper part), C (middle part), and A (lower part) for the reaction $^{28}Si(\alpha,\alpha'\gamma)$ at $E_\alpha = 10$ MeV. The meaning of the curves is the same as in Fig. 2.

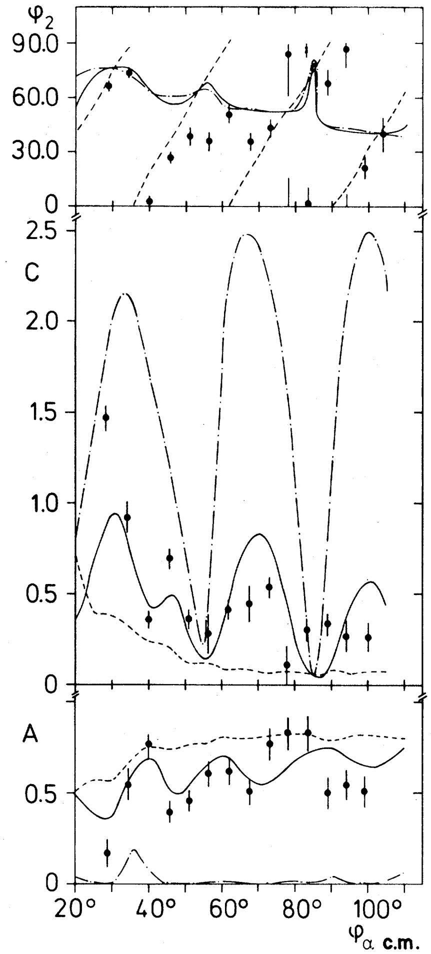

FIG. 4. Same as Fig. 3 for $E_\alpha = 16.5$ MeV.

disappears for CN reactions, achieving high values with pronounced structures for DI reaction processes. The phase φ_2 fluctuates strongly with the scattering angle for the CN part, whereas for the DI part it closely follows the adiabatic limit. We investigated the different behavior of these parameters for the two contributions in various calculations and found that it is independent of the potential parameters and of the spin cutoff parameter.

In a previous work[12] we studied $(\alpha,\alpha'\gamma)$ angular correlations at an incident energy of 104 MeV. At this energy, where only DI reaction processes occur, we found experimentally that the parameter A has a value close to zero and the phase φ_2 follows the adiabatic limit. Therefore we conclude that the typical behavior of the angular correlation parameters

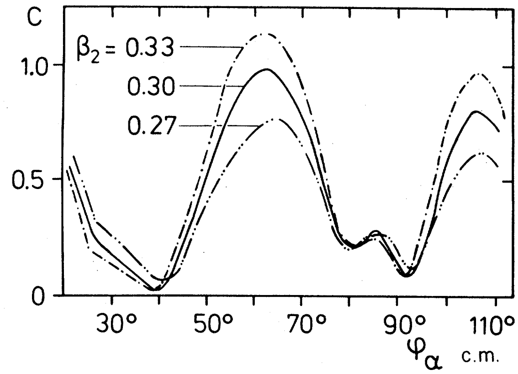

FIG. 5. Influence of a 10% variation of the deformation parameter β_2 on the DWBA + Hauser-Feshbach calculation of the correlation parameter C. The corresponding cross section curves are undistinguishable.

demonstrated in Fig. 3 is valid in general.

The full curves in Fig. 3 result from a calculation where the DWBA and the HF density matrices are added according to Eq. (1) and inserted in Eq. (2). Requiring an optimum description of all data a β_2 value of 0.3 is obtained in good agreement with the results of high energy scattering experiments.[13] The factor N is taken so as to give good agreement with the inelastic cross section. The value $N = 4.7$ thus obtained is in accordance with estimations on the basis of the Fermi gas model.

A comparison of the 16.5 MeV data with the calculations is shown in Fig. 4. The agreement between data and calculations is somewhat worse, but the same trends as for the lower energy data can still be seen. The less favorable agreement might come from a resonance in the energy average region which can be supposed from the pattern of the excitation function. Therefore the average interval might have been chosen too small.

In order to test the sensitivity of our method to changes in the norm of the two contributions, in Fig. 5 we again show the correlation parameter C. In the three calculations we changed only the value of β_2 and readjusted the factor N of the CN part so as to fit the experimental values of the cross section. Already a 10% modification of β_2 gives clear effects in the added calculation, especially in the correlation parameter C, allowing a fairly precise determination of β_2 and consequently of N. We therefore believe that the measurement of particle-γ angular correlations is a suitable method to separate DI and CN contributions.

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Ref. 14. As this work concentrates on spin-orbit effects its results refer only to particles with spin. In this case the spin-flip probability has also been shown to be very sensitive to CN contributions (Ref. 15). We exploited this sensitivity in previous studies (see, e.g., Ref. 16).

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[11]Of course we observed the well-known ambiguities of the optical model parameters. We have chosen one reasonable set and consequently used this in all calculations described following the citation of this reference in text. It turned out, however, that all statements made in this work are independent of the special set of the optical potential parameters and also widely independent of the spin cutoff parameter used in the Hauser-Feshbach calculations.

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