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Incident-Energy Dependence of the Analyzing Power in the ^{58}Ni$(p,^{3}$He$)^{56}$Co Rreaction between 80 and 120 MeV

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Abstract. We investigate the possible incident energy dependence of the analyzing power in the reaction ^{58}Ni($\vec{p}$,^{3}He)^{56}Co. Previous inclusive (p,^{3}He) reaction studies, described in terms of a statistical multistep formalism, have indicated a slight decrease in analyzing power at the very low excitation energies. This seems to contradict the understanding that the low excitation energy region is dominated by a direct reaction mechanism with large analyzing power values. To better understand this discrepancy, the excitation to low lying states in the residual nucleus has recently been investigated by means of a high resolution spectrometer at incident energies between 80 and 120 MeV. We present the experimental differential cross section and analyzing power angular distribution data for the three incident energies, compared with macroscopic Distorted-Wave Born Approximation (DWBA) calculations for a few discrete states of ^{56}Co, assuming a single-step deuteron pickup mechanism. The success of the DWBA calculations in tracing the data over the range of incident energies, provides confidence in the use of this simple direct pickup description in the multistep formalism. It seems also plausible that the analyzing powers of the prominent L-transfers can combine in such a way as to produce the observed quenching in the analyzing powers.

1 Introduction

Various pre-equilibrium reaction studies, involving the emission of light ^{3}He-clusters from the interaction of medium energy polarized protons, have been performed in the last decade or so on target nuclei such as ^{59}Co, ^{93}Nb and ^{197}Au [1–5]. These inclusive reactions were are successfully described in terms of the statistical multistep formalism of Feschbach, Kerman and Koonin (FKK). The reaction mechanism for the (p,^{3}He) reaction involves a final two-nucleon pickup process, following a few intra-nuclear proton-nucleon collisions. Here, a one-step process means a direct two-nucleon pickup. A two-step process means that the incident proton first collides with a nucleon in the target and then picks up a proton-neutron pair to exit as a ^{3}He-particle. Similarly for the three- and higher order steps. The final-step pickup processes is treated by means of the distorted-wave Born approximation (DWBA).

These inclusive (p,^{3}He) reaction studies have indicated a strong sensitivity of the analyzing power to the contributions of different order steps in the multistep reaction mechanism. Primarily, large analyzing power values, indicative of single-step direct reactions, were observed at the small scattering angles and low excitation energies, while higher order steps become dominate at increasing incident energies.

Also consistent with the multistep theory is the observed decrease in the analyzing power as the incident energy is increased. However, a slight quenching of the analyzing power was also observed at the lowest excitation energies, contrary to the understanding that low excitation implies a direct reaction mechanism with large analyzing powers. Possible reasons for this phenomenon may include the effect of the competition of the incident energy dependence of the direct reaction with higher order steps of the multistep mechanism, or the effect of a fortuitous combination of different discrete states. To shed more light on this discrepancy, as well as the role of the simple zero-range DWBA for the one-step direct pickup process, the ^{58}Ni($\vec{p}$,^{3}He)^{56}Co reaction to a few low lying states of ^{56}Co has been investigated with a high resolution magnetic spectrometer at incident energies of 80, 100 and 120 MeV.

2 Experimental

Measurements were performed at the cyclotron facility of iThemba LABS (Laboratory for Accelerator Based Sciences) near Faure, South Africa, using the K600 magnetic spectrometer. Differential cross section and analyzing power angular distributions were measured for several discrete states in the (p,^{3}He) reaction on a solid ^{58}Ni target at beam energies of 80, 100 and 120 MeV, and scattering angles between 25° and 60° in 5° steps.

An inline polarimeter, consisting of two similar NaI(Tl) detectors at equal angles on either side of the beam direction, was used to measure the beam polarization between data runs throughout the experiment. The polarization in the up(down) direction with respect to the scattering plane, the $\hat{n}$-direction in Figure 1, is determined form the known analyzing power for the ^{12}C$(p,p)^{12}$C$_{g.s.}$ reaction at a fixed detector angle, $e.g. A_y$ = 0.74 for θ = 40°, using the expression

$$p^{\uparrow(\downarrow)} = \left(\frac{1}{A_y}\right) \frac{L^{\uparrow(\downarrow)} - R^{\downarrow(\uparrow)}}{L^{\uparrow(\downarrow)} + R^{\downarrow(\uparrow)}}\,, \tag{1}$$

where $L^{\uparrow(\downarrow)}$ and $R^{\uparrow(\downarrow)}$ are the number of counts in the left and right detector when the beam polarization is up(down). The average polarization achieved during the experiment was generally between 60% and 80% with a difference between up and down polarisation of around 10% to 30%.

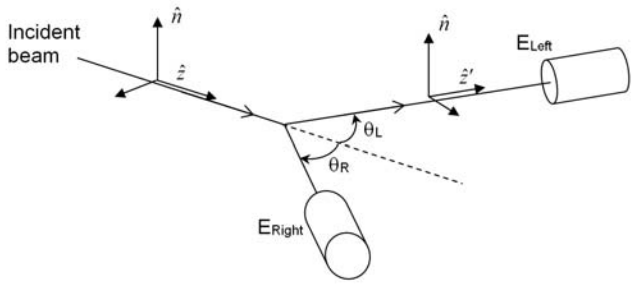

Figure 1. The P-line polarimeter setup. The incident beam is in the positive $\hat{z}$-direction, and "up" and "down" polarization refers to the positive and negative $\hat{n}$-direction.

The ^{3}He-particles were clearly identified using standard time-of-flight (TOF) techniques. The energy calibration of the detector focal-plane was done by means of the known Q-values for the ^{12}C(p,^{3}He), ^{16}O(p,^{3}He) and ^{27}Al(p,^{3}He) reactions to ground and excited states. The resulting excitation energy resolution was about 100 keV, limited mostly by the thickness of the target. The excitation energy spectrum for the 80 MeV beam, for example, is shown in Figure 2. The most prominent states identified are those having large angular momentum transfers, as indicated.

The measured differential cross section (in mb sr^{-1}) for a specific lab angle θ is calculated from

$$\frac{d\sigma(\theta)}{d\Omega} = \left(\frac{10^{27}}{n}\right) \frac{N_c}{N_0 \Delta\Omega} \,, \tag{2}$$

where n is the target area density (in cm^{-2}), N_c is the net counts in an energy peak, N_0 is the total number of incident protons, and $\Delta\Omega$ is the solid angle of the spectrometer defined by the collimator. The absolute (unpolarized) differential cross section is then given by

$$\left(\frac{d\sigma(\theta)}{d\Omega}\right)_{unpol} = \frac{p^{\downarrow}\sigma^{\uparrow} + p^{\uparrow}\sigma^{\downarrow}}{p^{\downarrow} + p^{\uparrow}} \,, \tag{3}$$

The analyzing power is determined from the expression

$$A_y = \frac{N^{\uparrow} - N^{\downarrow}}{p^{\downarrow}N^{\uparrow} + p^{\uparrow}N^{\downarrow}} \,, \tag{4}$$

where $N^{\uparrow(\downarrow)}$ represent the number of counts when the beam polarization is up(down).

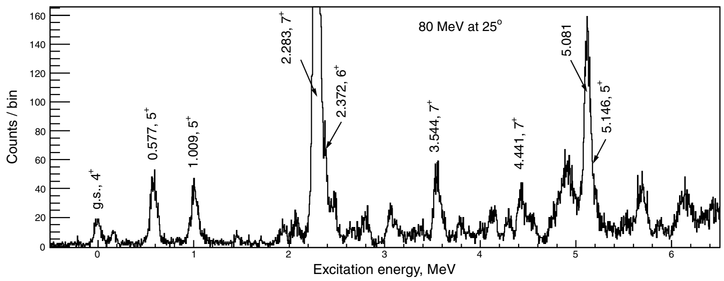

Figure 2. Excitation energy spectrum of the ^{58}Ni(p,^{3}He)^{56}Co reaction at 80 MeV for θ_{lab} = 25°. A few prominent states are indicated with their known J^π assignments.

3 Theoretical

We assume that the (p,^{3}He) reaction is a single-step direct two-nucleon pickup process, described by the distorted-wave Born approximation (DWBA). The computer code DWUCK4 [6], which calculates the reduced cross section in a zero-range approximation for the interaction between the projectile and the two-nucleon cluster, was used to calculate the differential cross section and analyzing powers.

The macroscopic cross section for the two-nucleon pickup is given by

$$\left(\frac{d\sigma(\theta)}{d\Omega}\right)_{exp} = \frac{2S_{^3He}+1}{2S_p+1}\mathbf{C} \times \sum_{LSJ} b_{ST}^2 D_{ST}^2 \left\langle T_B N_B; TN | T_A N_A \right\rangle^2 \frac{2S+1}{2J+1}\left(\frac{d\sigma(\theta)}{d\Omega}\right)^{DW}, \quad (5)$$

where **C** is an overall normalization factor, b_{ST}^2 = 0.5 is the overlap function, D_{ST}^2 are the interaction strengths between the transferred proton and neutron, and are equal to 0.30 and 0.72 for S = 0 and S = 1 respectively, and the Clebsch-Gordan coefficients for the isospin transfers are 1.0 and 2.0 for the cases with T = 1 and T = 0 respectively. The last DW-factor is the reduced cross section from the DWUCK4 code for a transfer with LSJ quantum numbers. The spin and isospin of the transferred proton-neutron pair are related by $S + T = 1$ (Ref. [7]).

The distorted waves for the proton and ^{3}He-particles in the entrance and exit channels respectively, are determined from Woods-Saxon type potentials with potential parameters taken from energy dependent global optical potential studies. In the macroscopic description, the transferred proton-neutron pair, or "deuteron", is bound in a cluster shell-model state with quantum numbers N, L, S and J. The bound state wave function is determined by the usual separation energy procedure with mean radius r_0 and diffuseness parameter a equal to 1.15 and 0.76 fm respectively, chosen so that the macroscopic approach gives form factors similar in shape to the microscopic approach [8].

The analyzing power A_y is derived from the definition of the polarization $p^{\uparrow(\downarrow)}$ of a beam of spin-1/2 particles, polarized in the "up"("down") direction with respect to the scattering plane (see Figure 1), and the cross section $\sigma^{\uparrow(\downarrow)}$,

$$\sigma^{\uparrow(\downarrow)}(\theta) = \sigma_0(\theta)\left(1 + p^{\uparrow(\downarrow)} A_y\right) , \tag{6}$$

and is defined as

$$A_y = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} p^{\downarrow} + \sigma^{\downarrow} p^{\uparrow}} . \tag{7}$$

The total analyzing power for a combination of different states with LSJ is written as

$$A_y = \frac{\sum_{LSJ} \left(\frac{d\sigma}{d\Omega}\right)^{LSJ} A_y^{LSJ}}{\sum_{LSJ} \left(\frac{d\sigma}{d\Omega}\right)^{LSJ}} . \tag{8}$$

4 Results and Conclusion

The differential cross section and analyzing power angular distributions for the J = 7^+ state at 2.283 MeV excitation with L = 6 (Ref. [7]) is shown in Figure 3. The DWBA calculations follow the angular trends sufficiently well for the whole range of incident energies. The limited energy resolution does not allow a complete separation of closely spaced states, and so a small contribution from the J = 6^+, L = 6 state at 2.372 MeV was added to give the total fit. The average analyzing power is also largely negative, as in the data, reflecting a sensitivity to the particular J-value of the transferred pair.

The results for the 0.577 MeV state with J = 5^+ and L = 4 + 6 is shown in Figure 4. Two L-values are possible, though the data seem to favour an L = 4 transfer. Again the definite sign of the analyzing power angular distributions is noticeable which, unlike the J = 7^+ state, is largely positive.

In conclusion, we have measured new differential cross section and analyzing power angular distributions for a few discrete low lying states of ^{56}Co at beam energies of 80, 100 and 120 MeV and at scattering angles between 25° and 60° by means of the reaction ($\vec{p}$,^{3}He) on ^{58}Ni. Based on the good agreement between the calculations and the experimental data it would seem that the direct one-step deuteron pickup description in terms of a zero-range DWBA is indeed suitable to describe the (p,^{3}He) reaction for the range of incident energies investigated.

The DWBA calculations are relatively sensitive to the choice of potential parameters, especially those of the spin-orbit parts of the ^{3}He potentials and, even more so, the bound state. The apparent quenching of the analyzing power at increasing incident energy is not obvious, though it is conceivable that the combined effect from different discrete states with possible opposite signs can contribute in such a way to produce such a tendency.

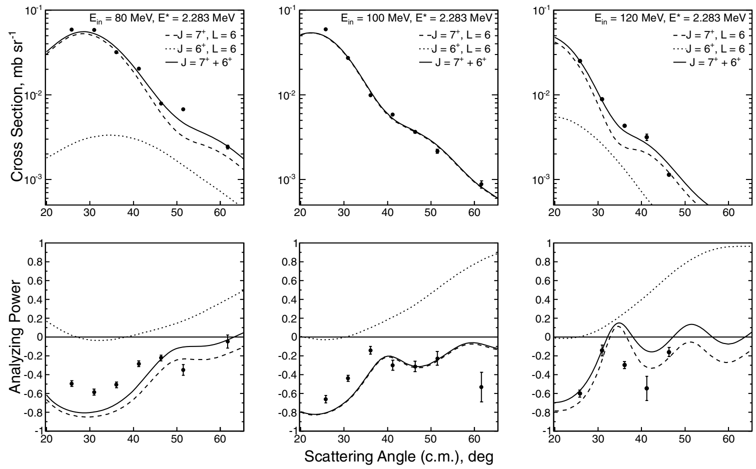

Figure 3. Differential cross section (top) and analyzing power (bottom) for E^* = 2.283 MeV at 80 (left), 100 (middle) and 120 MeV (right)

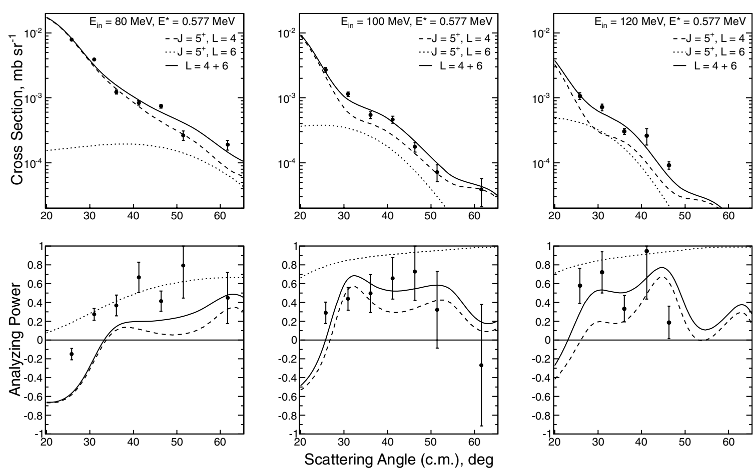

Figure 4. Differential cross section (top) and analyzing power (bottom) for E^* = 0.577 MeV at 80 (left), 100 (middle) and 120 MeV (right)

Further improvements, such as a double folding potential for the ^{3}He-particles, will be investigated in collaboration with colleagues from the Institute for Nuclear Research and Nuclear Energy (INRNE) in Sofia, Bulgaria and the Joint Institute for Nuclear Research (JINR) in Dubna, Russia.

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