EPJ Web of Conferences **38**, 13002 (2012)
DOI: 10.1051/epjconf/20123813002

Incident-energy dependence of the analyzing power in the ^{58}Ni$(p,^3$He$)^{56}$Co reaction between 80 and 120 MeV

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Abstract. This project looks at the angular distributions of the differential cross sections and analyzing powers of a few low lying states of ^{56}Co in the reaction ^{58}Ni(**p**,^{3}He)^{56}Co at three different incident energies between 80 and 120 MeV. The measurements are compared with zero-range distorted-wave Born approximation (DWBA) calculations in which we assume a simple direct two-nucleon pickup process. Earlier inclusive $(p,^3$He) reaction studies on similar targets were successfully treated in terms of a statistical pre-equilibrium multistep formalism, in which the final stage of the reaction involved a deuteron pickup, described by means of the DWBA. The analyzing power was shown to be rather sensitive to the contributions of the different order steps. However some features observed in the analyzing powers of these inclusive studies, though reproduced by the theory, are not fully understood. We therefore investigate the ability of the DWBA model to describe the $(p,^3$He) pickup reaction to discrete states at different incident energies using a high resolution spectrometer.

1 Introduction

Many inclusive, pre-equilibrium reaction studies involving the emission of light ^{3}He- and α-clusters following the interaction of medium energy polarized protons with target nuclei such as ^{59}Co and ^{93}Nb have been done in the past decade [1–4]. These reactions were successfully described in terms of the statistical multistep formalism of Feschbach, Kerman and Koonin (FKK). In the multistep formalism, a one-step process means a direct two-nucleon pickup, in the case of the $(p,^3$He) reaction, and an α-particle knockout process for the (p,α) reaction. In a two-step process the incident proton first collides with a nucleon in the target nucleus before picking up a proton-neutron pair or knocking out the α-particle. Similarly, for the three- and higher order steps, the incident proton first undergoes a few intra-nuclear proton-nucleon collisions, followed by the final stage pickup or knockout. In both the $(p,^3$He) and (p,α) reaction studies, the final stage process have been described by means of the distorted-wave Born approximation (DWBA). These studies showed that the analyzing power is a sensitive indicator of the contributions of the different steps in the reaction mechanism. Large analyzing power values observed at the lowest excitation energies and forward scattering angles, are dominated by single-step processes, while at larger excitation energies the analyzing powers quickly decrease as higher order steps begin to dominate.

Most of the results in these earlier inclusive studies are well understood from the theory, however some features are still unclear. The average analyzing power tends to decrease at larger incident energies, consistent with the multistep theory, but it is not certain why this decrease also appears at the lowest excitation energies where the more direct single-step processes are expected to dominate. In order to test the adequacy of the zero-range DWBA description for the final stage pickup process in the inclusive $(p,^3$He) studies, we investigated the differential cross section and analyzing power angular distributions of the ^{58}Ni(**p**,^{3}He) reaction to a few low lying states of ^{56}Co by means of a high resolution magnetic spectrometer at incident energies of 80, 100 and 120 MeV. The data are compared to zero-range DWBA calculations assuming a simple one-step, direct two-nucleon pickup mechanism.

2 Experimental

Measurements were performed at iThemba LABS (Laboratory for Accelerator Based Sciences) cyclotron facility, Faure, South Africa, using the K600 magnetic spectrometer. The main accelerator facility hosts two solid pole injector cyclotrons (SPC1 and SPC2) and a main Separated Sector Cyclotron (SSC) capable of accelerating the polarized protons to a maximum kinetic energy of 200 MeV. A schematic layout of the accelerator facility is shown in figure 1. Differential cross section and analyzing power angular distributions were measured for the $(p,^3$He) reaction on ^{58}Ni at beam energies of 80, 100 and 120 MeV, and scattering angles between 25° and 60° in 5° steps for several discrete states.

The degree of beam polarization in the direction normal to the scattering plane was measured regularly throughout the experiment by means of a polarimeter located in the P-section of the beam line, before the last 90° bending magnet. A schematic view of the P-line polarimeter is shown in figure 2. The P-line polarimeter consists of two similar NaI(Tl) detectors at equal angles on either side of the beam direction. The polarization in the up(down) direction is

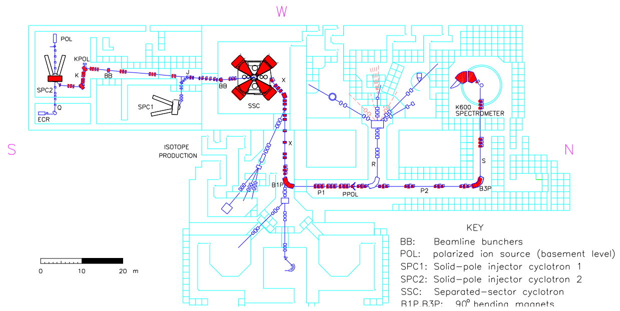

Fig. 1. Schematic overview of the cyclotron facility at iThemba LABS, Faure, South Africa.

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 $\theta = 40°$, 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 elastically scattered events in the left and right detector when the beam polarization is up(down). The average polarization achieved during the experiment was between 60% and 80% and the difference between up and down polarisation around 10% to 30%.

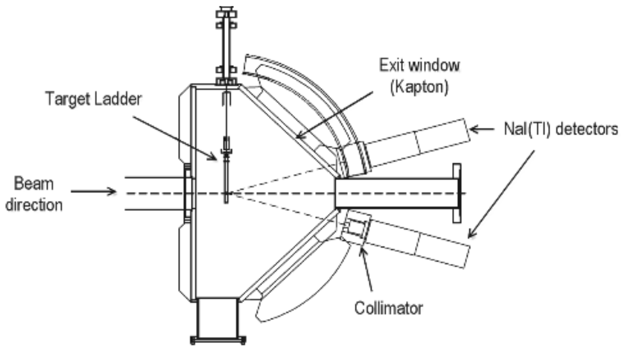

Fig. 2. Schematic view of the P-line polarimeter consisting of two symmetrical NaI(Tl) detectors down-stream from the target.

Reaction products were detected with a standard focal-plane detector array, positioned just after the spectrometer exit window, consisting of a position-sensitive multiwire drift chamber (VDC) followed by two rectangular plastic scintillators or *paddles*, used for event triggering and particle identification. The desired ^{3}He-particles were identified by means of standard time-of-flight (TOF) techniques and it was possible to clearly isolate the ^{3}He reaction products as seen in figure 3.

The focal-plane energy calibration was done using the known Q-values of the ground and excited states of the ^{12}C$(p,^3$He$)$, ^{16}O$(p,^3$He$)$ and ^{27}Al$(p,^3$He$)$ reactions. An example of the resulting excitation energy spectrum is given in figure 4. The energy resolution was about 100 keV, corresponding to the energy loss of the ^{3}He-particles passing through the thick 2.5 mg cm^{-2} ^{58}Ni target. The most prominent states identified are those having large angular momentum transfers, consistent with those expected from momentum matching conditions.

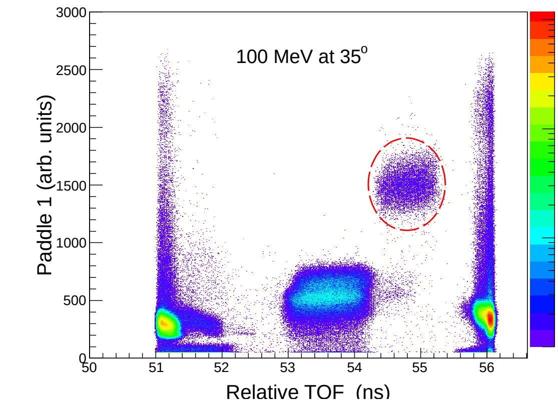

Fig. 3. Paddle 1 vs. time-of-flight (TOF) spectrum for the 100 MeV beam at 35° showing the ^{3}He locus (dashed circle). See online version for colour.

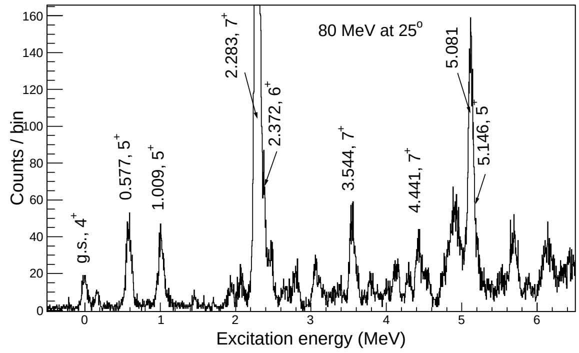

Fig. 4. Excitation energy spectrum of the ^{58}Ni$(p,^3$He$)^{56}$Co reaction at 80 MeV for $\theta_{lab} = 25°$. A few prominent states are indicated, labeled by the their excitation energies and known J^π assignments.

The measured differential cross section (in mb sr^{-1}) for a specific lab angle is determined 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 background corrected counts in an energy peak, N_0 is the total number of incident protons, and $\Delta\Omega$ is the acceptance solid angle of the spectrometer defined at 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 A_y is determined in a similar way from

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

where $N^{\uparrow(\downarrow)}$ is the number of events with the beam polarization in the up(down) direction.

3 Theoretical

The differential cross sections and analyzing powers are calculated in terms of the zero-range DWBA using the code DWUCK4 [5]. The macroscopic cross section for a deuteron pickup is given by

$$\frac{d\sigma(\theta)}{d\Omega} = \frac{2S_{^3He}+1}{2S_p+1}\mathbf{N}\sum_{LSJ} C^2_{ST}\frac{2S+1}{2J+1}\left(\frac{d\sigma(\theta)}{d\Omega}\right)^{DW} , \quad (5)$$

where $\mathbf{N}$ is an overall normalization factor and the last DW-factor is the output from DWUCK4 for a transfer with LSJ quantum numbers. The factor C^2_{ST} is given by

$$C^2_{ST} = b^2_{ST}D^2_{ST}\,\langle T_B N_B; TN|T_A N_A\rangle^2 , \quad (6)$$

where the overlap function b^2_{ST} is 0.5, the interaction strengths D^2_{ST} between the transferred proton and neutron are 0.30 for $S = 0$ and 0.72 for $S = 1$, 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 spin and isospin of the transferred proton-neutron pair are related by the selection rule $S + T = 1$.

The analyzing power is determined from the definition of the polarization $p^{\uparrow(\downarrow)}$ for a beam polarized in the "up"("down") direction with respect to the scattering plane, and the cross section $\sigma^{\uparrow(\downarrow)}$, i.e.

$$\sigma^{\uparrow(\downarrow)}(\theta) = \sigma_0(\theta)\left(1 + p^{\uparrow(\downarrow)}A_y\right) , \quad (7)$$

and is defined as

$$A_y = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow}p^{\downarrow} + \sigma^{\downarrow}p^{\uparrow}} . \quad (8)$$

The total analyzing power for a combination of different contributing states with quantum numbers L, S and J, is written as

$$A_y = \frac{\sum_{LSJ}\left(\frac{d\sigma}{d\Omega}\right)^{LSJ} A_y^{LSJ}}{\sum_{LSJ}\left(\frac{d\sigma}{d\Omega}\right)^{LSJ}} . \quad (9)$$

The distorted waves for the interaction of the incident proton and emitted ^{3}He-particle are determined using global optical potential parameters in Woods-Saxon type optical potentials. The bound state of the transferred deuteron is determined by the usual separation energy method with range and diffuseness parameters of 1.15 and 0.76 fm respectively, which give the correct shape of the radial form factor in the macroscopic approach.

4 Results and conclusion

The resulting differential cross section and analyzing power angular distributions for the $J = 7^+$ state at 2.283 MeV with known $L = 6$ transfer [6], is given in figure 5. The DWBA calculations are able to represent the angular trends quite well for all three incident energies. Because of the limited energy resolution, the complete separation of some closely spaced states was not always possible. A small contribution from the $J = 6^+$, $L = 6$ state at 2.372 MeV was added to the calculations of the $J = 7^+$ state to give the final fit. The analyzing powers, which are sensitive to the J-value of the transferred pair, are largely negative, consistent with the theory.

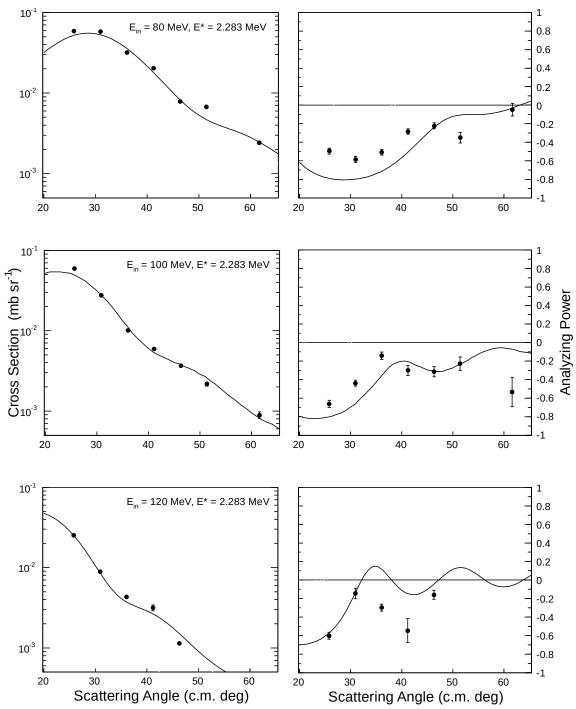

Fig. 5. Differential cross section (left) and analyzing power (right) for the excitation energy region around 2.3 MeV for the 80 (top), 100 (middle) and 120 MeV (bottom) beam energies.

Similarly, the results for the 0.577 MeV state with $J = 5^+$ and $L = 4 + 6$ are given in figure 6. Two L-values are possible, however the data seem to favour the $L = 4$ transfer. The analyzing power angular distributions of this state are largely positive, as opposed to the 7^+ state.

In conclusion, we have measured new differential cross section and analyzing power angular distributions for a few discrete states of ^{56}Co for the ^{58}Ni($\mathbf{p}$,^{3}He) reaction at beam energies of 80, 100 and 120 MeV and scattering angles from 25° to 60°. The relatively good agreement between the calculations and the data seems to indicate that the zero-range DWBA formalism, assuming a simple direct one-step deuteron pickup mechanism, is indeed suitable to describe the (p,^{3}He) reaction for the range of incident energies investigated. It is also conceivable that the combined analyzing powers from different discrete states with possible opposite phases can contribute in such a way to produce the apparent quenching at increasing incident energy, observed in inclusive studies. A possible future improvement is the use of a double folding potential for the ^{3}He-particles, and this is planned 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.

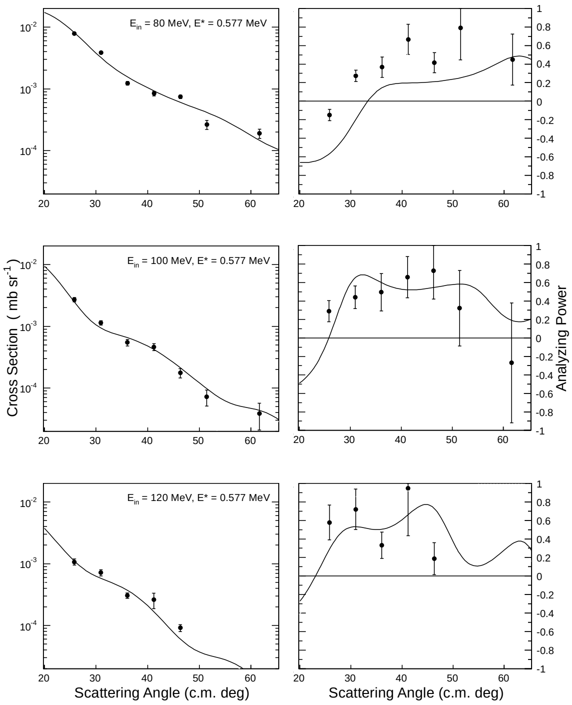

Fig. 6. Differential cross section (left) and analyzing power (right) for the state at E^* = 0.577 MeV for the 80 (top), 100 (middle) and 120 MeV (bottom) beam energies.

Acknowledgements

J.J. van Zyl thanks the Faculty of Science and the Division of Research Development, Stellenbosch University, South Africa as well as the National Research Foundation (NRF) of South Africa for their financial support.

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