Angular Distributions of the Analyzing Power in the Excitation of Low Lying States of ^{56}Co

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Abstract

We present new differential cross section and analyzing power measurements as a function of scattering angle for the reaction ^{58}Ni($\vec{p}$,^{3}He)^{56}Co at three incident energies, 80, 100 and 120 MeV. The experimental results are compared to macroscopic, zero-range DWBA calculations, assuming a direct single-step deuteron pickup mechanism. The dependency of the angular distributions on incident energy is investigated in order to evaluate the viability of such a simple one-step pickup process for the final stage in inclusive (p,^{3}He) reaction studies within a multistep formalism. It was found that the DWBA calculations give a good representation for the one-step direct pickup process and consistently follow the observed angular trends at all three incident energies.

1 Introduction

The current project involves the measurement of differential cross section and analyzing power angular distributions for a few discrete states in ^{56}Co at different incident energies. The investigation is largely motivated by studies done on the pre-equilibrium emission of light ^{3}He- and α-clusters from the interaction of medium energy polarized protons with target nuclei such as ^{58}Ni, ^{59}Co and ^{93}Nb [1–4].

These reactions were successfully described by the statistical multistep formalism of Feschbach, Kerman and Koonin (FKK), involving a final two-nucleon pickup or α-particle knockout process for the (p,^{3}He) and (p,α) reactions respectively, following a few intra-nuclear proton-nucleon collisions. In this context a one-step process, in the case of the (p,^{3}He) reaction for example, 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 have been described by means of the distorted-wave Born approximation (DWBA). The studies pointed out the sensitivity of the analyzing power to the contributions of the different steps. Large analyzing power values, seen at the lowest excitation energies, are dominated by direct single-step processes, while at larger excitation energies the analyzing powers decrease indicating the emerging prominence of higher order steps.

Most of the trends in the results are well understood from the theory, however some features are not that obvious. At larger incident energies the analyzing powers decrease, consistent with the multistep theory, but it is not certain why this decrease also appears at the very lowest excitation energies where one would rather expect the more direct single-step processes to be enhanced. In order to test the adequacy of the zero-range DWBA for the description of the final 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. The data are compared to a simple one-step, direct two-nucleon pickup description to see how well the DWBA theory is able to describe the direct reaction part.

2 Experimental

Measurements were performed at iThemba Laboratory for Accelerator Based Sciences (LABS) cyclotron facility near Faure, South Africa, using the K600 magnetic spectrometer, Fig. 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. An inline polarimeter, consisting of two similar NaI(Tl) detectors at symmetrical angles on either side of the beam direction, was used to measure the polarization during the experiment. The polarization in the up(down) direction is determined form the known analyzing power for a fixed detector angle, e.g. $A_y = 0.74$ for the elastic scattering of protons from ^{12}C at $\theta = 40°$, using the expression

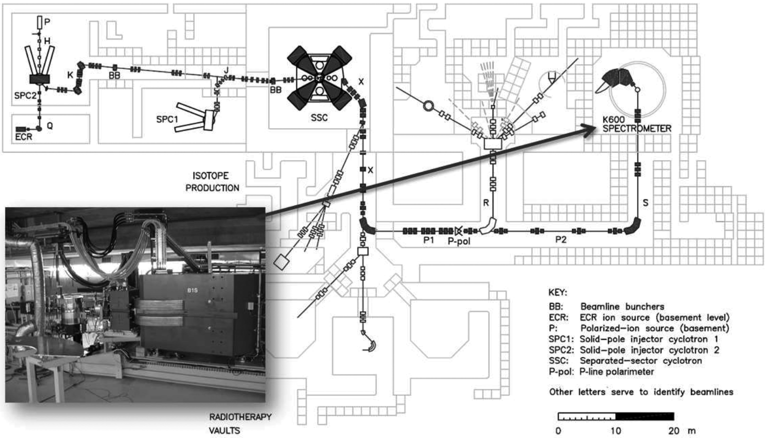

Fig. 1: Schematic overview of the cyclotron facility at iThemba LABS, Faure, South Africa.

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

where $L^{\uparrow(\downarrow)}$ and $R^{\downarrow(\uparrow)}$ 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%. Particle identification was done using standard time-of-flight (TOF) techniques and it was possible to clearly isolate the desired ^{3}He-particles as seen in Fig. 2. The energy calibration was done using 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, seen in Fig. 3, was about 100 keV, limited mostly by the thickness of the target. The most prominent states identified are those having large angular momentum transfers.

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

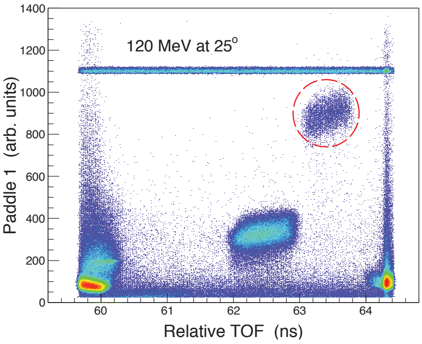

Fig. 2: Paddle 1 vs. time-of-flight (TOF) spectrum for the 120 MeV beam at 25° showing the ^{3}He locus (dashed circle)

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 number of target nuclei per 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 by the collimator. The absolute (unpolarized) differential cross section is then given by

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

$$\approx \frac{\sigma^{\uparrow} + \sigma^{\downarrow}}{2}.$$

The last approximation is valid only if $p^{\uparrow} \approx p^{\downarrow}$. Similarly, the analyzing power is determined from

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

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

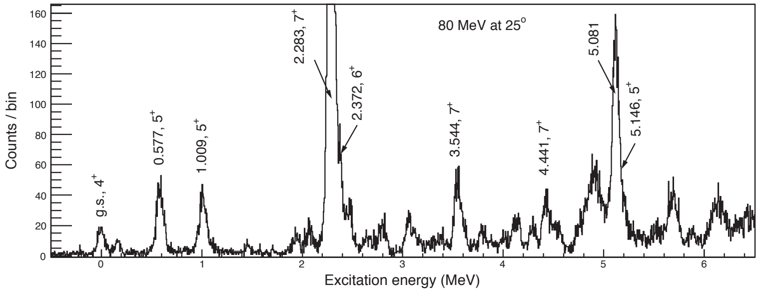

Fig. 3: Excitation energy spectrum of the ^{58}Ni(p,^{3}He)^{56}Co reaction at 80 MeV for θ_{lab} = 25°. A few prominent states are indicated with their known J^{π} assignments.

3 Theoretical

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

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

where **C** is an overall normalization factor, the overlap function b_{ST}^2 is 0.5, the interaction strengths D_{ST}^2 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 and 2 for the cases with $S = 0$ and $S = 1$ respectively. The last DW-factor is the output from DWUCK IV for a transfer with LSJ quantum numbers.

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

$$A_y = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} p^{\downarrow} + \sigma^{\downarrow} p^{\uparrow}} \,. \tag{6}$$

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

$$A_y = \frac{\sum_{LSJ} \left(\frac{d\sigma}{d\Omega}\right)^{LSJ} A_y^{LSJ}}{\sum_{LSJ} \left(\frac{d\sigma}{d\Omega}\right)^{LSJ}} \,. \tag{7}$$

4 Results and Conclusion

Figure 4 shows the differential cross section and analyzing power angular distribution for the $J = 7^+$ state at 2.283 MeV with known $L = 6$ transfer [6]. The DWBA calculations follow the angular trends well enough and especially the shape of the data for the different incident energies. Since the resolution did not allow the separation of closely spaced states, a small contribution of the $J = 6^+$, $L = 6$ state at 2.372 MeV was added to give the total fit. Of specific notice is the large negative analyzing powers which is sensitive to the J-value of the transferred pair.

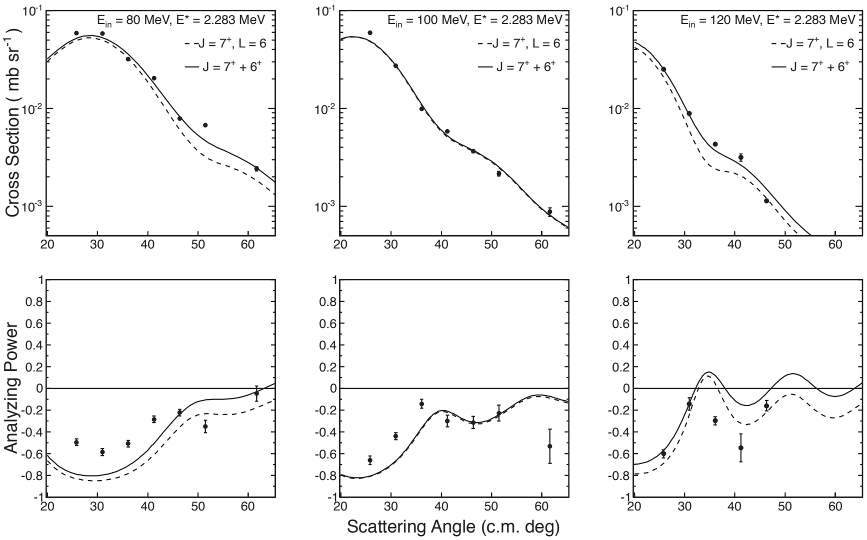

Fig. 4: Cross section (top) and Ay (bottom) for E^* = 2.283 MeV at 80 (left), 100 (middle) and 120 MeV (right)

Similarly, the results for the 0.577 MeV state with $J = 5^+$ and $L = 4 + 6$ are shown in Fig. 5. Two possible L-values can contribute, though the data seem to favour the $L = 4$ transfer. Again it is noticeable the definitive sign of the analyzing power angular distributions which, in this case, is largely positive.

In summary, we have provided new measured differential cross section and analyzing power angular distributions for a few discrete states of ^{56}Co at beam energies of 80, 100 and 120 MeV and at angles 25° to 60° by means of the reaction ($\vec{p}$,^{3}He) on ^{58}Ni. From the good correspondence between the calculations and the experimental data it would seem that the direct one-step deuteron pickup description

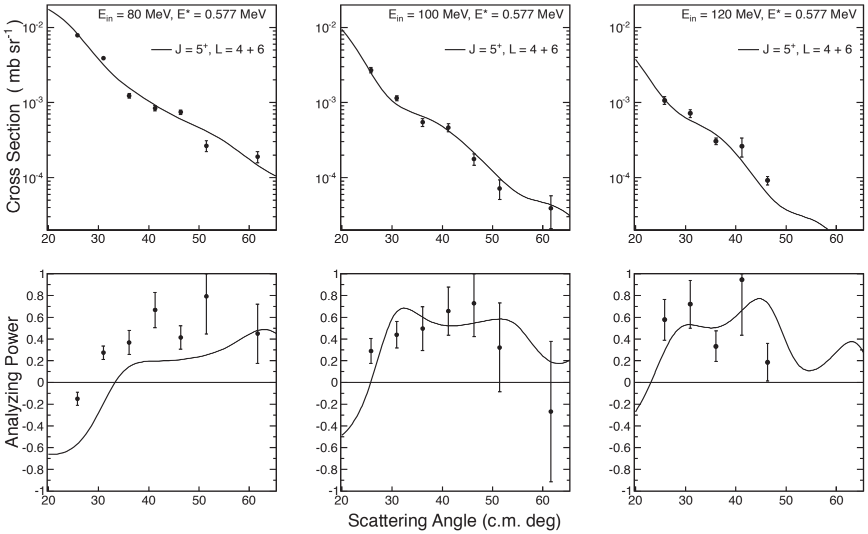

Fig. 5: Cross section (top) and Ay (bottom) for $E^* = 0.577$ MeV at 80 (left), 100 (middle) and 120 MeV (right)

in terms of the zero-range DWBA is indeed suitable to describe the pickup reaction for the range of incident energies investigated. The apparent quenching of the analyzing power at increasing incident energy is not obvious, though it can be expected that the combined effect from different discrete states with possible opposite phases can contribute in such a way to produce such a tendency. A future improvement to be investigated is a double folding potential for the ^{3}He-particles, and this will be done 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.

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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