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

J.J. van Zyl[1], **R. Neveling**[2], **A.A. Cowley**[1,2], **E.Z. Buthelezi**[2], **S.V. Förtsch**[2], **J. Mabiala**[1,2], **J.Mira**[1], **F.D. Smit**[2], **G.F. Steyn**[2], **J.A. Swartz**[1], **I.T. Usman**[2,3]

[1]Department of Physics, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa

[2]iThemba Laboratory for Accelerator Based Sciences, P.O. Box 722, Somerset West 7129, South Africa

[3]School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa

Abstract. Differential cross section and analysing power measurements for the reaction ^{58}Ni(p,^{3}He)^{56}Co are presented as a function of scattering angle for a few low lying states of ^{56}Co. The investigation is aimed at determining a possible incident energy dependency in the analysing power observed in previous cluster emission studies. Data at 80 and 100 MeV have already been analysed. These results are soon to be compared to distorted wave Born approximation calculations carried out within the framework of a direct deuteron pickup model.

1 Introduction

Many studies have been performed on reactions where light clusters like ^{3}He- and α-particles are emitted from the interaction of medium energy protons from a range of targets [1–4]. In general the differential cross section and analysing power angular distributions are quite successfully described in term of a statistical multi-step process [2]. The reaction formalism involves a final two-nucleon pickup process as in the case of (p,^{3}He), or knockout as for (p, α) reactions following a few intra-nuclear proton-nucleon collisions. It is clear from these analyses that especially the analysing power is quite sensitive to the multi-step mechanism. The analysing power proves to be a strong indicator of the reaction mechanism, as shown by Bonetti *et al.* [5].

It is observed that a single-step, direct process dominated the analysing powers at the highest emission energies, producing large absolute analysing power values. At lower emission energies where the excitation is greater, the analysing powers show a decreased trend in their angular distributions. This decreasing analysing power is attributed to the contributions of higher order steps which tend to average out the spin characteristics of the incident proton as illustrated in Figure 1.

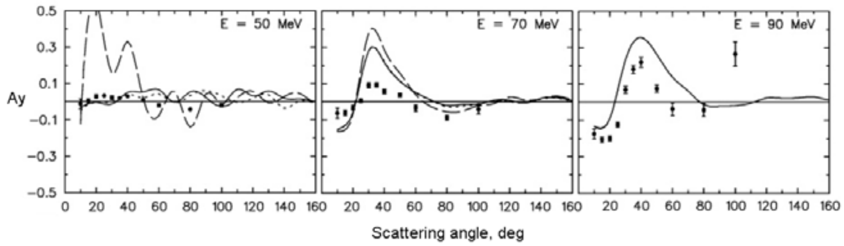

Figure 1. Inclusive analysing power results from Cowley *et al.* [1] for the reaction ^{59}Co(p,^{3}He) at incident energy of 100 MeV for various outgoing helion energies (E). Calculations are for a one-step reaction (- - -), a one-step plus a two-step reaction ($\cdots$), and a one- plus two- plus three-step reaction (continuous curves).

As the incident energy of the projectile is increased the analysing power also drops, consistent with the multi-step mechanism where deeper penetration can result in larger excitations. It is, however, not clear why this decreasing analysing power appears even at the lowest excitation energies. Here one would rather expect the more direct, single-step reactions to dominate, which should result in higher values for the analysing power. A possible explanation is that the measured analysing power is the fortuitous result of the contributions from different discrete states. It has also been suggested by Cowley *et al.* [2] that this quenching of the analysing power at larger incident energies may be a consequence of the competition between the incident energy dependence of the direct reaction and the multi-step mechanism.

2 Experimental Setup

In order to determine the dependence of analysing power on incident energy, the (p,^{3}He) reaction on a solid ^{58}Ni target has recently been investigated with the K600 Magnetic Spectrometer at iThemba LABS (Laboratory for Accelerator Based Sciences), South Africa. The main accelerator facility at iThemba LABS hosts two solid pole injector cyclotrons and a Separated Sector Cyclotron (SSC) capable of providing polarised protons of up to 200 MeV. Measurements were taken at incident energies of 80 and 100 MeV at spectrometer angles ranging from 25° to 60° in steps of 5°.

2.1 Focal-plane Detectors

Reaction products were detected with a standard focal-plane detector array consisting of two position-sensitive multi-wire drift chambers followed by a 1/4" and 1/2" plastic scintillator or paddle used for event triggering. Time-of-flight (TOF) techniques were employed to select the desired ^{3}He-particles. It can be seen from the TOF spectrum in Figure 2 (a) how the ^{3}He locus is clearly isolated from other particles in the focal-plane without the need for pulse selection.

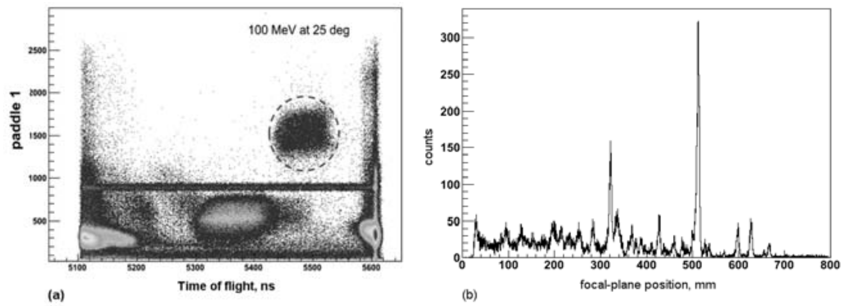

Figure 2. (a) Paddle 1 *vs.* time-of-flight (TOF) spectrum showing the ^{3}He locus (dashed circle) for the ^{58}Ni(p,^{3}He)^{56}Co reaction at 100 MeV and 25°. The two high peaks on either end of the spectrum represent protons while the central, low energy peak is assumed to be α-particles, consistent with TOF calculations. The horizontal "bar" is from pulser signals. (b) Typical focal-plane position spectrum for the same reaction showing a few resolved states in ^{56}Co.

An energy resolution of about 102 keV was achieved with the 100 MeV beam, limited by the energy loss of ^{3}He-particles in the 2.5 mg/cm^2 thick ^{58}Ni target, while being as low as 29 keV for ^{12}C$(p,p)^{12}$C measurements at the same beam energy. A few discrete, low lying states of ^{56}Co were clearly resolved as seen in the position spectrum in Figure 2 (b). Energy calibrations were done using the known Q-values for the (p,^{3}He) reaction on ^{12}C, ^{16}O and ^{27}Al targets to their ground and excited states.

2.2 Polarisation

During the experiment the beam polarisation was switched from up to down at 10 s intervals. This was done to minimize any systematic errors in the detector setup. The polarisation of the incident protons was measured with a polarimeter in the beam line between the cyclotron and spectrometer, and it consisted of two similar NaI(Tl) scintillator detectors positioned at equal angles to the left and right of the beam direction. The polarisation is then determined from the known analysing power (A_y) for the elastic ^{12}C$(p,p)^{12}$C reaction for a given detector angle (*e.g.* A_y = 0.74 at θ_{lab} = 40° and 80 MeV) and is defined by

$$p_{\uparrow(\downarrow)} = \left(\frac{1}{A_y}\right)\frac{L_{\uparrow(\downarrow)} - R_{\uparrow(\downarrow)}}{L_{\uparrow(\downarrow)} + R_{\uparrow(\downarrow)}}\,, \tag{1}$$

where $L_{\uparrow(\downarrow)}$ and $R_{\uparrow(\downarrow)}$ refer to the number of counts in the left and right detector when the beam polarisation was either up (↑) or down (↓). The average beam polarization was generally between about 65% and 75% with a difference between up and down polarization ranging between 8% and, at times, as much as 32%.

3 Measurements and Results

The measured differential cross section (in mb/sr) 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 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 (in sr).

The analysing power is determined from the number of counts $C_{\uparrow(\downarrow)}$ in the energy peak for each beam polarisation $p_{\uparrow(\downarrow)}$, and is written as

$$A_y = \frac{C_\uparrow - C_\downarrow}{p_\downarrow C_\uparrow + p_\uparrow C_\downarrow}\,. \tag{3}$$

The arrows ($\uparrow\downarrow$) indicate polarisation of up and down in the reaction plane.

Figure 3 shows the resulting excitation energy spectrum for the 100 MeV beam at 25°. Some of the most prominent nuclear states are indicated. These states are associated with relatively large orbital angular momentum transfers, expected due to momentum matching conditions between the projectile and emitted particle. Of particular interest is the large 2.27 MeV state. It has been reported by Bruge *et al.* [7] to be a 7^+ state corresponding to a $(\pi f_{7/2})^{-1}(\nu p_{3/2})^2$ configuration, and is the only $L = 6$ transition observed.

Experimental differential cross section and analysing power results for a few excited states in ^{56}Co are shown in Figure 4. The cross section at 100 MeV is consistently lower than that at 80 MeV as would be expected from mainly

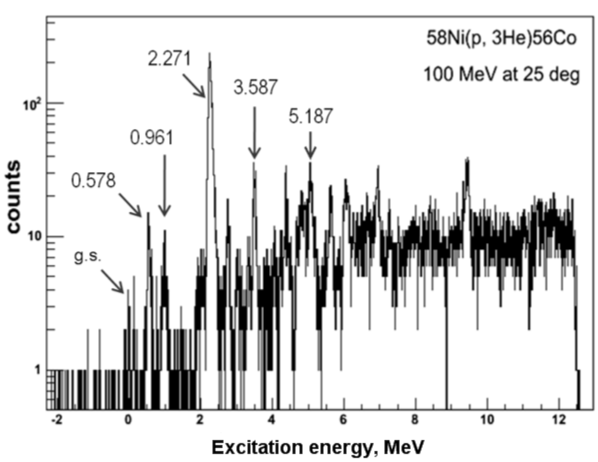

Figure 3. Excitation energy spectrum for the ^{58}Ni(p,^{3}He)^{56}Co reaction at 25° and 100 MeV beam energy indicating the energies of a few prominent states.

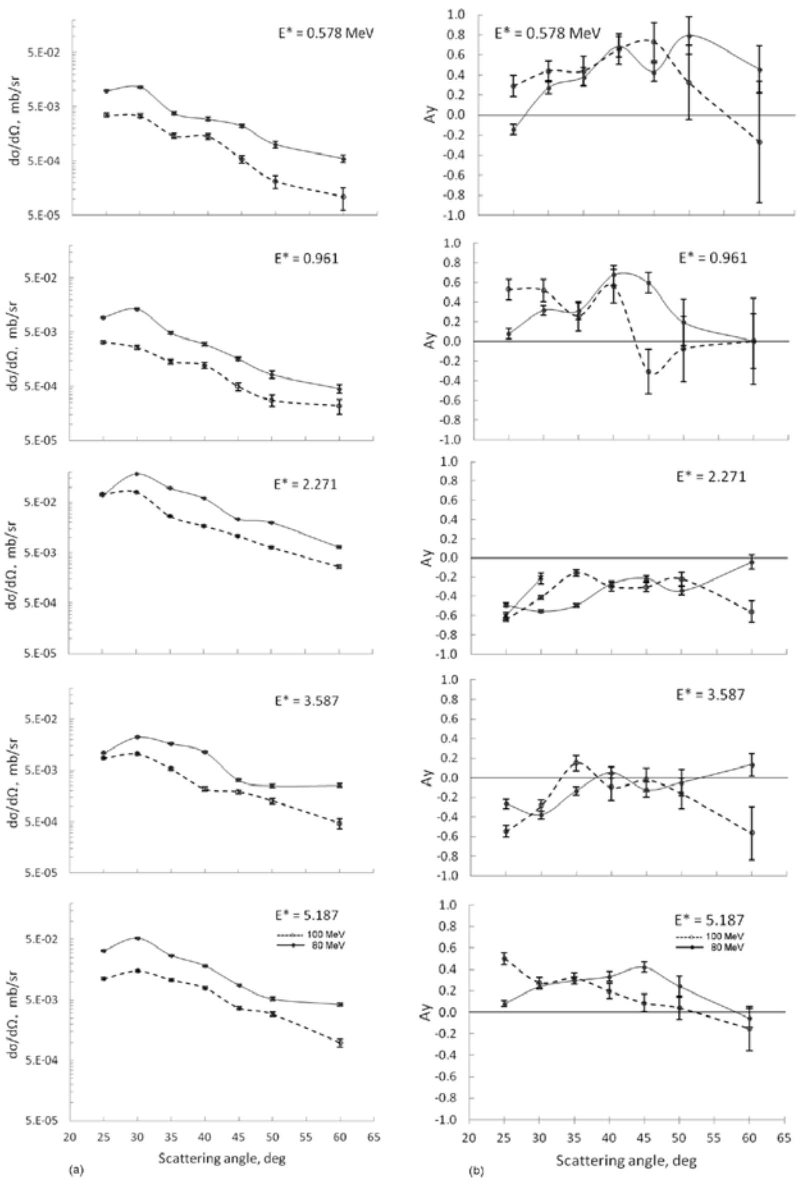

Figure 4. Differential cross sections (a) and analysing powers (b) for the a few prominent excited states of ^{56}Co in the ^{58}Ni(p,^{3}He)^{56}Co reaction at 80 MeV (solid circles and line) and 100 MeV (empty circles, dashed line). The excitation energy E* of each state is indicated. The lines connecting the data points are guides for the eyes only.

the effect of the change in momentum mismatch between the incident and exit channel. No clear incident energy dependence has yet been identified in the analysing power data, but the theoretical analysis is currently underway.

4 Conclusion

We investigated the reaction ^{58}Ni(p,^{3}He)^{56}Co for incident proton energies of 80 MeV and 100 MeV. A further experiment at 120 MeV is to be performed later this year in order to explore the incident energy dependence in the analysing power distributions. Differential cross section and analysing power angular distributions were presented for a few resolved states in ^{56}Co for angles in the range of 25° to 60°. The trend in the differential cross sections as a function of incident energy appears to be in agreement with previously measured data. The incident energy dependence of the analysing power is however still inconclusive at this stage. DWBA calculations, assuming a direct deuteron pickup model, is to be done in collaboration with the Institute for Nuclear Research and Nuclear Energy (INRNE), Sofia, Bulgaria in the near future.

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