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Contributions of Professor Anthony Cowley to the Field of Nuclear Reaction Studies

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Abstract. From the early $(p, 2p)$ knockout reaction experiments performed on light ^{2}H, ^{3}He and ^{4}He targets in the 1970s, to his last publication in 2021 looking at the extent to which knockout, as opposed to a pickup reaction mechanism, contributes in pre-equilibrium (p, α) reactions, Anthony Cowley leaves behind a legacy of experimental nuclear physics research and training not only in South Africa, but across the globe. In celebration of his person, this presentation looks at knockout reactions and the pre-equilibrium emission of composite ejectiles, such as ^{3}He and α particles, through the different contributions that Anthony Cowley made throughout his 50-year career in nuclear physics research.

1 Introduction

I once asked Anthony about the Cowley family name, to which he enthusiastically began telling me his whole family history, as far back as he was able to research. His ancestors, I learned, were Robert Cowley and Elizabeth Bloor who arrived here in South Africa in November 1847 from England, and between 1066 and 1290 his family occupied the Cowley Manor in Derbyshire. Such were the stories and the wealth of information that Anthony always enjoyed sharing. It is only fitting therefore to mention a little bit of his story, his history and the role he played in Nuclear Physics research, particularly in South Africa.

Anthony received his DSc degree in Nuclear Physics from the University of Pretoria, South Africa, in 1969. Between 1968 and 1980 he served as Research Scientist at the Council for Scientific and Industrial Research (CSIR), a leading South African research and development organization. During that time (1972-1973) he also held the position of Research Associate, and later Visiting Assistant Professor of Physics (1976 and 1979) at the University of Maryland, USA. It is through this association with colleagues at Maryland, such as Profs. N.S. Chant and P.G. Roos (or Nic and Phil, as he familiarly referred to them, I believe in his kind attempt to make me feel equally important), that valuable experimental facilities were brought to South Africa.

In the 1980's Anthony headed the Light Ion Physics group at what is today iThemba Laboratory for Accelerator Based Sciences (LABS) near Cape Town, consisting of only himself and a postdoc, as he jokingly boasted. At that time called the National Accelerator Center (NAC), only a few small groups existed, Isotope Production, Accelerator and Research (Light Ion Physics). Prior to the first beam of the main K200 separated sector cyclotron in 1987, low energy scattering experiments were conducted with the 8 MeV, K8 solid-pole injector cyclotrons and a 1.5 m diameter scattering chamber, donated by Maryland in 1984, and installed in the A-line vault. When the polarized ion source arrived in 1990, I believe from Argonne National Laboratory, Indiana also through Anthonys many connections, it opened the way for measurements of spin observables like analyzing power, which revealed a wealth of information about the nature of knockout and pre-equilibrium scattering mechanisms, as well as the nucleon-nucleon force.

From 1992 Anthony joined Stellenbosch University as Professor of Nuclear Physics, and during that time commissioned the locally manufactured K600 magnetic spectrometer (ca. 1993). The K600 spectrometer allowed for high energy resolution cross-section measurements, superior to what was achievable in the A-line scattering chamber. Between 1996 and 1998, Anthony took up the position of Head of the Physics Department at Stellenbosch University, followed by appointments as Visiting Professor at Maryland, as well as Research Scientist at the Thomas Jefferson National Accelerator Facility (Jefferson Lab), Virginia from 1998. He maintained an active research role at iThemba LABS from 2006 as Research Associate and later Honorary Senior Research Associate until 2014. Anthony continued his academic career as Lecturer, then Professor Emeritus and later Professor Extraordinary at Stellenbosch University until his passing in 2022, supervising more than a dozen PhD and MSc candidates, including myself, some of whom also became heads of Physics Departments.

Anthony Cowley published more than 200 nuclear physics research articles in international refereed journals, as attested to by his h-index of 21 (at the time of writing). He was an active member of the International Advisory Committee of the International Workshop on Nuclear Theory (IWNT), Bulgaria (2011-2022) and a regular contributor to the workshop since the early 2000's, having established several long-standing research collaborations with scientists from INRNE, Sofia and JINR, Dubna related to the theory of multistep direct reaction mechanisms.

He was also a member of the International Advisory Committee of the Varenna Conference on Nuclear Reaction Mechanisms (NRM) for over five years. This important nuclear physics conference had a strong focus on pre-equilibrium reaction studies, and the Chairman of the NRM Conference, Ettore Gadioli, in his parting address after serving for 30 years as chairman, considered it worthwhile to specifically mention Anthony by name, along with leading physicists such as Peter Hodgson and Herman Feshbach, writing [1]

> *In 1991 a large number of talks were once more devoted to decay before equilibration, multistep processes, multifragmentation with talks among others of P. Hodgson, A. A. Cowley (who presented the double differential spectra of protons inelastically scat-*

tered by nuclei varying from ^{58}Ni to ^{197}Au at incident energies of 100-200 MeV, data which allowed a very stringent test of the predictions of the FKK multistep direct reaction theory by the Milano Group of Roberto Bonetti). (p. 7)

2 Direct Knockout Reactions

Nuclear reaction studies have been used very successfully as a tool to probe the nature of nuclear structure, including single-particle properties of nuclei by means of proton-knockout reactions [2]. Nucleon-induced knockout reactions have also proven useful to unravel details of the nucleon-nucleon interaction, as well as the notion of ground state α-clustering in nuclei through, for example (p, $p\alpha$) reaction studies. Furthermore, statistical multistep processes such as proton-induced pre-equilibrium emission of α-particles can provide deeper understanding of the mechanisms involved in nuclear reactions [3], as well as fundamental nuclear properties such as the degree of α-clustering in nuclei.

The nuclear Shell model suggests that it would be possible to knock nucleons out of orbitals in nuclear reactions with energetic projectiles, and thereby shed light on the properties of these single particle shell states, their occupancy, and the binding energies and momentum distributions of nucleons inside the nucleus, thus providing a valuable tool for nuclear spectroscopy. During direct reactions, the collision is considered to be with a stationary nucleon in the nucleus while the residual nucleus likely acts only as a spectator to the reaction. Conservation of momentum would then require that the residual nucleus remains at rest. The reaction is considered quasi-free and can be approximated by a free collision between the projectile and target. One- and two nucleon, or cluster knockout reactions such as $(p, 2p)$, (p, pn), $(p, p\alpha)$, $(\alpha, 2\alpha)$ and $(e, e'p)$ prove valuable for investigating single-particle properties, whereas cluster knockout reactions like (p, α) can be described as a three-nucleon pickup or α-knockout, or a combination of both with different strengths. A proper analysis of the reaction needs to account for both.

The fast nature of the collision allows for the application of a sudden (impulse) approximation, and the cross section for the quasi-free knockout process can be written simply as a free projectile-nucleon (or cluster) scattering cross section. This non-relativistic Distorted Wave Impulse Approximation (DWIA) formalism was originally used by N.S. Chant and P.G. Roos [4] in the late 1970's. Distortions in the wave functions account for interactions of the projectile and the scattered particles with the target and residual. These distorted wave functions are usually generated from global Woods-Saxon optical potentials.

Quasi-free knockout reactions had already been studied for many years, however important contributions were still necessary to explain the complex dynamic phenomena observed during these types of reactions. In particular, Anthony's contributions to proton knockout reactions on light targets such as ^{12}C and ^{16}O, and heavier ^{208}Pb, as well as α-cluster knockout studies are highlighted here.

2.1 Proton Knockout on Light ^{16}O and ^{12}C Targets

In the early 1990's the ^{16}O$(p, 2p)^{15}$N knockout reaction was studied experimentally at quasi-free angles with a 150 MeV proton beam using the A-line scattering chamber at iThemba LABS [6]. The striking agreement between the measured and theoretical energy distributions predicted by the Distorted Wave Born Approximation (DWBA) demonstrated that the reaction mechanism was correctly identified. These results were similar to studies at higher proton energies [7], indicating that the spectroscopic factors are rather independent of the incident energy, and confirmed the expected occupation of the two valence orbitals of ^{16}O. The reaction process was now so well understood that this experimental technique could be applied to target nuclei for which theoretical calculations were not practically possible at the time.

Recently [8], Anthony and his collaborators revisited the ^{12}C$(p, 2p)^{11}$B data at 400 MeV from RCNP (Osaka, Japan) for transitions to the ground and low excited states in ^{11}B, and compared DWIA predictions for both cross sections and analyzing powers with a more advanced Faddeev/Alt-Grassberger-Sandhas (F/AGS) framework, which is an exact, non-relativistic description of the three-body scattering problem. The data from RCNP provided different kinematics conditions, including angular and energy-sharing distributions, which offered stringent constraints with which the different theoretical reaction formalisms could be benchmarked. The research pointed to a clear and expected sensitivity of the observables to the optical potential parametrization in the reaction formalism as well as the kinematic conditions.

2.2 Proton Knockout on Heavy ^{208}Pb Targets with K600

Although it was already known that the DWIA can also accurately predict cross sections for proton knockout from heavy targets and extract reliable spectroscopic factors in agreement with results from $(e, e'p)$ studies, despite the more severe distortion of the wave functions, the analyzing power predictions for quasi-free proton knockout reactions on light to medium mass targets were still poor.

To investigate this question further, high resolution coincidence measurements of the energy-sharing cross section and analyzing power distributions for the ^{208}Pb$(p, 2p)^{207}$Tl knockout reaction at 202 MeV proton energy were conducted using the K600 magnetic spectrometer at iThemba LABS [9]. Although the spectroscopic factors extracted from non-relativistic DWIA (NDWIA) calculations compared favorably with what was known from literature, the analyzing powers showed serious discrepancies. Inclusion of density-dependent nucleon-nucleon (NN) interactions reduced the analyzing powers to some degree, suggesting that further investigations into the density-dependent description of the nuclear matter was required. Hence, the first systematic analysis of the proton-knockout reaction within a relativistic DWIA framework, which included analyzing power, was performed by Anthony's group [10] soon afterwards. The exclusive nature of $(p, 2p)$ reactions could be exploited to knock out protons from deep- to low-lying single-particle states, offering information on the medium dependence of the NN interaction. The study looked at the effects of density-dependent corrections to the NN interaction. Both relativistic zero-range (ZR) and finite-range (FR) approximations to the DWIA provided an improved description of the analyzing power data, as can be seen by the solid (FR) and dot-dash (ZR) lines in both the cross section and analyzing power distributions in Figure 1. The figure demonstrates the superiority of the relativistic Dirac-equation *vs.* the non-relativistic Schrödinger equation for the description of the exclusive $(p, 2p)$ reaction within the DWIA. Clearly the relativistic ZR

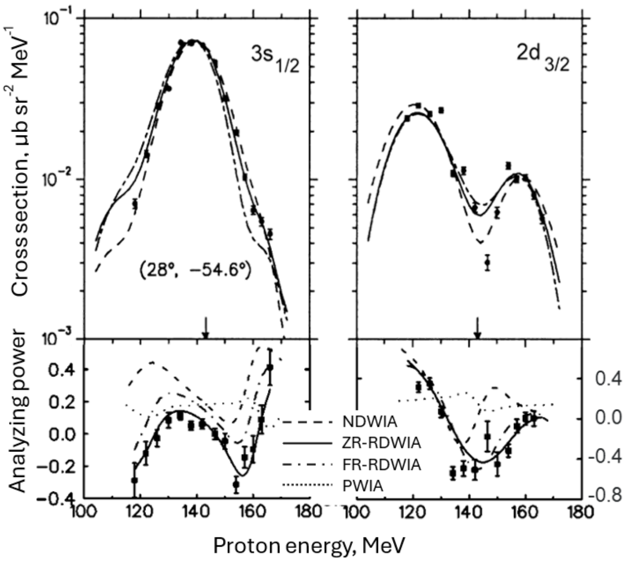

Figure 1. Relativistic predictions of exclusive ^{208}Pb$(p, 2p)^{207}$Tl analyzing powers at an incident energy of 202 MeV [9]. The different lines represent the non-relativistic (NDWIA), relativistic zero-range (ZR-RDWIA), relativistic finite-range (FR-RDWIA) and plane-wave (PWIA) approximations to the DWIA description, respectively [10].

predictions suggest that the free NN scattering description in the DWIA is sufficient to represent scattering in the nuclear medium, and hence it is not necessary to consider nuclear-medium modifications to the NN interaction. However, the relativistic FR results show that a $10 - 20\%$ reduction of meson-coupling and meson masses by the nuclear medium is necessary for a consistent description of the analyzing powers for different excited states. Proper Dirac optical potentials are therefore important, although the study also indicated that the analyzing power is relatively insensitive to different global Dirac optical potential parameter sets.

2.3 Cluster Knockout

Cluster knockout reactions such as $(p, p\alpha)$ can offer a direct technique to investigate the α-cluster structure of the nuclear medium, helping our understanding of α-cluster pre-formation probabilities in the ground state of nuclei as well as the momentum distribution of α clusters in nuclei. Under suitable kinematic conditions where the heavy residual nucleus has zero recoil momentum, a $(p, p\alpha)$ reaction may proceed as a quasi-free process. The impulse approximation then relates the two-body collision of the projectile with a bound, pre-formed α cluster at rest in the target. Under these conditions, the cross section and analyzing power distributions of a quasi-free reaction should resemble those of a free p-^{4}He elastic scattering process.

The ^{12}C$(p, p\alpha)^8$Be cluster knockout reaction was investigated in the A-line scattering chamber at iThemba LABS with a 100-MeV polarized proton beam [11]. The stunning agreement between the measured analyzing power distributions and those predicted for free p-^{4}He elastic scattering, as shown in Figure 2, confirmed the validity of the DWIA and demonstrated for the first time, convincingly, that direct α-cluster knockout is directly related to a free interaction, while the rest of the target remains a spectator. This gave compelling evidence for the existence of pre-formed α clusters in ^{12}C. The slight discrepancy observed in

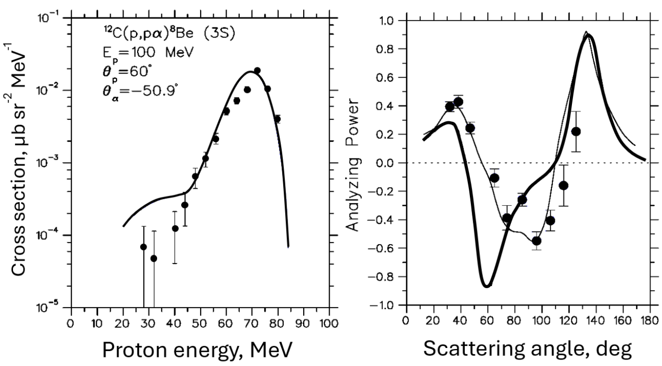

Figure 2. Cross-section energy distributions (left) and analyzing power angular distributions (right) for the reaction ^{12}C$(p, p\alpha)^8$Be (black symbols with statistical error bars) at an incident energy of 100 MeV. The thick solid curve is a DWIA prediction. The thin solid curve on the right represents experimental free p-^{4}He elastic scattering analyzing powers [11].

the analyzing power distributions points to possible problems with the optical potential parameters used for the p-^{4}He elastic scattering in the DWIA. These parameters were determined from a fit to only a cross section angular distribution at 100 MeV incident energy, and highlighted the need for optical potentials constructed from both cross section data and spin observables. Koning and Delaroche [12] state that a good optical model should simultaneously describe the angular distributions for elastic scattering for both cross sections and analyzing powers.

In one of his last publications [13], Anthony successfully demonstrated how the use of appropriate optical-model potentials which describe elastic scattering of α particles can resolve this problem to a remarkable extent. In fact, Koning and Duijvestijn [14] commented that spectra for the (p, xp) reaction at 100 MeV and higher all came from iThemba LABS, South Africa, attesting to the tremendous research contributions that Anthony Cowley made to our knowledge of nuclear structure and reaction mechanisms.

3 Pre-equilibrium Reactions

The energy distributions of particles emitted from nuclear interactions at moderate energies often show many features. Between the broad maximum at lower emission energies corresponding to particles emitted from a nucleus in which the excitation energy is shared statistically among nucleons, and the resolved peaks at higher emission energies resulting from direct reactions to particular states of the residual nucleus, is a relatively featureless continuum. At these intermediate energies the scattering yields show a forward excess, but with little structure. With increasing excitation energy, the successive states become wider until they form a continuum. The scattering cross section yields are due to a combination of direct processes and particles emitted after the direct process, but before statistical equilibrium is reached.

While the statistical theories of compound nuclear decay and the processes responsible for the direct reactions are reasonably well understood, the processes responsible for these pre-equilibrium or pre-compound particles are less well understood and have been the subject of many investigations over the years, for example [15]. Quantum-mechanical multistep theories assume the interaction occurs in stages of increasing complexity. A projectile can collide with a nucleon to produce a 2-particle-2-hole (2p2h) excitation, secondary particles can themselves interact, producing 3p2h excitations, and so on. At each stage there is a possibility that the reaction can proceed directly into the continuum, causing pre-equilibrium emission.

Anthony spearheaded several pre-equilibrium reaction studies over many years which investigated proton-induced emission of light compound particles into the continuum. Notably is the inclusive ^{59}Co(p,^{3}He) reaction at 100 MeV, performed with a polarized proton beam in the iThemba LABS A-line scattering chamber [15]. The statistical multistep direct theory of Feshbach, Kerman, and Koonin (FKK) was used for the description of the intra-nuclear scattering, while the final step was treated using the DWBA for a deuteron pickup in the final step, in the case of (p,^{3}He), or α-knockout, as in the case of a (p, α) reaction. Figure 3 shows the contributions of the different steps in the multi-step treatment. The solid curves represent the sums of the contributions from the different steps to the cross section and analyzing powers. The results of these pre-equilibrium

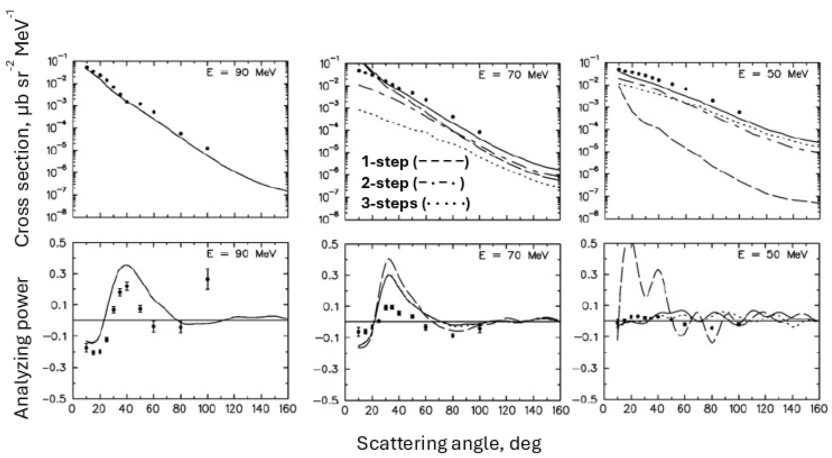

Figure 3. Double differential cross sections and analyzing powers as a function of scattering angle for the ^{59}Co(p,^{3}He) reaction at 100 MeV and various outgoing energies E. Theoretical cross section calculations for one step (- - -) two step (-·-·-), and three step (.....) are shown, with the sums of the contributions given as continuous curves. The experimental analyzing power distributions are compared with theoretical calculations for a one-step reaction (- - -), a one-step plus a two-step reaction (.....), and a one- plus two- plus three-step reaction (continuous curves) [15].

investigations were able to show how the various steps change with excitation energy. At low excitation (large emission energy) the first step tends to dominate, as is seen in the shapes of the analyzing power angular distributions. With increasing excitation, the higher order steps reduce the analyzing power to zero, washing out any information of the initial spin of the incoming proton. These studies clearly showed how sensitive the analyzing power distributions are to the reaction mechanism. It also showed that although it seems that the reaction mechanism responsible for the emission of single nucleons is understood as a progression of multistep nucleon-nucleon scattering interactions dominated by statistical considerations, the processes contributing to the emission of complex ejectiles such as ^{3}He and α particles are not as clear.

4 Knockout *vs.* Pickup

It has been shown in much of Anthony's research on the proton-induced emission of light composite particles like ^{3}He and α's how the analyzing power, which is a ratio of cross sections for different spin orientations, is much more sensitive to the specific reaction mechanism than the cross section [16], and does not suffer from some of the issues associated with the absolute magnitude of the cross sections. In the case of $(p,^3\text{He})$ and (p,α) reactions, the analyzing powers can be used to determine the relative contributions of knockout *vs.* pickup to the observables. In Figure 4 on the right the dominance of the knockout process in the analyzing power distributions for the $^{58}\text{Ni}(p,\alpha)$ reaction at 72 MeV is dramatic, whereas the pickup description even has the wrong sign. However, for the $^{93}\text{Nb}(p,\alpha)$ reaction at 65 MeV the distinction in the analyzing power for the two processes is not that clear. In both cases the cross sections show little sensitivity to the two descriptions. A further investigation of the (p,α) reaction at 100 MeV

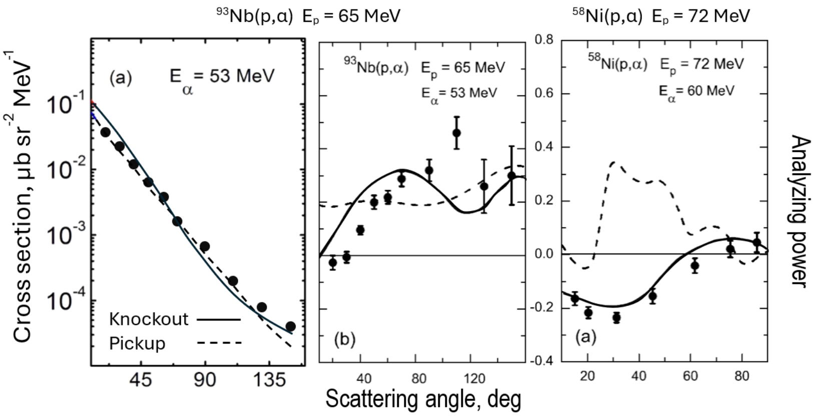

Figure 4. Cross section and analyzing power angular distributions for the $^{93}\text{Nb}(p,\alpha)$ reaction at 65 MeV (left) and analyzing power for the $^{58}\text{Ni}(p,\alpha)$ reaction at 72 MeV (right). The solid curves are for a knockout description and the dashed curves represent pickup calculations. The emission energies E_α are indicated [16].

also showed that pickup competes strongly with a knockout process [17], which is in strong contrast with the trend at both higher (160 MeV) and lower (65 MeV) incident energies where knockout appears to be overwhelmingly dominant. Anthony was able to successfully argue how the kinematic conditions for different orbital angular momentum transfers favor a particular reaction process which accounts for the incident energy dependence of the reaction mechanisms [16].

Up to now pre-equilibrium proton-induced particle emission reactions have been studied on relatively few target species. During the last few years of Anthony's life he was still very actively pursuing (p,α) reactions to determine how α-clustering on the surface of heavier nuclei change with increasing asymmetry in proton and neutron numbers, and how it affects the (p,α) pre-equilibrium reaction mechanism.

Conclusion

Anthony retired as a B1 rated scientist, according to the South African National Research Foundation's rating scheme. The international panel of reviewers all agreed that he enjoys "considerable international recognition for the high quality and impact of his recent research outputs", with some indicating that he was a "leading international scholar in the field". His many research contributions to direct knockout reaction mechanisms, the description of pre-equilibrium reactions and α-clustering in nuclei testify to the weight of his work. Anthony knew many prominent people, but remained humble about it. He loved telling me stories about everyone he knew. His value to nuclear physics throughout his five-decade career is immeasurable, as he did not only produce publishable outcomes, but affected the lives of many students and colleagues. I am proud to have known my lecturer, employer, supervisor and colleague as my friend. In fond memory of Professor Anthony Adverse Cowley.

Acknowledgements

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