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REFINEMENTS TO MULTISTEP DIRECT CALCULATIONS FOR INCIDENT ENERGIES UP TO 200 MEV[1]

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Extensive comparisons of multistep direct calculations for (p,p') inclusive reactions, based on the Feshbach, Kerman and Koonin theory, with data obtained with the open-sector cyclotron at the National Accelerator Centre, Faure, indicate that good general agreement is obtained for angular distributions up to incident energies of 200 MeV. However, some remaining discrepancies at very high and low emission energies require special consideration, and possible remedies are discussed.

1. Introduction

During the past few years many pre-equilibrium (p,p') cross-section measurements have been carried out at the National Accelerator Centre, Faure, South Africa employing the 200 MeV separated-sector cyclotron. Angular distributions and energy spectra have been measured for incident proton energies from 80 to 200 MeV on target nuclei with masses ranging from $A = 58$ to $A = 181$. For all the inclusive experimental measurements a simple detector telescope has been employed using standard $\Delta E - E$ particle identification techniques. The telescope consisted of an active collimator, one or more ΔE Si detectors and a NaI(Tl) photomultiplier. Details of the equipment and experimental techniques closely resemble those given in Refs. [1, 2, 3]. The overall systematic error in the cross-section data is considered to be less than 10%.

Multistep direct calculations have been carried out for all the nuclei involved using the Feshbach, Kerman and Koonin statistical multistep direct (MSD) reaction theory [4], employing the multistep direct reaction code of Bonetti and Chiesa [5]. The targets and incident energies used, and the references for the MSD calculations, are summarized in the following table:

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(p,p') EXPERIMENTS ON 200 MEV OPEN-SECTOR CYCLOTRON, NATIONAL ACCELERATOR CENTRE, FAURE

• Nov. 1989	^{90}Zr	$E_p = 80, 120$ MeV	PRC 43 (1991) 678
• Feb.– Aug. 1991	^{90}Zr ^{89}Y ^{92}Mo ^{94}Mo ^{96}Mo ^{98}Mo	$E_p = 120$, 160, 200 MeV	PRC 49 (1994) 1001
• May– Oct. 1992	^{115}In ^{141}Pr ^{167}Er ^{173}Yb ^{181}Ta	$E_p = 120$, 150, 175, 200 MeV	Submitted to PRC
• Also older data for MSD calcs:	^{58}Ni ^{100}Mo ^{197}Au	$E_p = 120$, 150, 175, 200 MeV	PRC 46 (1992) 1030

For the two-body interaction between the incident proton and the target nucleons, a simple short-range Yukawa (1 fm range) with an energy-independent interaction strength V_0 has been mostly used.

In general good agreement has been obtained between theoretical and experimental cross-sections for a wide range of target masses and incident and emission energies. Some typical results of the comparisons between experiment and theory are shown in Fig. 1.

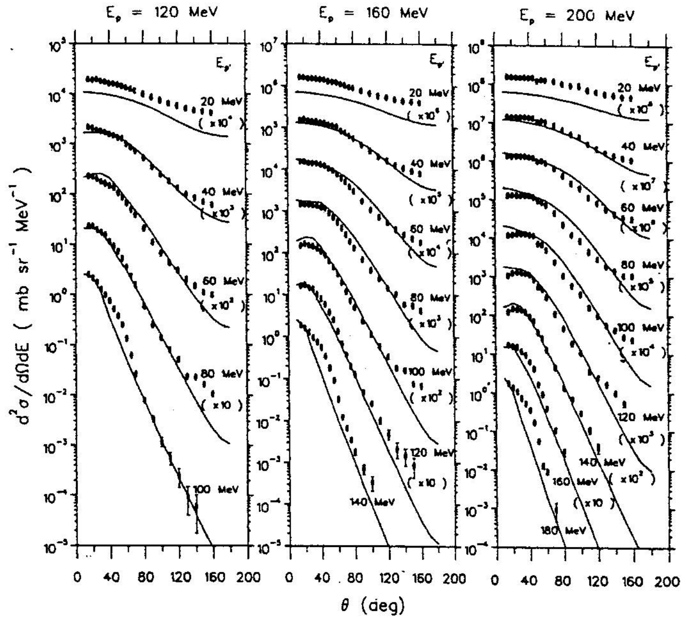

Fig. 1. Angular distributions for ^{89}Y(p,p') at incident energies E_p of 120, 160 and 200 MeV and various emission energies $E_{p'}$ [10]. Statistical error bars are shown where these exceed the symbol size. The curves are results of MSD calculations based on single-nucleon emission. Results are multiplied by the indicated factors for display.

It is evident that some systematic discrepancies are found particularly at very high and very low emission energies, where the theoretical predictions fall significantly below the experimental cross-sections. These are the most crucial aspects that will be focused on.

2. Possible refinements in the calculations

Since any multistep direct calculation is based on a number of assumptions and simplifying approximations, which could influence the accuracy of the calculations, it is necessary to consider the influence of these. Many of the parameters entering into a calculation have been investigated by the Stellenbosch University group and its collaborators. A list of important factors to consider follows, with references to recent discussions, mainly for (p,p') inclusive reactions in energy region 80 – 200 MeV.

1) The level densities assumed, usually expressed in terms of a level density parameter a, and a spin cut-off parameter σ [6].

2) Multiparticle emission, which contributes to the experimental cross-section, but is not considered explicitly in the theory [6, 7].

3) Collective effects, which are prominent at low excitation energies of the residual nucleus.

4) Sensitivity of the calculations to the optical model potential used [6].
5) The effect of distinguishing between protons and neutrons in the multistep chain [8].
6) The form of the two-body effective interaction employed [9, 6, 10].
7) Variations in the effective interaction strength for the various steps in the multistep cascade [11].
8) Possible transitions between the multistep direct (P) and multistep compound (Q) chains in sequential decay processes [12].
9) Multistep compound contributions at low emission energies [10].
10) Ad hoc factors included in MSD codes, e.g. 0.25 in the expression for the level density in the first step of the Bonetti code to simulate the effect of proton-neutron distinguishability [13, 8].
11) Sensitivity of calculations to the choice of particular single-particle states in the $p-h$ excitations [13].
12) Consistency between results calculated with different codes, e.g. the codes of Bonetti and Chiesa, Koning and Akkermans, and Chadwick and Young.

Of these, perhaps the most important to consider at present for energies up to 200 MeV, are multinucleon emission and the adequacy of the two-body nucleon-nucleon interaction adopted for multistep direct calculations. These will be considered in turn in the next two sections.

3. Multinucleon emission

The original formulation of the FKK theory [4] only takes into account the pre-equilibrium emission of one particle (primary pre-equilibium emission), whereas it is possible for a second accompanying nucleon (secondary pre-equilibium emission) to carry away some of the available energy and to leave the residual nucleus in a different state. Either one of the two emerging particles can be observed in the single detector employed in inclusive experiments. The emission of more than one particle in the pre-equilibrium energy region can originate from different mechanisms:

1. A fast direct knock-out process, where the incoming nucleon imparts enough energy for both nucleons to be emitted into the continuum.
2. A nucleon excited in a $p-h$ excitation process to a loosely bound excited state, may subsequently be emitted.
3. Finally, nucleons may also be emitted from the equilibrated compound nucleus.

None of these mechanisms are included in the standard FKK theory of multistep direct reactions, where energy is dissipated only by the excitation of one or more particle-hole excitations.

Mechanisms 1 and 3 are expected to play a role only at very high emission and very low emission energies respectively. The first mechanism has been discussed in Ref. [6]. The discrepancy between the FKK theory and experiment at low excitation energy ($\approx 20-40$ MeV) can possibly be explained in terms of a direct two-particle knock-out process. This is dealt with in a contribution at this conference by A.A. Cowley, and will not be discussed further. It is also evident that for the highest emission energy the shape of the angular distribution is not well reproduced by the theory. Hence it is not possible to normalize the theory at such a high emission energy, and we generally choose a V_0 value so that a good fit is obtained at about half the incident energy.

The second mechanism has been investigated by Chadwick *et al.* [7], and they have described an approximate procedure to estimate the contribution of two-nucleon emission to the primary double-differential cross-section. The basic input required for the multiple emission program consists of the primary double differential cross-sections calculated by some multistep direct (MSD) code. Since our cross-sections were calculated using the Milan code [5], this code was adapted to provide an input for the multiple emission programme of Chadwick *et al.* [7]. It is also necessary to provide double differential cross-sections for both neutron and proton emission since the secondary particle may be either type. However, the required (p,n) data to normalize the (p,n) angular distributions, i.e. choosing the appropriate V_0 value, is generally not available at the higher incident energies. Hence our strategy was to use some available (p,n) data in the energy region of interest, viz. at 160 MeV for a ^{90}Zr target nucleus [9, 14], to obtain $\frac{V_0(p,p')}{V_0(p,n)} = 1.1$, which can be used to estimate the (p,n) normalization from (p,p') data.

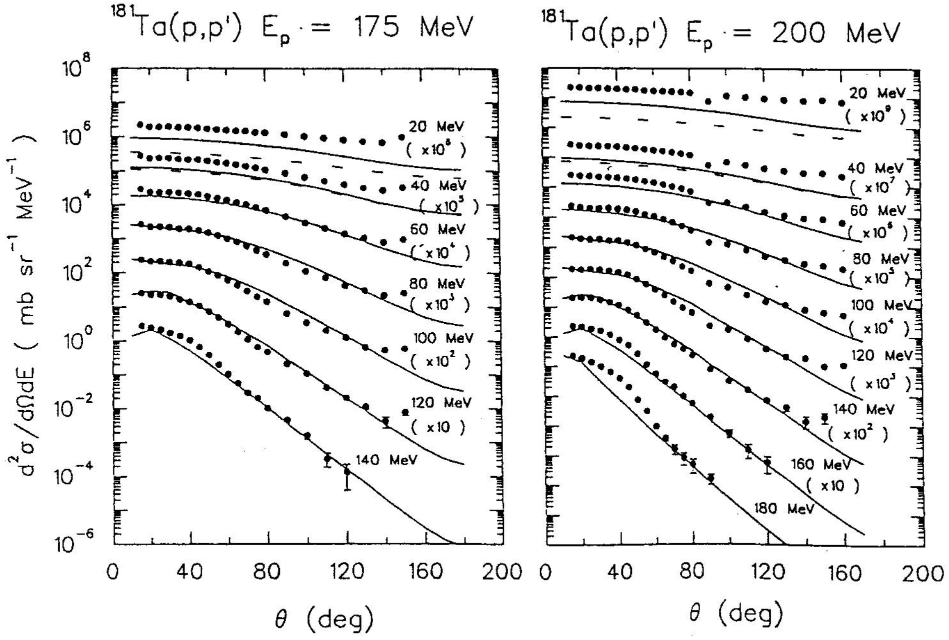

Fig. 2. Angular distributions for ^{181}Ta(p,p') at 200 MeV incident energy E_p and various emission energies $E_{p'}$. The same conventions are used as in Fig. 1. The dashed line corresponds to primary emission only and the solid line to primary emission plus two-nucleon emission.

The results for the nucleus ^{181}Ta are shown in Fig. 2. The experimental angular distributions for incident energies of 175 and 200 MeV are compared with the theoretical angular distributions, with and without the inclusion of two-nucleon emission. At an emission energy of 100 MeV the calculated correction for two-nucleon emission is almost negligible, and hence the V_0 value can be determined from a consideration of the primary emission of protons only.

It is evident that the inclusion of multinucleon emission is quite important for high excitation energies and forward angles. However, there is still a shortfall in the theoretical values by a factor 2-3 at the highest excitation energies. The amount of this discrepancy is very much dependent on the energy dependence assumed for the two-body effective interaction, as will be shown in the next section.

4. The two-body effective nucleon-nucleon interaction

It has been customary to assume a simple Yukawa force of 1 fm range, with effective interaction strength V_0, in studies of multistep direct interactions. The systematics of V_0, such as its energy dependence, has also been extensively studied [9, 6, 10].

In the cascade of nucleon-nucleon interactions in a multistep direct reaction, the incident projectile is continually losing energy as it progresses through the various stages (characterised by different $p-h$ excitations) of the multistep chain. As a result the strength of the effective interaction should be increased for decreasing energy, as previous studies have also shown. Fig. 3 shows calculations where an energy-dependent V_0 has been used. The solid line shows a theoretical calculation with a constant V_0, and the dashed line an exponential energy variation found previously [9] of

$$V_0 \propto \exp(-0.0049E).$$

The dotted line is based on a linear dependence, namely

$$V_0 = 18.2 - 0.048E,$$

with a slope chosen to approximate the energy variation of V_0 as found in recent calculations for the set of targets with $A = 115 - 181$.

As may be seen in Fig. 3, the specific choice of the energy dependence implies large uncertainties at low emission energies where the multinucleon contribution is largest. This uncertainty makes it difficult to draw a reliable conclusion about the adequacy of the calculated multinucleon contribution.

It is also evident that the convenient Yukawa interaction form has some limitations. In a study of analyzing power measurements in the $^{58}\mathrm{Ni}(\vec{p},p')$ in 1982, Bonetti *et al.* [15] showed that it is not possible to reproduce the magnitude and energy variation of the measurements without the inclusion of noncentral terms, such as spin-orbit and tensor terms, in the interaction.

6. Conclusions

It has been shown that multinucleon emission makes a significant contribution to inclusive (p,p') cross-sections for incident energies near 200 MeV, particularly at high excitation energies and forward angles. However, it has also been argued that uncertainty about the form of the effective two-body interaction to use, and in particular its energy dependence, makes it difficult to judge the accuracy of the two-nucleon emission calculations properly.

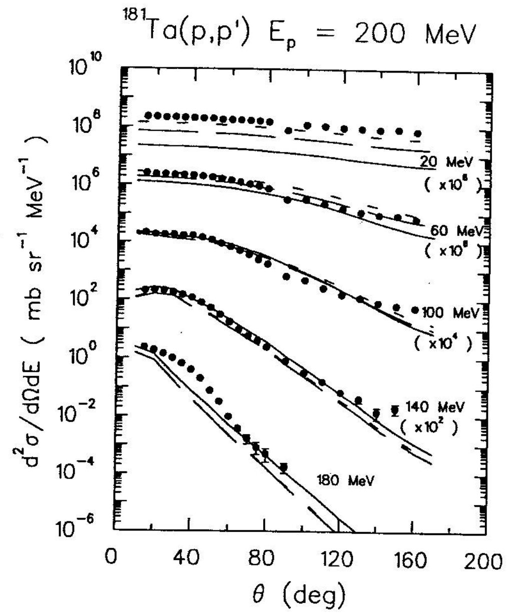

Fig. 3. Theoretical predictions with different functional forms of the energy dependence of the effective interaction in the multistep calculations. The solid line is a calculation with no energy dependence, the broken line an exponential energy dependence and the dashed line a linear energy dependence. See the text for the parameters used in the different forms.

It is clear that at the present stage of multistep direct calculations, a more realistic interaction form than a simple Yukawa potential is called for, which would also make possible the prediction of polarization observables such as the analyzing power. More stringent tests of the two-body effective interaction, which require a simultaneous fit of cross-sections and analyzing powers are required. Experiments employing the polarised beam facility of the 200 MeV open-sector cyclotron at the National Accelerator Centre, South Africa, are being planned with this goal in mind.

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References

[1] J.V. Pilcher, A.A. Cowley, D.M. Whittal, J.J. Lawrie: *Phys. Rev. C* **40** (1989) 1937

[2] A.A. Cowley, S.V. Förtsch, J.J. Lawrie, D.M. Whittal, F.D. Smit, J.V. Pilcher: *Z. Phys. A* **336** (1990) 189

[3] S.V. Förtsch, A.A. Cowley, J.J. Lawrie, D.M. Whittal, J.V. Pilcher, F.D. Smit: *Phys. Rev. C* **43** (1991) 691

[4] H. Feshbach, A. Kerman, S.Koonin: *Ann. Phys.* **125** (1980) 429

[5] R. Bonetti, C. Chiesa, MSD code, Milano University *(unpublished)*

[6] W.A. Richter, A.A. Cowley, R. Lindsay, J.J. Lawrie, J.V. Pilcher, S.V. Förtsch, R. Bonetti, P.E. Hodgson: *Phys. Rev. C* **46** (1992) 1030

[7] M.B. Chadwick, P.G. Young, D.C. George, Y. Watanabe: *Phys. Rev. C* **50** (1994) 996

[8] Y. Watanabe, M. Avrigeanu, W.A. Richter: Oxford laboratory report OUNP-93-30, 1993

[9] A.A. Cowley, A. van Kent, J.J. Lawrie, S.V. Förtsch, D.M. Whittal, J.V. Pilcher, F.D. Smit, W.A. Richter, R. Lindsay, I.J. van Heerden, R. Bonetti, P.E. Hodgson: *Phys. Rev. C* **43** (1991) 678

[10] W.A. Richter, A.A. Cowley, G.C. Hillhouse, J.A. Stander, J.W. Koen, S.W. Steyn, R. Lindsay, R.E. Julies, J.J. Lawrie, J.V. Pilcher, P.E. Hodgson: *Phys. Rev. C* **49** (1994) 1001

[11] W.A. Richter, S.W. Steyn, A.A. Cowley, J.A. Stander, J.W. Koen, R. Lindsay, G.C. Hillhouse, R.E. Julies, J.J. Lawrie, J.V. Pilcher, P.E. Hodgson: *Phys. Rev. C* **49** (1994) 1001

[12] M.B. Chadwick, P.G. Young: *Phys. Rev. C* **47** (1993) 2255

[13] *Multistep Direct Reactions (Ed. R.H.Lemmer).* World Scientific Co., Singapore 1992

[14] W. Scobel, M. Trabandt, M. Blann, B.A. Pohl, B.R. Remington, R.C. Byrd, C.C. Foster, R.Bonetti, C. Chiesa, S.M. Grimes: *Phys. Rev. C* **41** (1990) 2010

[15] R. Bonetti, L. Colli Milazzo, I. Doda, P.E. Hodgson: *Phys. Rev. C* **26** (1982) 2417