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THE USE OF EFFECTIVE INTERACTIONS IN PRE-EQUILIBRIUM REACTIONS[1]

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Most analyses of multi-step direct reactions, which are based on the FKK formalism, use a phenomenological nucleon-nucleon interaction of Yukawa form with a range of 1 fm to calculate the DWBA matrix elements. The overall strength of the interaction is then fairly arbitrarily normalized. The use of more realistic interactions has become common in recent years. In this paper, the use of such interactions in the FKK formalism will be discussed, and preliminary results shown. The more realistic M3Y interaction predicts larger cross sections compared to the simpler interaction. This result has important implications for the FKK description of pre-equilibrium processes.

1. Introduction

The Feshbach-Kerman-Koonin(FKK) formalism [1] has proved to be quite successful in describing (p,p') and (p,n) pre-equilibrium data during the last 10–15 years [2, 3, 4, 5, 6, 7, 8]. The multi-step direct analysis has been found to be acceptable up to an incident energy of 200 MeV, and an overall fit to the data seems to give a perhaps surprisingly good fit to the data considering the complicated processes involved and the relatively unsophisticated models used in the input.

Some of the important simplifying assumptions will be discussed in the next section as well as some of the remaining uncertain aspects of the application of the FKK theory. The importance of pinning down the interaction will be justified. In section 3 aspects of effective interaction relevant to pre-equilibrium analysis will be discussed and the results presented in section 4 with the conclusions given in the last section.

2. Assumptions used in the implementation of FKK analysis

Consider the expression for the first step in the FKK cross sections:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}U\mathrm{d}\Omega} = \sum_L (2L+1)\rho_n(U)R_n(L)\langle(\mathrm{d}^2\sigma/\mathrm{d}U\mathrm{d}\Omega)_{DW}\rangle_L \tag{1}$$

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where the DWBA differential cross section depends on

$$\int\int \chi^{(-)*}\langle\psi_p|V_{eff}|\psi_h\rangle\chi^{(+)}\mathrm{d}\mathbf{r}_a\mathrm{d}\mathbf{r}_b. \tag{2}$$

In this equation, L is the angular momentum transfer, $\omega(U, L)$ is the density of particle hole states and the other symbols have their usual meaning- see below and Ref. [8] chapter 7.

This expression has a sound theoretical justification, but the actual calculations based on it include the following simplifying assumptions, at least in the implementation in the Milan code [9] which has been used to analyse the extensive data measured at the National Accelerator Centre(NAC) in South Africa [2, 4, 5]:

(i) Simple shell model states are used to construct the particle-hole excitations, ψ_p and ψ_h above.

(ii) A level density parameter which is independent of any shell structure is used in ρ_n.

(iii) Global optical model potentials are used to calculate the distorted waves χ^+ and χ^-.

(iv) No distinction is made between protons and neutrons.

(v) Most calculations, including the Milan code [9], obtain the DWBA cross-sections by using DWUCK [10] which does not include exchange effects.

(vi) A Yukawa interaction with range 1 fm is used in the matrix element $\langle p|V_{eff}|h\rangle$ which provides the form factor for the DWBA calculation. This nucleon-nucleon (NN) interaction is based on purely phenomenological studies [11].

The first three assumptions may undoubtedly play a role in the accuracy of the fits, but it would be unlikely that they could hide a major problem. The same cannot be said of the last assumption. Should there be processes which are not included in the FKK formalism which contribute say 50% of the cross section, the scaling of V_0 may hide this. Or indeed if the FKK formalism is actually in error due to the matrix elements used in the multi-step part, as some physicists believe, the scaling of V_0 may compensate for this inadequacy. The extracted V_0 values are broadly in agreement with the values found in phenomenological inelastic scattering reactions [11] but, as will be argued below, this is not a very strong argument in view of the proton-neutron equivalence assumed.

Recent results of experiments at NAC [12, 13] and work by Chadwick *et al.* [6] have shown that unitarity considerations may imply that multiple emission may be substantially higher than expected. The total calculated (p, p') and (p, n) cross section in pre-equilibrium scattering alone, which fits the data, is very close to or even *greater* than the total reaction cross section as predicted by an optical model calculation. The use of an effective interaction which has been independently normalized will help a great deal in unravelling this and other similar issues.

3. Effective NN interactions

The purpose of the present paper is to consider more realistic effective NN interactions which have proved to be fairly accurate in predicting inelastic scattering data.

A large number of papers published during the last 20 years have looked at the correct NN effective interaction to use in predicting nucleon-nucleus elastic and inelastic scattering [14, 15, 16]. These studies are still continuing, but there has been notable agreement about the important components of the force.

The NN interaction can be written in different ways. The central part can be written in terms of of the spin-isospin exchange terms:

$$v_{eff}(r) = v_{00}(r) + v_{01}(r)\tau_1.\tau_2 + [v_{10}(r) + v_{11}(r)\tau_1.\tau_2](\sigma_1.\sigma_2) \tag{3}$$

where σ and τ refer to the spin and isospin of the different nucleons and $v_{i,j}$ corresponds to the spin(i) and isospin(j) exchange parts of the interaction. For theoretical calculations it is usually more convenient to rewrite this in terms of the singlet/triplet odd/even parameters [14], but it is easy to transform between the two descriptions [16, 17]. The full NN interaction also includes spin-orbit and tensor components.

There are broadly two ways in which effective interactions are constructed: Firstly, by fits to bound nucleon states (so-called G matrix techniques) [16] and secondly by looking at free NN scattering, the t-matrix approach [18]. At energies up to a 100 MeV, the former is more relevant, whereas the t-matrix approach is better justified at higher energies [14].

The different components of the force are often parameterized as the sum of three Yukawa interactions with different ranges. One of the first examples was the so-called M3Y interaction [16]. This interaction is purely real and seems to be applicable up to energies of about 100 MeV [14]. A well known parameterization at higher energy is the one by Love and Franey [18, 19]. The M3Y interaction will be used in the present work, since only scattering at less than 100 MeV will be considered. At incident energies above 100 MeV, the Love and Franey interaction will be applicable, although the lower energies that occur in the multi-step parts of the calculation, will have to be treated differently.

The usual way of performing the FKK analysis uses ONLY the v_{00} term parameterized as one Yukawa with a one fermi range. This was a common assumption at the time that the Milan group started coding the MSD theory. The strength of 28 MeV was used as a starting point attributed to Austin [11] and comparison to inelastic scattering [20]. Although this figure of 28 MeV is often quoted, it is interesting to note that Austin actually implied that it was dated and needed to be looked at again [11]. Furthermore, it is *not really the correct interaction to use, since v_{00} is of course NOT the only component of the effective interaction contributing to the particle hole excitations considered in an FKK analysis.* The $v_{\tau.\tau}$ term also plays a role since the projectile is interacting with a target nucleon. The v_{00} term is the only one to consider when looking at collective excitations when one expects more or less equal excitations of neutrons and protons. If one distinguishes between collisions with protons and neutrons in the target, then one certainly has to take the second term in eq. (3) into account [21].

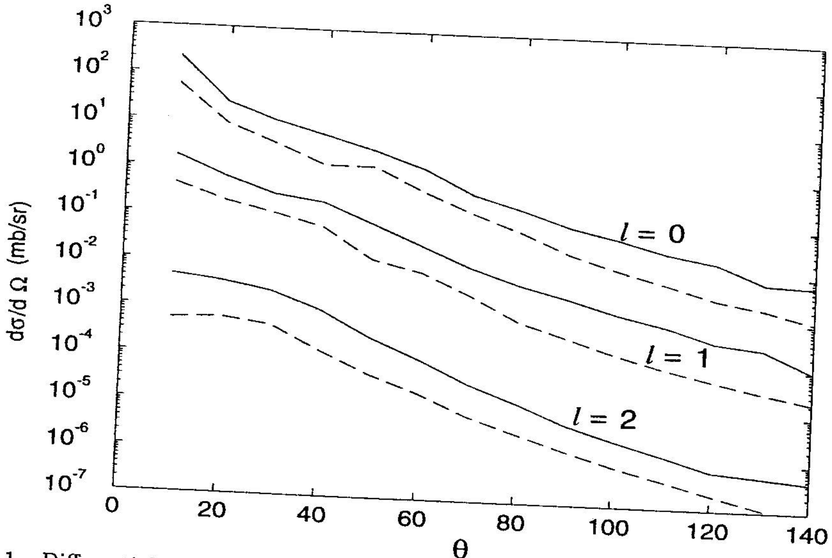

Fig. 1. Differential cross-sections for transitions between states in ^{90}Zr corresponding to angular momentum transfers of 0,1 and 2 calculated with the M3Y interaction (solid line) and the 1Y interaction(dashed line). The l=0 and l=1 values have been multiplied by 10^4 and 10^2 respectively.

To perform FKK calculations using a more complicated interaction is easier when one uses a program such as DW81 [22] which is adapted to accept the NN interaction as sums of Yukawa forms. The use of such effective interactions has several advantages over the simple single Yukawa shape:

(i) The central interaction is better in that v_{00} is not the only term used and the shape of v_{00} is more realistic.

(ii) The spin-orbit and tensor parts of the NN interaction can be included and studied.

(iii) The interaction is normalized by theory and its success in many other studies, hence any scaling needs to be justified.

(iv) The p-n, n-n and p-p interactions can be properly treated without the simplifying assumption of p-n indistinguishability. This point may seem minor, but in the Milan implementation of the FKK formalism, there are assumptions relating to the level densities built in which were not well described and which has led to much confusion and caused a difference in the strength of the extracted V_0's in the papers by Chadwick *et al.* [6] and papers based on the Milan code [23].

The use of a code such as DW81 [22] allows one to calculate the direct and exchange contributions to the cross-section.

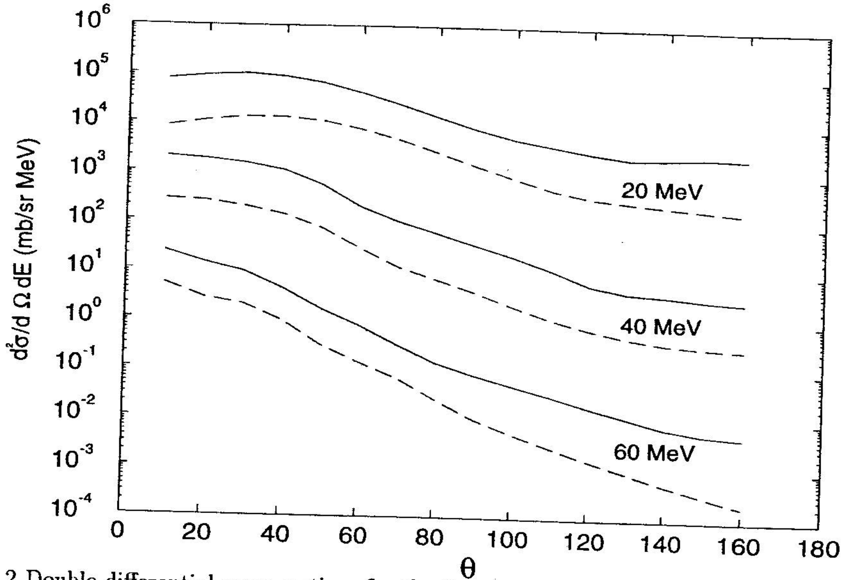

Fig. 2 Double differential cross sections for the first step calculations using the FKK theory with the M3Y interaction (solid line) and the 1Y interaction (dashed line). The different outgoing energies are indicated. The values have been multiplied by by 10^4 and 10^2 for E$'$=20 and 40 MeV respectively.

4. Results and discussion of calculations using a realistic effective interaction

The results of calculations using the M3Y interaction and the single Yukawa(1Y) interaction of strength 25 MeV and range 1 fm, that is usually used in FKK work, are compared in fig. 1.

The results for typical particle-hole excitations inducing l transfers of 0, 1 and 2 are shown. The calculations have been performed for (p,p') reactions on a ^{90}Zr target at an incident energy of 80 MeV. The particle-hole excitations were taken to be neutron excitations creating a target excited by 20 MeV.

The M3Y results include exchange contributions, but the 1Y results do not, since the strength of this interaction was essentially fixed including mainly the direct part.

A comparison of the predictions of the two interactions for all the different angular momentum and energy transfers shows a fairly wide spread of ratios between the two results. The ratio of the cross-sections is close to one in some cases, but the M3Y predictions are on average about 5 times the 1Y results for the excitation of neutron particle-hole states. The ratio is around 1.5 for proton particle hole states. This reflects the well known dominance of the proton-neutron over the proton-proton interaction [11]. The first step MSD prediction is shown for neutron target states in fig. 2, where only the creation of neutron particle-hole states have been considered.

There are a number of possible improvements to these calculations as will be discussed below. However, the results found thus far indicate that a substantially *larger* cross section is predicted by the M3Y interaction. The 80 MeV (p,p') data was fitted in Ref. [2] where a reduction in the strength of the 1Y interaction from 28 to 23 MeV was found to be needed to fit the data. The M3Y interaction thus substantially over-predicts the data.

There are a number of possible reasons that need to be looked at to confirm these preliminary results, e.g.:

(i) The M3Y interaction, which is energy and density independent, may perhaps not be as good as assumed. Most work on effective interactions have concentrated on the t-matrix approach and has looked at proton scattering above 100 MeV. The M3Y interaction has been widely used, especially in producing double folded potentials for heavy-ions where only part of the interaction is tested. FKK analyses have in general found an energy dependent strength which follows the optical model description [8]. Other interactions such as the one developed by Amos and collaborators [24, 25] should be tried.

(ii) Other parameters in the model such as the level density may be in error. Both proton and neutron level densities can now be considered. The exact level densities used were not so crucial in the past, since errors in the level densities were compensated by the rescaling of the effective interaction strength.

(iii) The most crucial problem may be the choice of possible particle/hole states. The usual procedure has been to choose combinations that will lead to bound particle states, even when the usual well depth of around 50 MeV has to be made deeper to make sure that the particle is bound. Inclusion of these artificial states may cause an over-estimation of the predicted cross sections.

5. Conclusions and future work

This work has shown that calculations based on a more realistic effective nucleon-nucleon interaction leads to predictions of larger cross sections compared to the phenomenological effective interaction usually employed in practical application of the FKK theory.

This result still needs to be further investigated to look at other effective interactions, the proper treatment of protons and neutrons and the choice of particle hole combinations.

References

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

[2] 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

[3] 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

[4] 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

[5] 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

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

[7] R. Bonetti, A.J. Koning, J.M. Akkermans, P.E. Hodgson: *Phys. Rep.* **247** (1994) 1

[8] E. Gadioli and P.E. Hodgson: *Preequilibrium Nuclear Reactions* Clarendon Press, Oxford 1992

[9] R. Bonetti, C. Chiesa: MSD code, University of Milan *(unpublished)*

[10] P.D. Kunz and E. Rost *Computational Nuclear Physics 2*, ed. K Langanke *et al.*, Chapter 5 Springer Verlag 1993

[11] S.M. Austin:*Proceedings Conference on (p,n) reactions and ..., Telluride, Colorado* Plenum Press N.Y. 1980, p. 203

[12] W.A. Richter, A.A. Cowley, S.W. Steyn, J.A. Stander, J.W. Koen, R. Lindsay, G.C. Hillhouse, R.E. Julies, J.J. Lawrie, J.V. Pilcher, P.E. Hodgson: *submitted to Phys. Rev. C*

[13] A.A. Cowley: *private communication*

[14] W.G. Love: *Proceedings, Conference on (p,n) reactions and ..., Telluride, Colorado* Plenum Press, N.Y. 1980, p 29

[15] J.J. Kelly, J.M. Finn, W. Bertozzi, T.N. Buti, F.W. Hersman, C. Hyde-Wright, M.V. Hynes, M.A. Kovash, . Murdock, P. Ulmer, A.D. Bacher, G.T. Emery, C.C. Foster, W.P. Jones, D.W. Miller, B.L. Berman: *Phys. Rev. C* **41** (1990) 2504

[16] G. Bertsch, J. Borysowicz, H. McManus, W.G. Love: *Nucl. Phys. A* **284** (1977) 399

[17] N.K. Glendenning: *Direct Nuclear Reactions* Academic Press, 1983, Chapter 9

[18] W.G. Love, M.A. Franey: *Phys. Rev. C* **24** (1981) 1073

[19] M.A. Franey, W.G. Love: *Phys. Rev. C* **31** (1985) 488

[20] R. Bonetti, L. Colombo: *Phys. Rev. C* **28** (1983) 980

[21] P. Demetriou, P.E. Hodgson, A. Marcinkowski, Y. Watanabe: *in preparation*

[22] R Schaeffer, J. Raynal: *Program DWBA70. (unpublished)*; J.R. Comfort: *Extended version DW81. (unpublished)*

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

[24] P.J. Dortmans, K. Amos: *Phys. Rev. C* **49** (1994) 1309

[25] S. Karataglidis, P.J. Dortmans, K. Amos, R de Swiniarski: *Phys. Rev. C* **52** (1995) 861