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THE PRE-EQUILIBRIUM MULTISTEP DIRECT
FESHBACH-KERMAN-KOONIN THEORY

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Analysis of the (p, α) Reaction using the Pre-Equilibrium Multistep Direct Feshbach-Kerman-Koonin Theory

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Abstract

The Feshbach-Kerman-Koonin theory of multistep pre-equilibrium reactions has been used to analyse the (p, α) reaction at incident energies of 30 and 44.3 MeV on several nuclei. It is assumed that the reaction takes place by the direct knockout of a preformed alpha-particle bound in a shell model state of the core. Zero-range, Gaussian and Yukawa forms are used for the proton-alpha interaction and several parameter sets for the proton and alpha-particle optical potentials. The theory is able to fit the data at the higher emission energies, and most of the remaining cross-section is attributable to compound nucleus emission. There is little evidence for multistep compound emission.

1. Introduction

In 1980 Feshbach, Kerman and Koonin (FKK) published a fully quantum-mechanical theory for calculating the double differential cross sections of pre-equilibrium particle (or particle cluster) emission from nuclei (Feshbach *et al* 1980). The theory considers the reaction as a series of two-body interactions between the projectile and the target nucleons. The reaction thus proceeds from very simple configurations to more complex ones with the creation of particle-hole pairs at each stage, and emission can take place from any stage. The reaction is divided into the multistep compound (MSC) and the multistep direct (MSD) processes. All the particles in the MSC reaction are bound, whereas in the MSD reaction at least one particle is unbound. The MSC reaction cross section is symmetric about 90° , whereas the MSD cross section is forward-peaked even at low incident energies. The total reaction cross section is the sum of contributions from both processes and from the decay of the fully equilibrated compound nucleus.

The FKK theory has been applied to calculate both the angle-integrated and the double differential cross sections of pre-equilibrium nucleon emission from nuclei by the (n, n') , (n, p) , (p, p') and (p, n) reactions. The details of the formalism have been described by Bonetti *et al* (1991, 1994) and by Gadioli and Hodgson (1992). In general the angular and energy distributions of the ejectile are well reproduced by adjusting the only free parameter, the strength of the effective interaction between the projectile and the target nucleons.

Though many studies have been made of nucleon reactions using the FKK formalism, it has been applied to cluster emission from nuclei only by Bonetti *et al* (1984) for $^{90}\text{Zr}(\alpha, \alpha')$ scattering, and by Bonetti *et al* (1989) to the differential cross-sections and analysing powers of the $^{58}\text{Ni}(p, \alpha)$ reaction.

The purpose of this work is to apply the FKK theory to nucleon-induced pre-equilibrium alpha emission from medium-heavy and heavy nuclei. There are very few measurements of $(\text{nucleon}, \alpha)$ reactions at both low and high energies. The two most comprehensive are those of Watanabe *et al* (1987) of (p, α) cross sections on several nuclei at 15 and 18 MeV and those of Fererro *et al* (1978) of (p, α) cross sections for several nuclei at various incident energies between 20 and 44 MeV. We have analysed the Fererro data at 30 and 44.3 MeV because at this incident energy there is a wide outgoing energy region where the pre-equilibrium contribution is dominant.

In this analysis it is necessary to distinguish between the MSD, the MSC and the fully-equilibrated compound nucleus contributions. Inspection of the data at 44.3 MeV incident energy shows that most of the alpha-particles with energies higher than 20 MeV are emitted in the forward direction and are therefore due to the MSD reaction. Since both the MSC and compound contributions are symmetric about 90° in the centre of mass system, the contribution due to MSD can be determined by subtracting the backward angle cross sections from the complementary forward angle cross-sections in the centre of mass system. This forward excess is due to the MSD reaction, and may therefore be analysed using the MSD theory. The strength of the nucleon-nucleon MSD effective interaction has been determined recently by Demetriou *et al* (1993) for several nuclei using this subtraction method. In the next section we briefly review the MSD theory with particular reference to its application to (N, α) reactions, and justify our choice of the knock-out mechanism. The results of the analysis of the experimental data are given in Section 3 and our conclusions in Section 4.

2. The MSD formalism for the $(\text{nucleon}, \alpha)$ reaction

The FKK MSD formalism has been described by Feshbach *et al* (1980) and by Bonetti *et al* (1984) so here we give just a brief discussion related to the (N, α) reaction. The cross-section for emission of the alpha-particle at the first stage of

the interaction is

$$\frac{d^2\sigma^{(1)}(\vec{k}_f, \vec{k}_i)}{dU d\Omega} = \sum_L \rho_n(U_1) R_n(L) \left\langle \left[\frac{d\sigma}{d\Omega} \right]_L^{DW} \right\rangle \quad (1)$$

where n is the number of excitons due to this first interaction, $\rho_n(U_1)$ is the density of states in the residual nucleus whose excitation energy is U_1 and $R_n(L)$ is the angular momentum distribution.

$$R_n(L) = \frac{(2L+1)}{\sqrt{\pi}(2\sigma)^3} \exp\left(-\frac{(L+\frac{1}{2})^2}{2\sigma^2}\right) \quad (2)$$

The spin cut-off parameter σ^2 is taken to be $0.24 n A^{\frac{2}{3}}$ (Gruppelaar, 1983). The term within the angular brackets in equation (1) is the DWBA cross section averaged over the different possible p-h configurations for each angular momentum transfer. The DWBA cross section was calculated using a modified version of the program DWUCK4 (Kunz, 1973) treating the nucleons as spinless particles.

In the case of the nucleon inelastic MSD reaction, the projectile is assumed to remain in the continuum while it excites proton and neutron p-h pairs from the Fermi sea and the number of excitons at each stage is taken to be two. In the charge exchange reaction the projectile is captured into a shell model state of the nucleus and at the same time the ejectile is knocked out. Similarly, in the (nucleon, α) reaction the nucleon can either pick up a triton from the nucleus or be captured into a shell model state and at the same time knock out an alpha particle.

Several authors have analysed the (N, α) reaction that leaves the effective nucleus in low energy discrete states (Gadioli *et al* 1982, 1984, 1986; Smits and Siemssen 1976) and on the whole they have achieved greater success with the pick-up model than with the knock-out model. There have been rather few analyses of (N, α) reactions to continuum states. Dragun *et al* (1981) used the pick-up model to fit the same data as we analyse and ignored the possibility of contributions from the knock-out process. Tamura *et al* (1981, 1982) fitted the differential cross-sections and analysing powers for the (p, α) reaction on ^{93}Nb at 65 MeV using the pick-up model but did not consider the knock-out model. The only analysis of both differential cross-sections and analysing powers using both the pick-up and the knock-out models is that of Bonetti *et al* (1989). They found that the (p, α) reaction on ^{58}Ni to discrete states is better fitted by the pick-up model, and that to the continuum is better fitted by the knock-out model. In particular, the sign of the analysing power indicates the knock-out model, and this is why we use it in the present analysis. This choice is strengthened by studies showing that surface nucleons are likely to coalesce to form alpha-particles (Hodgson, 1994). Thus Bonetti *et al* (1984) found a better fit to the data on $^{90}\text{Zr}(\alpha, \alpha')$ scattering when they assumed that there are alpha clusters at the surface of the nucleus. Extensive studies by Buck, Merchant and Perez (1990, 1992) have provided further evidence for the alpha cluster model.

In this analysis we therefore assume that the target consists of a core to which an alpha cluster is bound in a shell model state. The projectile is captured into

a state of the effective nucleus and at the same time the alpha particle is ejected through a effective nucleon-alpha interaction.

The alpha cluster is composed of correlated pairs of protons and neutrons from states near the alpha Fermi level. The alpha Fermi energy was taken to be equal to the sum of the four nucleon Fermi energies plus the binding energy of an alpha-particle, and the nucleons were assumed to occupy harmonic oscillator shell model states. The principal quantum number, N , the orbital angular momentum quantum number, L , and the binding energy of the alpha were determined from the quantum numbers (n_i, l_i) and the binding energies of the cluster nucleons. Assuming the nucleons to be in relative S quantum state the quantum numbers of the alpha were determined from harmonic oscillator energy conservation,

$$2(N - 1) + L = \sum_{i=1}^4 2(n_i - 1) + l_i. \quad (3)$$

The transition amplitude for such a knock-out interaction $A(p, \alpha)B$ is given by

$$T_{KO} \propto \int \chi_{\alpha}^{(-)*}(\vec{r}_{\alpha}) \phi_p^*(\vec{r}_p) V_{p\alpha}(\vec{r}_{p\alpha}) \phi_{\alpha}(\vec{r}_{\alpha}) \chi_p^{(+)}(\vec{r}_p) d\vec{r}_{\alpha} d\vec{r}_p \quad (4)$$

where $\phi_{\alpha}(\vec{r}_{\alpha})$ and $\phi_p(\vec{r}_p)$ are the wave functions of the alpha-particle and proton bound states, and $\chi_{\alpha}(\vec{r}_{\alpha})$ and $\chi_p(\vec{r}_p)$ are the distorted waves of the alpha particle and proton respectively and $V_{p\alpha}(\vec{r}_{p\alpha})$ the proton-alpha interaction. The differential cross-section is related to the transition amplitude

$$\frac{d\sigma(\theta)}{d\Omega} \approx \sum_{M_A M_B m_a m_b} |T_{KO}^{M_A M_B: m_a m_b}|^2 \quad (5)$$

and these calculations are performed by DWUCK4 (Kunz, 1973). The final expression for the DWBA cross-sections for a given p-h configuration is given in terms of the orbital angular momentum transfer L by

$$\begin{aligned} \frac{d\sigma^{DW}}{d\Omega}(\{n_i\}^4, N, L) &= \frac{2J_B + 1}{2J_A + 1} \frac{1}{2L + 1} \mathcal{N} G^2(\{n_i\}^4) \\ &\times \frac{d\sigma^{DWUCK4}}{d\Omega}(\{n_i\}^4, N, L) \end{aligned} \quad (6)$$

where $\{n_i\}^4$ represents all possible combinations of the four nucleons forming the alpha-cluster and the last factor is the output of DWUCK4 which determines the form of the above expression. The factor $\mathcal{N}$ corresponds to the square of the fractional parentage coefficient for the dissociation of the target nucleus into a core plus an alpha-cluster and is absorbed into our adjustable parameter W_0 which determines the magnitude of the cross-section. The square of the parameter W_0 is defined as the product of $\mathcal{N}$ and the square of the strength V_0 of the effective p- α interaction and therefore contains the uncertainties involved in determining both these quantities. $G(\{n_i\}^4)$ is the spectroscopic factor for the transition of a $\{n_i\}^4$ alpha bound-state corresponding to orbital and total angular momentum transfer

L, J and was calculated explicitly by the method of Ichimura *et al* (1973). J_B and J_A are the total angular momenta of the target and effective nuclei respectively. The system was taken to consist of an excited nucleon-particle and alpha-hole pair.

The density of the alpha particle-hole states was taken to be $g_a = \frac{1}{4}g$, where g is the single particle level density for a nucleon. If another value is used, this just scales the adjustable parameter W_0 . The incoming nucleon is captured into states above the nucleon Fermi level or into a state just vacated by a similar nucleon in the alpha cluster. The binding energies were used to fix the depth of the real Saxon-Woods potential binding the particle and the geometrical parameters of the potential were taken to be $r_0 = 1.25$ fm and $a = 0.6$ fm. Three forms were used for the effective proton-alpha interaction, the zero-range, the Gaussian with range 1.7 fm and the Yukawa with range 1 fm.

We include in our calculations the contribution due to two-step emission by the $(p, p')(p', \alpha)$ process which is smaller than that from the first step by two orders of magnitude. This is in accord with the results of Bonetti *et al* (1989). At higher energies the two-step processes become increasingly important (Tamura *et al*, 1977, 1982)

Ferrero *et al* (1978) could not discriminate against ^3He in the data. They however estimated that the contribution from $(p, ^3\text{He})$ is less than 10%, so we have not included this contribution in this calculation. Since ^3He has very small binding energy compared with an alpha particle, it is very likely to be produced by deuteron pickup.

The analysis requires alpha-particle optical potentials from about 10 to 50 MeV. We use the potential of Avrigeanu *et al* (1994), obtained by extending to lower energies the potential of Nolte *et al* (1987), and also that of McFadden and Satchler (1966) at 24.7 MeV and of Kumabe *et al* (1974). The results are also sensitive to the proton potentials, and we use those of Perey (1963), Barrett *et al* (1965) and Menet *et al* (1971). Compound nucleus emission cross-sections were evaluated using the code STAPRE (1976).

3. Results

The experimental data were transformed into the CM frame as described by Demetriou *et al* (1993) and the cross sections at backward angles subtracted from those at the complementary angles in the forward direction. The calculated forward excess was then fitted to the experimental forward excess by adjusting the parameter W_0 . This was done using the optical potentials of Perey (1963) and of Avrigeanu *et al* (1994) for the proton and alpha-particle respectively, and three forms of the effective proton-alpha interaction : zero-range, Gaussian of range 1.7 fm (Batty *et al* 1971) and Yukawa of range 1 fm (Jackson and Kembhavi, 1969). Some typical results are shown in Fig. 1 and the values of W_0 for all calculations are given in Table 1 (only statistical errors are included; in addition, the systematic errors are estimated to be about 20%). For each reaction, the values of W_0 for each pair of complementary angles should be the same and this may be assessed

Figure 1a. Subtracted double differential cross-sections for the (p, α) reaction at 30 MeV (Ferrero *et al* , 1978) for several nuclei compared with similarly-subtracted zero-range MSD FKK calculations using the alpha-particle knock-out model.

Figure 1b. Subtracted double differential cross-sections for the (p, α) reaction at 44.3 MeV (Ferrero *et al.*, 1978) for several nuclei compared with similarly-subtracted zero-range MSD FKK calculations using the alpha-particle knock-out model.

Table 1. Values of the adjustable parameter W_0 for various nuclei, angle-pairs and interactions at $E_p = 30$ and 44.3 MeV obtained by the subtraction method. The indicated uncertainties are statistical only.

$E_p = 30$ MeV					
angles($^\circ$)	30-150	45-135	60-120	$W_{0average}$	Interaction
^{93}Nb	58	76	100	70 ± 10	Zero-range
	166	207	177	178 ± 12	Gaussian
	330	410	529	378 ± 44	Yukawa
^{107}Ag	72	93	137	84 ± 12	Zero-range
	260	323	280	281 ± 19	Gaussian
	459	519	600	518 ± 41	Yukawa
^{118}Sn	84	75	116	83 ± 6	Zero-range
^{169}Tm	61	75	100	71 ± 9	Zero-range
$E_p = 44.3$ MeV					
angles($^\circ$)	30-150	45-135	60-120	$W_{0average}$	Interaction
^{93}Nb	49	64	88	60 ± 8	Zero-range
	115	177	196	143 ± 25	Gaussian
	246	348	600	347 ± 88	Yukawa
^{118}Sn	61	70	88	67 ± 6	Zero-range
	172	247	284	210 ± 31	Gaussian
	319	401	573	375 ± 53	Yukawa
^{165}Ho	70	100	110	83 ± 11	Zero-range
	364	636	737	517 ± 70	Gaussian
	332	449	647	400 ± 63	Yukawa
^{169}Tm	50	77	90	54 ± 6	Zero-range
	270	424	598	335 ± 70	Gaussian
	299	301	555	329 ± 51	Yukawa

by the quality of fit of the curves in Fig.1 that are obtained from the average value of W_0 for each set of angle pairs. The differences between theory and data are discussed below. There is some excess cross-section at the higher emission energies attributable to direct reactions to discrete final states; these are not included in the theory and so we do not expect to fit the data in this region.

The sensitivity of the results to the proton and alpha-particle optical potentials is indicated by energy and angular distributions shown in Figs. 2 a) and b). The differences are substantial, indicating the great importance of accurate alpha-particle and proton potentials.

The results of calculations with different forms of the proton-alpha interaction are shown in Fig.3. The fits are of comparable quality, although of course the values of W_0 are different. This parameter W_0 , which determines the overall normalisation of the cross-section, is the product of the fractional parentage coefficients for all possible configurations $\{n_i\}^4$ and the strength V_0 of the effective proton-alpha interaction, and also absorbs other uncertainties in the model such as those in the level density and optical model parameters. The value of V_0 has been found to be about 50-70 MeV by several folding model analyses of alpha-particle elastic scattering (Batty *et al* 1971; Jackson 1964, 1970; Jackson and Morgan 1968), but an absolute calculation of the fractional parentage coefficients requires a more detailed analysis of the reaction and we are thus not able to make a direct comparison of our results for W_0 with other analyses.

The MSD calculations are compared with angle-integrated cross-sections in Figs. 4 a) and b). On the whole these energy spectra are well-fitted at the higher alpha-particle energies with the average values of W_0 obtained from the analysis of the double differential cross-sections. The excess cross-section at lower energies is attributable to the MSC and compound nucleus processes. The peak around 15 MeV is largely attributable to compound nucleus processes, so the cross-sections of all such alpha-emission reactions were calculated and the results are included in the Figures. In most cases the total compound nucleus cross-section from all alpha-emitting reactions was similar to the experimental data; to facilitate comparisons the calculated cross-sections were normalised to the peak in the data at about 15 MeV. The sum of the MSD and the compound nucleus cross-sections is in overall agreement with the data except perhaps around 25 MeV, where shortfalls may indicate MSC contributions.

The MSD and compound nucleus cross-sections are compared with the angular distributions for selected emission energies in Figs. 5 a) and b). The sum of the MSD and compound nucleus cross-sections generally agrees well with the data at the lowest emission energies but falls short thereafter. This may be due to the MSC emission and assuming that this is the case the MSC contributions were estimated and the results gave an energy distribution consistent with the shortfall around 25 MeV, thus confirming the identification as MSC.

Figure 2a. Subtracted double differential cross-sections for the (p, α) reaction at 30 MeV (Ferrero *et al* , 1978) compared with similarly-subtracted zero-range MSD FKK calculations using the alpha-particle knock-out model with three different alpha-particle potentials and three different proton potentials.

Figure 2b. Angular distributions of the (p, α) reaction at 30 MeV (Ferrero *et al* , 1978) compared with zero-range MSD FKK calculations with three different alpha-particle potentials and three different proton potentials.

Figure 3. Subtracted double differential cross-sections for the (p, α) reaction at 30 and 44.3 MeV (Ferrero *et al* , 1978) for several nuclei compared with similarly-subtracted MSD FKK calculations using the alpha-particle knock-out model with three different proton-alpha interactions.

Figure 4a. Angle-integrated cross-sections for the (p, α) reaction at 30 MeV (Ferrero *et al* , 1978) compared with zero-range MSD FKK and compound nucleus calculations.

Figure 4b. Angle-integrated cross-sections for the (p, α) reaction at 44.3 MeV (Ferrero *et al* , 1978) compared with zero-range MSD FKK and compound nucleus calculations.

Figure 5a. Angular distributions of the (p, α) reaction (Ferrero *et al* , 1978) compared with zero-range MSD FKK calculations for several nuclei at $E_p = 30$ MeV and outgoing energies compared with zero-range MSD FKK and compound nucleus calculations.

Figure 5b. Angular distributions of the (p, α) reaction (Ferrero *et al* , 1978) compared with zero-range MSD FKK calculations for several nuclei at $E_p = 44.3$ MeV and outgoing energies compared with zero-range MSD FKK and compound nucleus calculations.

4. Conclusions

We have analysed the cross-sections of the (p, α) reaction to the continuum at 30 and 44 MeV on ^{93}Nb , ^{107}Ag , ^{118}Sn , ^{165}Ho and ^{169}Tm using the alpha-particle knock-out model. The multistep direct component is extracted using the subtraction method and compared with calculations using the Feshbach-Kerman-Koonin theory. The cross-sections are compared with the zero-range, Gaussian and Yukawa forms of the proton-alpha effective interaction.

The compound nucleus cross-section is also evaluated and added to the MSD cross-section for comparison with the angle-integrated data. There is a slight shortfall at intermediate alpha-particle energies that may indicate the presence of a small MSC component. Comparison is also made with the angular distributions for selected outgoing energy ranges.

Some satisfactory fits are obtained with optical potentials obtained from elastic scattering data. (It may be noted that Dragun *et al* were able to fit the data with the pick-up model only by reducing the value of the absorbing potential W from 22.3 to about 6 MeV). In other cases, however, the fits are rather poor. In view of the sensitivity to the optical potentials shown in Figs. 2 a) and b) this may be due to our use of proton and alpha-particle potentials obtained in most cases from analyses of scattering from other nuclei at other energies. It is thus likely that further progress can come only by using potentials fitted to the scattering data for each nucleus analysed, and at the required energies. Additional uncertainty is introduced by lack of knowledge of the proton-alpha interaction.

Our values of the parameter W_0 in Table 1 depend on those of the other parameters in the calculations. Some, like those of the optical potentials, are fixed by other data. Others, like the alpha-particle pre-formation and level density parameters, have assigned values, and so if they change, then so will the value of W_0 , since comparison with data only determines their product.

Thus at present the knock-out and pick-up models give comparable fits to the data, and any differences between them are less than the uncertainties attributable to the optical potentials. It is quite likely that both processes contribute, but this can only be established by detailed analyses of more cross-sections and especially of analysing powers.

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