acta physica slovaca vol. 45 No. 6, 749 – 756 December 1995

APPLICATIONS OF THE FESHBACH-KERMAN-KOONIN MODEL TO (p,p') REACTIONS AT LOW INCIDENT ENERGIES[1]

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Received 23 October 1995, accepted 27 October 1995

The Feshbach-Kerman-Koonin theory is applied to analyses of (p,p') reactions on ^{93}Nb, ^{98}Mo and ^{106}Pd at incident energies ranging from 12 to 26 MeV. The subtraction method is used to isolate the multistep direct (MSD) component and analyze it alone. It is found that there is a rather strong dependence of the strength V_0 of the effective N-N interaction on incident energy compared with (n,n') reactions. The multistep compound (MSC) and Hauser-Feshbach (HF) formulas are extended so that the isospin can be introduced as a conserved quantum number. The experimental data are reproduced quite well by the quantum-mechanical calculation including MSD and MSC emission, direct collective excitation to low-lying discrete levels, and HF equilibrium emission.

1. Introduction

The multistep reaction theory of Feshbach-Kerman-Koonin (FKK) [1] has been used to analyze data on nucleon-induced reactions both from the aspects of basic and applied nuclear physics [2, 3, 4]. It has been found that the FKK model calculation fits various experimental data well by adjusting some model parameters, especially the strength V_0 of the effective N-N interaction. Inclusive emission spectra observed in the low energy experiments show the superposition of contributions from various possible reaction processes: multistep direct (MSD), multistep compound (MSC), collective(COLL), and compound nucleus (CN) processes. It is therefore desirable to separate those processes and analyze each process in order to find a consistent set of the model parameters. Some analyses based on such methodology have recently been made toward a goal to describe the whole nucleon emission spectra for nucleon-induced reactions [5, 6, 7].

In this work, our attention is paid to (p,p') reactions on medium-heavy nuclei at energies ranging from 12 to 26 MeV. So far, fewer FKK model analyses [8] of the (p,p')

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[1] Presented at the International Symposium on Pre-Equilibrium Reactions, Smolenice Castle, 23 – 27 October, 1995

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data at such low energies have been made than those of the (*n*,*n*') and (*p*,*n*) data. One of the features of the (*p*,*p*') reactions at low energies is that isospin as a conserved quantum number plays an essential role in the formation and decay of the compound nucleus by the isospin selection rule [9, 10, 11, 12, 13, 14]. Thus, some of the (*p*,*p*') data are analyzed again using the modified version of the code FKK-GNASH [15], with particular attention to isospin effects in MSC and CN processes. Also, systematics of the V_0 values used in the MSD calculation are discussed in comparison between (*n*,*n*') and (*p*,*p*').

2. Analysis with the FKK model

2.1. Multistep direct process and collective excitation

According to the FKK model, the one-step MSD process is known to contribute predominantly in the nucleon-induced reactions at incident energies lower than 30 MeV [8, 15]. So, the multistep MSD components are not included in the present analysis. We use the subtraction method [6] to isolate the MSD component from the continuum spectrum and analyze it using the one-step FKK-MSD model. It should be noted that the subtracted component may contain collective contributions to the continuum [5, 7]. As for collective excitations, however, only strong low lying collective states (the first 2^+ and 3^- for even-even nuclei) are taken into account using the macroscopic DWBA method with the experimental deformation parameters as in ref. [8]. In such a way, we can determine the strength V_0 of the effective *N*-*N* interaction assuming a Yukawa potential of range 1 fm. All the parameters used in the one-step MSD calculation have been summarized elsewhere [8].

2.2. Multistep compound and compound nucleus processes

The FKK-MSC model introducing the gradual absorption effect [16] is extended so that the isospin can be included as a conserved quantum number. The detail of the extension will be described in the forthcoming paper [17]. The outline is summarized below.

Two possible isospin states, $T_< = T_0 - 1/2$ and $T_> = T_0 + 1/2$, can be excited in the composite nucleus formed by the proton bombardment, where T_0 is the isospin of the target nucleus. Neutron decay from the $T_>$ states is remarkably suppressed owing to the isospin selection rule, if the excitation energy of the compound nucleus is not enough high compared with the threshold of the neutron decay and the isospin mixing between $T_>$ and $T_<$ states is negligible. Thus, the isospin conservation is expected to cause the enhancement of proton emission in the MSC and CN processes in (*p*,*p*') reactions at low incident energies. For simplicity, one assumes no CN decay following the MSC particle emission from states with isospin $T_>$ and no isospin mixing during the MSC process; hereafter this assumption will be referred to as (A). For the case (A), the extended MSC formulas for each isospin are given by the same expression as eq.(4) in ref. [8], except that two physical quantities become isospin-dependent: the transmission coefficients multiplied by the isospin coupling coefficients [18] and the isospin-dependent state densities given in first-order approximation as

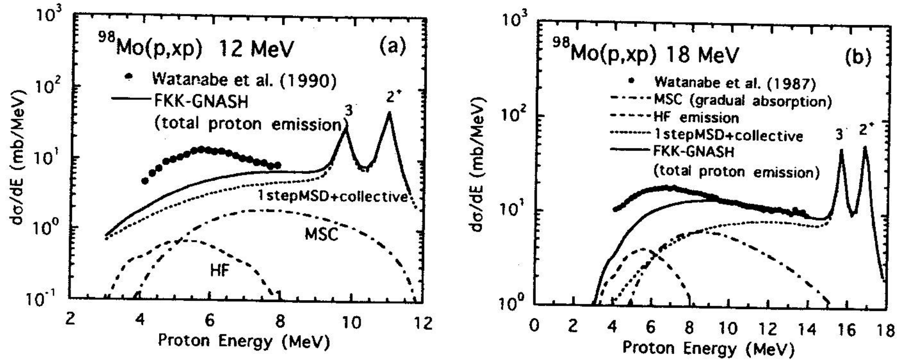

Fig. 1. Comparison of the FKK-GNASH calculation and experimental data for the (*p*,*p*') reactions on ^{98}Mo at (a) 12 MeV and (b) 18 MeV. These figures are taken from Ref. [8].

$$\omega^{<}_{p,h}(E) \simeq \omega_{p,h}(E) \quad \text{and} \quad \omega^{>}_{p,h}(E) \simeq \omega_{p,h}(E - E_{sym}),$$

where $\omega_{p,h}(E)$ is the widely-used one- component Williams expression [19] and E_{sym} is the symmetry energy [20].

As another limiting case, hereafter called (B), we consider a case where all Q fluxes entering to the $T_>$ states proceed toward the equilibrium stage without MSC decay and damping into the $T_<$ states, and thus contributing only to the CN emission. In this case, we take into account the isospin mixing after the system reaches the equilibrium stage using the extended Hauser-Feshbach (EHF) model [18]. Note that the model parameters used in the present MSC and CN calculations for the cases (A) and (B) are the same as in ref. [8]

3. Results and discussions

The above-mentioned models have been applied to (*p*,*p*') reactions on ^{98}Mo and ^{106}Pd at 12, 14, 16, 18 and 25.6 MeV [8, 13, 14] and (*p*,*p*') data for ^{93}Nb at 18 MeV [13].

The previous results [8] not taking account of the isospin are shown in Fig. 1. The calculation underpredicts remarkably the experimental data in the low ejectile energy region where the MSC and CN contributions are expected to be dominant.

In Fig. 2, the calculations for both cases (A) and (B) are compared with the experimental angle-integrated spectra for ^{98}Mo. Such underestimations as in Fig. 1 are not seen for 12 and 18 MeV. Rather, the results of the case (A) overpredict the experimental data in the low outgoing energy region. At three energies, all $T_>$ fluxes were found to be escaped as proton and/or neutron emission before the equilibrium is reached. Therefore, this overprediction may be because the isospin mixing is neglected in the preequilibrium process. To include the isospin mixing effect in the MSC process properly, we will need knowledge on how the isospin mixing depends on the stage number N in the MSC processes or the equilibrating time.

On the other hand, the calculation (B) with the EHF model [18] introducing the isospin mixing parameter μ shows excellent agreement with the experimental data. In these calculations, the adjustable parameter μ was estimated to be 48 to 55 %, not depending strongly on the incident energy. The values are consistent with the other results [21] extracted from the decay from the $T_>$ giant dipole resonance (GDR) for a few nuclei in the same mass region. Note that the changes in the calculated (p,n) spectra were negligible even when the isospin selection rule was considered, because the overwhelming evaporation components from $T_<$ states and the $T_>$ flux itself is very small compared to the $T_<$ flux.

In Fig. 3, the calculated angular distributions are compared with the experimental data. The angular distributions of the MSC and CN processes are assumed to be isotropic about 90° in the c.m. system. The MSC and the CN components corresponds to the case (B). The FKK+CN calculation reproduces the experimental angular distributions quite well. This is also true for other outgoing energies.

Thus, we have found it important to take into account the isospin in (p,p') reactions, especially at incident energies less than 18 MeV, and have solved the underpredition seen in the previous FKK result [8] by addition of the MSC and CN components of $T_>$ states. For further detailed discussion about the isospin mixing in the MSC process, it will be necessary to incorporate a coupled master equation approach [10] which gives a unified description of the time-evolution of the isospin-mixing between both $T_>$ and $T_<$ states in the equilibrating system.

The V_0 values extracted from (p,p') reactions for incident energies from 12 to 26 MeV are shown in Fig. 4 together with those [8] of (n,n') reactions on ^{93}Nb. They are nearly proportional to $1/\sqrt{E_{inc.}}$, whereas the energy dependence of V_0 for (n,n') is similar to the energy dependence of the real part of the nuclear optical potential within the errors. Furthermore, there is a difference in V_0 values between (p,p') and (n,n') at the same incident energy, especially at lower energies. The extracted energy dependence of V_0 for (p,p') is similar to that found by the previous (n,n') analysis [15] and by Koning [22] who used a collective form factor. However, our result for (n,n') is different from that in ref. [15] and shows a somewhat weaker energy dependence. The extracted V_0 values are also different from the values extracted in the other FKK analyses [2, 3] with the Bonetti-Chiesa code [23] and are generally larger than those. These discrepancies are due to the input parameters and corrections used. Some possible explanations may be given on the finding that the V_0 values of (n,n') are smaller than those of (p,p') at the same incident energy: (i) the difference in nucleon kinetic energy in the peripheral region of the nucleus due to the Coulomb barrier [8], (ii) a more appropriate choice of optical potentials necessary, and (iii) neutron-proton distinguishability in the state density and the effective N-N interaction. Even when such effects are considered, the discrepancy still remains. To resolve this problem, we will need further systematic

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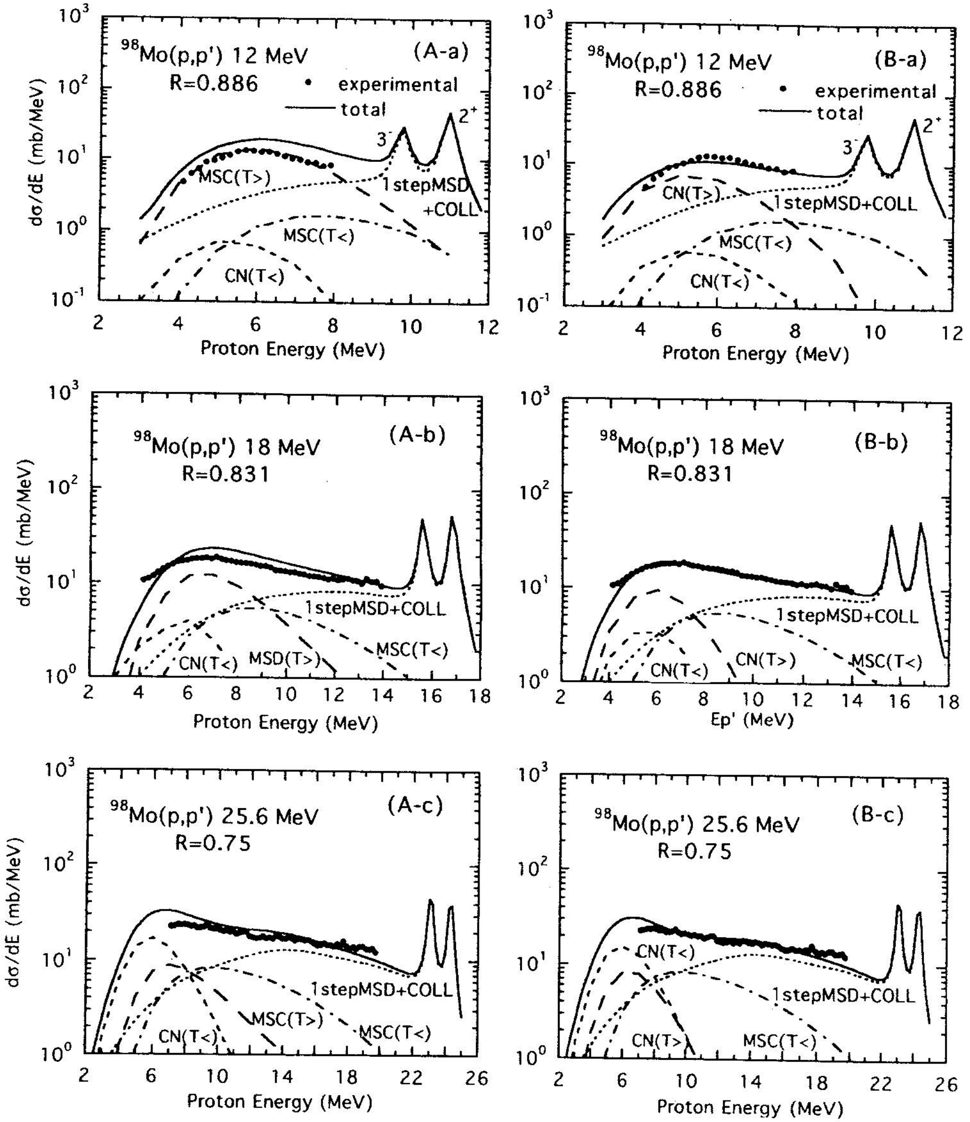

Fig. 2. Comparison of the angle-integrated proton emission spectra of the p+^{98}Mo reaction at (a) 12 MeV, (b) 18 MeV and (c) 25.6 MeV. Each figure in the left and right sides corresponds to the MSC and CN calculation for the $T_>$ states under the conditions (A) and (B), respectively. The quantity R represents the reduction factor of incoming flux by MSD+COLL processes. The experimental data are taken from Ref. [8, 13, 14].

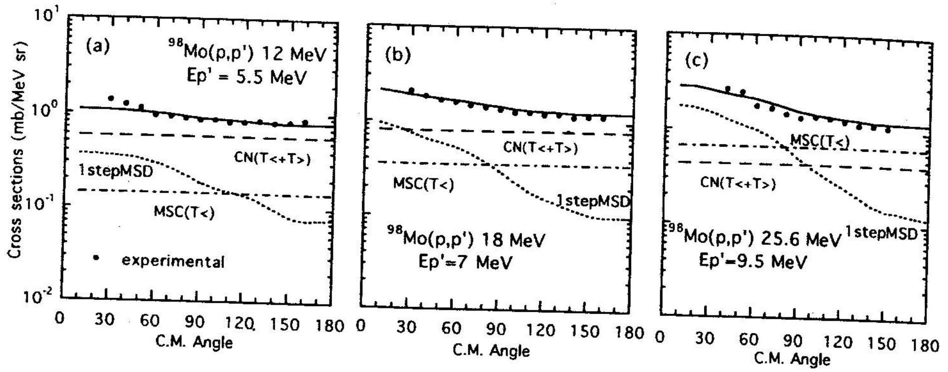

Fig. 3. Angular distributions of (p,p') reactions on ^{98}Mo at incident energies (a) 12 MeV, (b) 18 MeV and (c) 25.6 MeV. The experimental data are taken from Ref. [8, 13, 14].

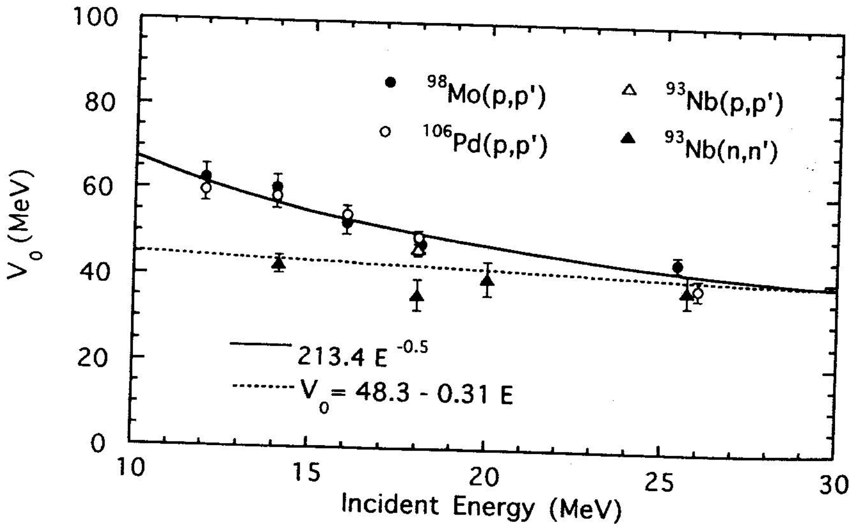

Fig. 4. The extracted strength V_0 for (p,p') and (n,n') as a function of the incident energy.

measurements of (p,p') data and a more sophisticated FKK model analysis introducing a two-component approach in which proton- and neutron-shells are treated separately and effective N-N interactions based on the G-matrix, such as M3Y interactions [24], are used.

4. Conclusion

The (p,p') data on ^{93}Nb, ^{98}Mo and ^{106}Pd at energies from 12 to 26 MeV were analyzed using the FKK-GNASH code modified so as to take into account the isospin. The importance of the isospin conservation in the MSC and/or the CN processes of (p,p') reactions at lower incident energies was confirmed. The obtained isospin mixing parameters μ were about 50 % over the excitation energy region of the compound nucleus under consideration. The values were almost consistent with the previous experimental result of the $T_>$-GDR decay. In addition, we have found a difference in the strength of the effective N-N interaction between (p,p') and (n,n') reactions at the same energy region, namely the former has a stronger dependence on the incident energy than the latter. The reason is not understood well at present, although some possibilities can be suggested.

Acknowledgments The author is grateful to the EPSRC for a visiting fellowship (1995) and to the British Council for a Grant-in-Aid (1993). He also thanks Dr. P.E. Hodgson for his hospitality, encouragement and useful discussions during his stay at Nuclear Physics Laboratory, Oxford.

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