SCDW Analysis of DDX in (*N,N'X*) Reactions for a Wide Range of Mass Number

Sun Weili[a)*], Y.Watanabe[b)], K. Ogata[c)], M. Kohno[d)], and M. Kawai[c)]

[a)] *Department of Energy Conversion Engineering, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*

[b)] *Department of Advanced Energy Engineering and Science, Kyushu University, Kasuga, Fukuoka 816-8580, Japan*

[c)] *Department of Physics, Kyushu University, Fukuoka 812-8581*

[d)] *Physics Division, Kyushu Dental College, Kitakyushu 803-8580*

**email: sun@aees.kyushu-u.ac.jp*

The applicability of a newly improved semiclassical distorted wave model with Wigner transform of a one-body density matrix has been investigated to a wider range of target mass number. The (*p,p'x*) reactions on ^{12}C, ^{27}Al, ^{58}Ni, ^{90}Zr, and ^{197}Au, and (*p, nx*) reaction on ^{90}Zr are chosen to be analyzed. Comparisons with the calculations of other models, AMD, QMD, and FKK, are also carried out. The results shows that our model can reproduce the experimental double differential data well over a wider range of target mass number, and have predictive powers similar to the other models. The possible reason for overestimation in (*p,nx*) reaction is discussed from the viewpoint of two-body nucleon-nucleon scattering. The sensitivity of SCDW calculations to single particle potential parameters is also investigated.

1. Introduction

Recently we have proposed a new semiclassical distorted wave (SCDW) model with Wigner transform of a one-body density matrix[1], in which the jj-coupling shell model is used to describe the single particle wave functions in a finite range of single particle potential, instead of the local density Fermi gas (LFG) model used in the previous SCDW model [2]. We also performed practical analyses of experimental data for the ^{90}Zr(*p, p'x*) reactions at 80 and 160 MeV incident energies. The results showed that the new SCDW model improved remarkably the previous calculations of the SCDW model. In particular, the one-step cross sections increased greatly at backward angles. The reason was explained from the viewpoint of nucleons momentum distributions. In the LFG model, the target nucleons have only momenta less than the local Fermi momentum. The range of scattering angles, therefore, is subject to a stringent kinematic restriction. In the new SCDW model, the higher momentum components are incorporated into the calculations because of the use of realistic single particle wave functions. Accordingly the stringent kinematic restrictions of the Fermi models that tend to reduce the cross sections at large and very small angles are relaxed.

In this paper, we present more comparisons of new SCDW calculations in order to investigate the applicability of this model for other reactions over a wider range of target mass and incident energy. Since there exists several MSD calculations by FKK, AMD, and QMD, for ^{58}Ni(*p,p'x*) and ^{90}Zr(*p,p'x*) reactions, it is also interesting to see the similarities and differences among the calculations by these models and the SCDW model.

2. Applications to a wider range of target mass number and incident energy

The (*p,p'x*) reactions on ^{12}C, ^{27}Al, ^{58}Ni, ^{90}Zr, and ^{197}Au and (*p, nx*) reaction on ^{90}Zr are chosen for our analyses. Their experimental data show the evidence that MSD processes provide the significant

fraction of the cross sections, *i.e.*, the presence of smoothly forward-peaked angular distributions (over a wide range of outgoing energy), which is of interest for the present study. On the other hand, these reactions cover an interesting range of mass and incident energy. In the all SCDW calculations, the Woods-Saxon potential with global parameters[3] is used as the finite range of single particle potential.

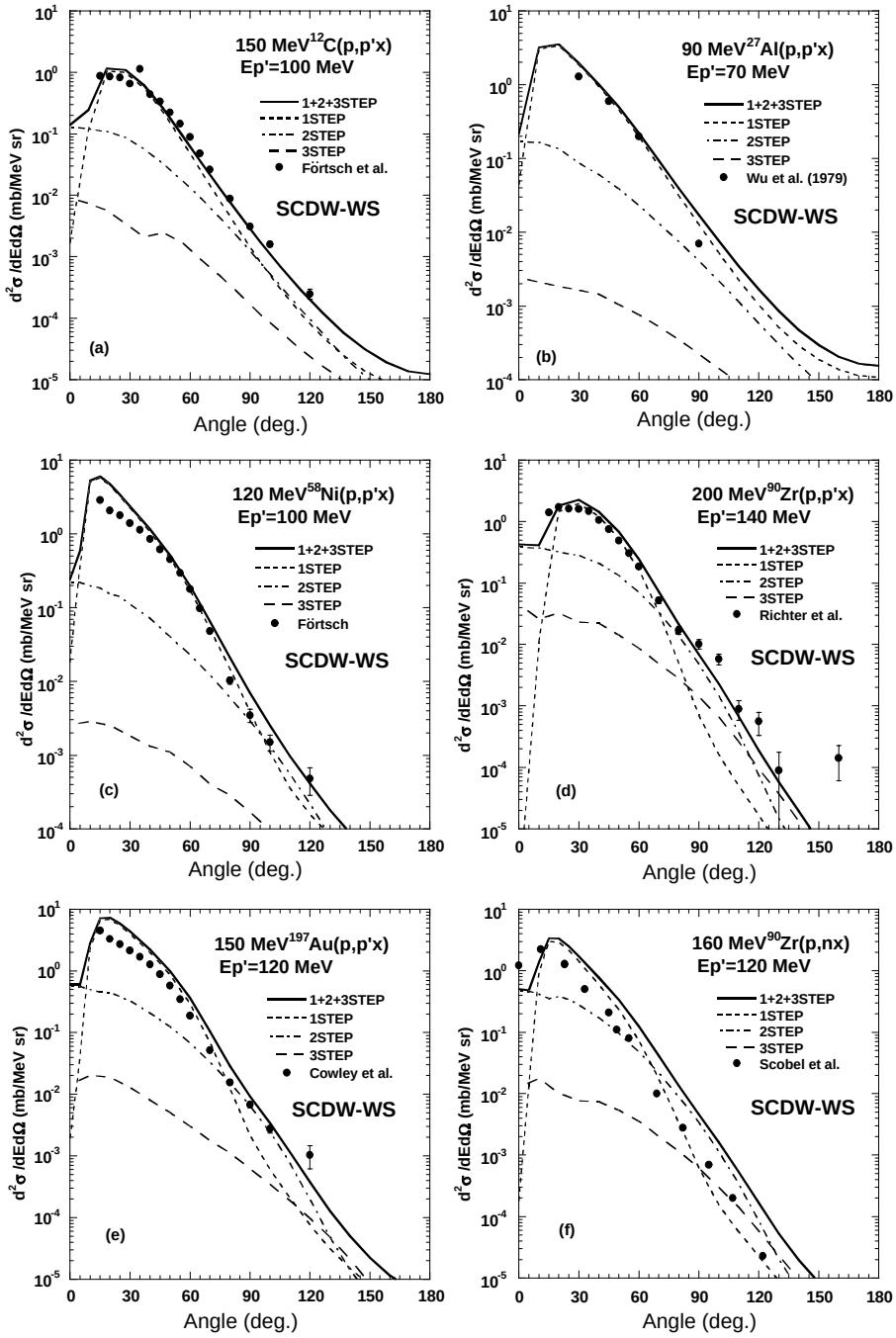

Fig. 1. Comparison of SCDW calculations with measured double differential cross sections for the (*p,p'x*) reactions on ^{12}C, ^{27}Al, ^{58}Ni, ^{90}Zr, and ^{197}Au, as well as the (*p,nx*) reaction on ^{90}Zr. In each panel, the cross sections of one-, two-, and three-step processes are represented by the short-dashed, the dashed-dotted, and the long-dashed lines. The solid lines corresponds to their sum.

Figures 1(a) through 1(e) show the applicability of the SCDW model to a wider range of mass number. It is seen that the new SCDW model reproduces well the experimental data for ($p,p'x$) reactions. Agreement of the calculations with measured data is satisfactory except at small angles for the higher emission energies. The one-step cross sections do not drop off at the very forward and large angles as the previous ones [2]. Apparently the one-step cross section provides the major part of the total cross section. In particular, the one-step is predominant at the highest emission energy, and is almost sufficient to explain the data. This result is reasonable because the one-step process dominates the pre-equilibrium reaction for high emission energy. For the highest emission energy, however, the one-step cross section still drops at the very forward angle. Also the new calculations still overestimate the experimental data near the quasielastic scattering (QES) angle by a factor of about 2-3 similar to the previous calculations, although the peak is slightly deduced and shifted to forward angles.

Figures.1(a) and 1(b) show that the SCDW calculations reproduce excellently the experimental data for light target nuclei ^{12}C and ^{27}Al. Fig 1(d) shows that the SCDW calculation is also applicable to the higher incident energy up to 200 MeV, and has similar features as those reactions shown at other incident energies. Figs. 1(f) shows the applicability to (p,nx) reaction. However, the calculation overestimates the data in the whole angular region.

3. Comparison with other models

We compare the SCDW calculations with the results of the other models, AMD, QMD, and FKK in order to investigate whether our SCDW model is comparable in quality with the other models and to discuss the similarities and differences.

Firstly, a comparison with AMD[4] is made for ^{58}Ni($p,p'x$) at 120 MeV in Fig 2. Agreement is generally good, although the SCDW three-step cross sections are somewhat smaller than the AMD ones. It is noticeable that the AMD one-step cross sections also show peaks near the QES angles, though slightly shifted forward. Such peaks do not appear in the cross sections in QMD calculations.

Secondly, SCDW and QMD[5] are compared in Figs. 2 and 3. One sees some differences in one-step angular distributions, in particular at very forward angles. The QMD one-step cross sections show forward peaks without the steep fall in the vicinity of zero degree that is seen in the SCDW ones.

The QMD used the Gaussian-like shape of momentum distribution which also include the higher momentum components of target nucleons. The authors[5] once investigated the effect of the momentum distribution to the angular distribution by using the different momentum distributions: a) Unified Fermi gas distribution which is similar to our LFG distribution, and b) Gaussian-like shape of momentum distribution which is similar to our distribution for Woods-Saxon potential. It was found that the higher momentum components can not lead to the dramatic increase in one-step cross section in the vicinity of zero degree, but leads to the shift of the QES peak to the forward angles. In this aspect, our new SCDW model shows similar feature to the QMD model. It seems that the reason why one-step cross section drops off in the vicinity of zero degree can not be explained by the Fermi-motion of the target nucleons.

It was also mentioned in Ref.[5] that the behavior of the QMD one-step cross sections near zero degree was strongly affected by the refraction of the incident and outgoing particles by the mean field, and the steep drop at the very forward angles can be totally washed out by the refraction effect. The SCDW calculations also automatically takes account of the refraction by the distorting potentials. However, the effect was found to be small. As for the two- and three-step cross sections, the SCDW and QMD cross sections are similar in shape, although SCDW yields smaller cross sections at the highest emission energy than the QMD.

Thirdly, a comparison of SCDW with FKK[5] is made in Fig. 3. Considerable difference in one-step cross sections is seen between the predictions of the two models, although the higher-step cross sections do not differ as much. FKK gives steeper fall of one-step cross sections towards large angles than SCDW. The relative contributions of the two- and the three-step processes at backward angles

are larger in FKK than in SCDW.

From the above comparisons, we can understand that the calculated angular distribution of the one-step process is strongly model-dependent and those of the multistep processes are not. In addition, the relative magnitude of the contributions of individual multisteps is rather similar in all the models compared. It is concluded that the SCDW model can reproduce the experimental data to the same extent as the other models (FKK, QMD, and AMD).

4. Discussions

a) Two-body nucleon-nucleon scattering

Although the SCDW model is improved by introducing the realistic single particle wave functions, there still exists three problems to be further investigated: 1) the overestimation for (*p,nx*) reaction, as shown in Fig. 1(f), 2) the drop of one-step cross section near zero degree, and 3) the overestimation near the QES angle for the highest emission energy. As for the first problem, we attempt to explain the possible reason from the viewpoint of two-body nucleon-nucleon (*NN*) scattering.

In the SCDW calculations, the two-body *NN* scattering cross sections in free space, denoted by σ_{pp} and σ_{pn}, are used. The values of free space as well as the in-medium *NN* cross sections of Cugnon [6] are shown in Fig. 4(a). It is seen that the free σ_{pn} is larger than the free σ_{pp}. By considering two cases, we made test calculations of the cross sections in the ^{90}Zr(*p,nx*) and ^{90}Zr(*p,p'x*) reactions at 160 MeV incident and 120 MeV emission energies. One case is that the free σ_{pp} and σ_{pn} is taken as different, as we did in all calculations. Another case is that the value of σ_{pn} is assumed to be same as that of σ_{pp}. The results are shown in Figs. 4(b) and 4(c). It is seen that the cross section in ^{90}Zr(*p,nx*) reaction for the second case is reduced and closer to the experimental data in the magnitude. And, the cross section in ^{90}Zr(*p,p'x*) reaction is also reduced.

It is noted that, in the QMD calculations, the in-medium *NN* cross sections of Cugnon are used for the (p,p'x) and (p,nx) reactions, which have almost same magnitude with a difference less than 30 percent in the energy range of 50-300 MeV, and are closer to the free space σ_{pp} as shown in Fig. 4(a). On the other hand, the FKK calculations use the same values of the strength V_0 of effective nucleon-nucleon interactions for both types of reactions, which corresponds to our second case. The QMD and FKK calculations showed the agreement with the experimental data for both types of reactions. This might indicate that a weak isospin dependence is required for simultaneous fits to the MSD cross sections of (*p,p'x*) and (*p,nx*) reactions. Therefore, it is suggested to investigate further the effect of isospin dependence of in-medium *NN* scattering cross sections on the calculations of the MSD cross sections, because the two-body NN cross sections are important input parameters for various model calculations.

As for the other two problems, namely the drop of one-step cross section near zero degree, and the overestimation near the QES angle for the highest emission energy, the reasons are not clear at present. Further study will be necessary.

b) Sensitivity of SCDW calculations to single particle potential parameters

In the calculations of Wigner transform, the Woods-Saxon potential with global parameters is used for all target nuclei chosen for this study. It might be argued that the SCDW calculations can be further improved if the best-adjusted potential parameters are used. To investigate the effect of the potential parameters on the SCDW calculations. we calculated DDX by using two type of potential parameters for the ^{12}C(*p,p'x*) at 150 MeV incident and 100 MeV outgoing energy. One set of potential parameters is the global one, and another is the best-adjusted potential parameters given by Bear and Hodgson [7].

Figure 5 shows the SCDW calculations corresponding to two cases of potential parameters. It is seen that the results do not change so much, which indicates that the cross sections do not depend strongly on the particular choice of potential parameters. The Woods-Saxon potential with global parameters is good enough to reproduce overall the experimental data. This can be regard as one of

the advantages of the SCDW model from the viewpoint of application.

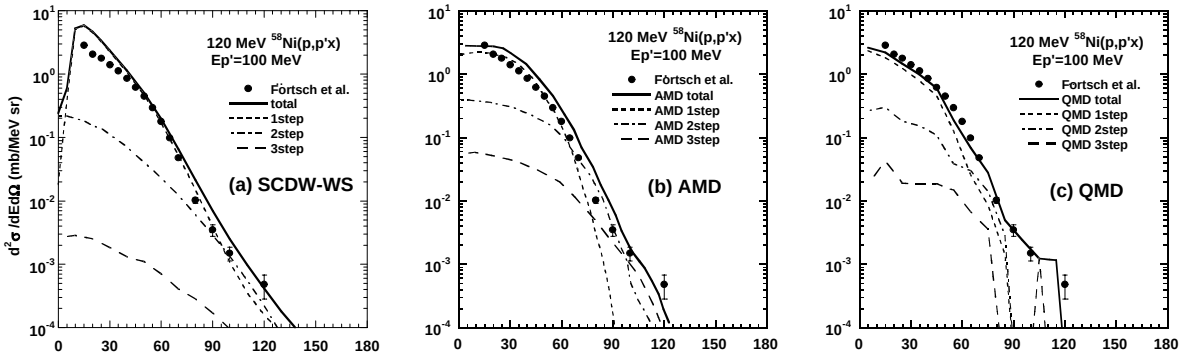

Fig. 2. Comparisons of SCDW calculations with AMD and QMD calculations for the reaction ^{58}Ni($p,p'x$) for 120 MeV incident and 100 MeV outgoing energies.

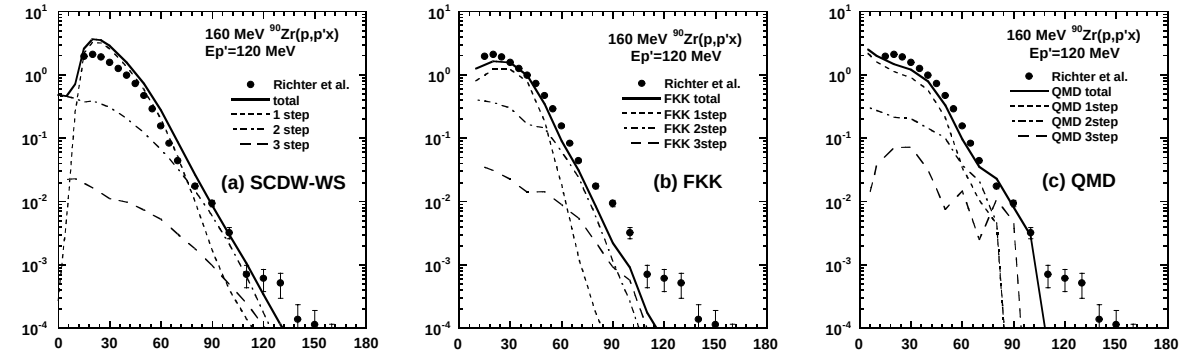

Fig. 3. Comparison of SCDW calculations with FKK and QMD calculations for the reaction ^{90}Zr($p,p'x$) for 160 MeV incident and 120 MeV outgoing energies.

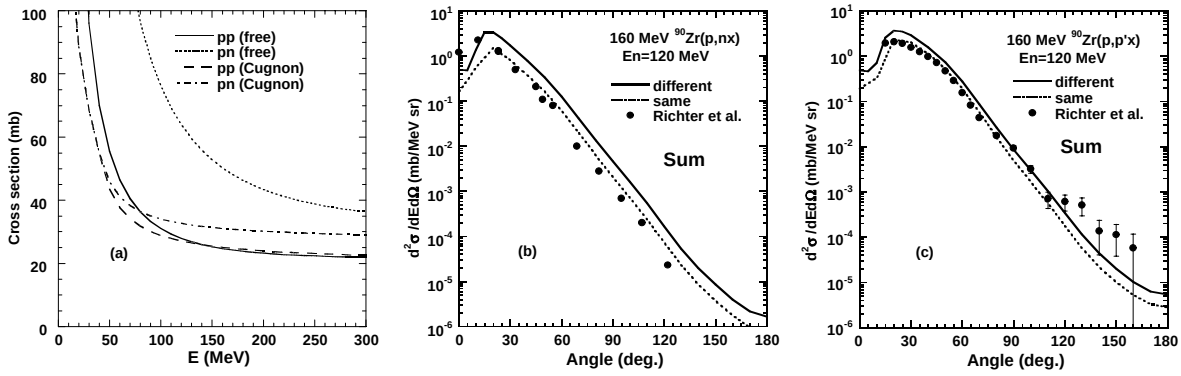

Fig. 4. Dependence of SCDW calculations on two-body nucleon-nucleon scattering. (a) The free nucleon-nucleon scattering cross sections and in-medium ones by Cugnon. (b) Comparisons of the double differential cross sections (summed over the individual step cross sections) for two cases: 1) free σ_{pp}(solid line) and σ_{pn} (dotted line). 2) σ_{pn} is assumed to be same as σ_{pp}. The reaction is ^{90}Zr(p,nx) at 160 MeV incident and 120 MeV outgoing energies. (c) Same as (b), but for ^{90}Zr($p,p'x$) at 160 MeV incident and 120 MeV outgoing energies.

5. Summary

In this paper, the SCDW analyses are carried for the (*p,p'x*) and (*p,nx*) reactions on the target nuclei ^{12}C, ^{27}Al, ^{58}Ni, ^{90}Zr, and ^{197}Au in order to examine the applicability of the SCDW model over a wider range of mass number and incident energy. The SCDW calculations are also compared with those of other models(FKK, AMD, QMD).

The results show that the SCDW model can indeed reproduce well the experimental data for both (*p,p'x*) and (*p,nx*) reactions over a wider range of mass number and incident energy. Agreement is satisfactory except at forward angles for the higher emission energies. In particular, the calculation for ^{12}C(*p,p'x*) agrees excellently well with the experimental data. The results also show that this model is applicable to higher incident energy up to 200 MeV. The comparisons with the other models show that the SCDW model can reproduce the experimental data to the same extent as these models, although there are some difference in individual step cross sections. It is noticed that there are some problems to be further investigated. One of them is the overestimation for (*p,nx*). The possible reason for this overestimation is discussed from the viewpoint of two-body nucleon-nucleon scattering. It is suggested that the effect of isospin dependence of in-medium *NN* scattering cross sections on the calculations of the cross sections should further be investigated. Finally, the sensitivity of SCDW calculations to single particle potential was investigated. It is seen that the dependence of the SCDW model on the potential parameters is not strong, which can be regard as one of the advantages of the SCDW model from the viewpoint of application.

References:

[1] Sun Weili *et al*., Phys. Rev. C **60**, 064605 (1999).
[2] Watanabe *et al*., Phys. Rev, C **59**, 2139 (1999).
[3] A. Bohr and B. R. Mottelson, *Nuclear Structure*, (Benjamin, New York, 1969). Vol. **I**, p. 238-239.
[4] E. I. Tanaka *et al*., Phys. Rev, C **52**, 316 (1995).
[5] S. Chiba *et al*., Phys. Rev, C **53,** 1824 (1996).
[6] J. Cugnon *et al*., Nucl. Phys. **A352,** 505 (1981); J. Cugnon, Phys. Rev. C **22**, 1885 (1980).
[7] K. Bear and P.E. Hodgson, J. Phys. G: Nucl. Phys. Vol. **4,** L287 (1978).

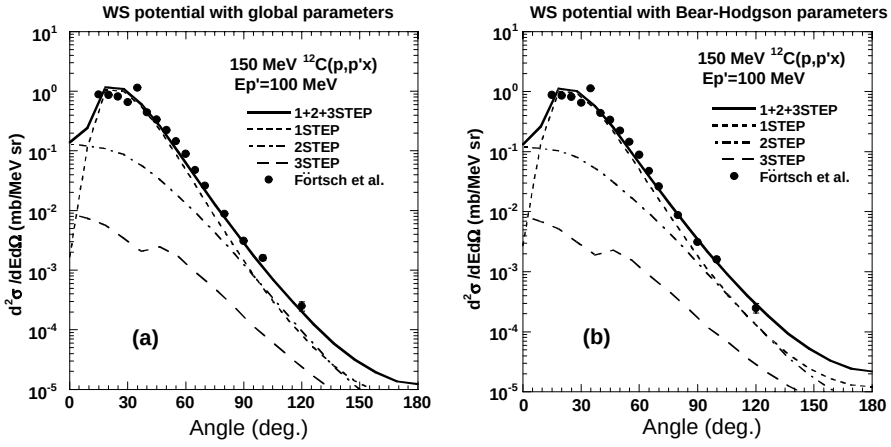

Fig. 5 Comparison of the SCDW calculations with different Woods-Saxon potentails parameters for the ^{12}C(*p,p'x*) reaction at 150 MeV incident and 120 MeV outgoing energies: (a) global ones [3], and (b) Bear-Hodgson's ones [7].