Average effective-interaction strength of first nucleon-nucleon collision in multistep reactions*

M. Avrigeanu§, A. Harangozo, and V. Avrigeanu
Institute of Physics and Nuclear Engineering, P.O. Box MG-6, 76900 Bucharest, Romania

A.N. Antonov
Institute of Nuclear Research and Nuclear Energy, Sofia 1784, Bulgaria

Abstract

Effective NN-interaction strength $\overline{V}_0$ averaged along the trajectory of the incident nucleon, for the first NN collision, is obtained with respect to both the nuclear density and the first NN-collision probability. Good agreement is found between the average strengths obtained with the Hartree-Fock potential plus the dispersive component and by using the parametrization based on the Brueckner-Hartree-Fock nuclear matter calculations. The nuclear-density dependence of the effective NN interaction may account for the low-energy phenomenological V_0 values. The effect of using $\overline{V}_0$ values within the multistep direct (MSD) reaction formalism is shown.

1. Introduction

Various semiclassical models and quantum-statistical theories (e.g. [1]) describe the energy equilibration in nuclear reactions by a sequence of nucleon-nucleon (NN) interactions leading to particle-hole excitations. A real finite-range Yukawa potential with a range parameter r_0=1 fm has been thus generally used within the multistep direct (MSD) and multistep compound (MSC) reaction theory of Feshbach, Kerman, and Koonin (FKK) [2], and the respective two-body interaction strength V_0 has been adjusted to reproduce the experimental data. This effective NN-interaction strength has been finally the only free parameter of the FKK calculations. Adoption of a consistent model-parameter set as well as consideration of several other effects were performed whereas discrepancies in the systematics of the phenomenological V_0 values still exist [3,4]. A more realistic NN interaction

---

*Presented at the *OECD NEA/NSC Specialists' Meeting on the Nucleon-Nucleus Optical Model up to 200 MeV*, Bruyères-le-Châtel, 13-15 November 1996.

§e-mail: mavrig@roifa.ifa.ro

has been suggested in the meantime [4,5], while it is already observed that so-called M3Y interaction may perhaps not be as good as assumed [6].

In spite of natural prevalence of the theoretical approach taken to obtaining the effective interaction, the empirical one is yet keeping the advantage shown by Austin [7]. A particular meaning has had the strength renormalization due to the automatical correction of the uncertainties in the reaction mechanisms. The monotonic decrease of V_0 with the projectile energy has been found consistent with the similar trend of the real part of the nucleon optical potential, as it is expected from the simple folding model. Thus Cowley *et al.* [8] assumed that V_0 has the same energy variation as the real optical potential and then normalized it, at the incident energy of 20 MeV, to the value obtained by Austin from a survey of the analysis of inelastic proton scattering in the energy range 20-50 MeV to discrete final states [7]. On the other hand, the different behaviour of the actual V_0 systematics below 30 MeV might be related to some effect which has been neglected untill now and should be added to the theory [9]. Nevertheless, it seems justified to look again on the theoretical background of the effective interaction, while consideration of features more significant at lower incident energies could improve the model calculations.

2. Energy dependence of the effective-interaction strength

The real part of the optical potential is given within the simple folding model approximation in terms of the nuclear density and the effective NN interaction

$$V(r) = \int d\mathbf{r}'\, \rho(\mathbf{r}') v_0(|\mathbf{r} - \mathbf{r}'|) \tag{1}$$

from where it follows (e.g. [7])

$$\int d\mathbf{r}\, v_0(r) = \frac{1}{A} \int d\mathbf{r}\, V(r) \tag{2}$$

It results that the strength of an 1 fm range Yukawa interaction is related to the volume integral per nucleon of the real optical potential by

$$V_0 = \frac{1}{4\pi} J_V/A \tag{3}$$

We have used in this respect the same depth V_H of the Hartree-Fock component of the real optical potential found by Johnson *et al.* [10] for neutrons on lead in the energy domain [1,120 MeV], which was involved by Cowley *et al.* as guidance for the energy dependence of V_0. Thus the Eq. (3) becomes

$$V_0 = 0.727\, V_H(E_i) = 33.7\exp[-0.31(E_i - E_F)/46.4] \tag{4}$$

where E_F is the Fermi energy defined with respect to the zero energy point. Alternatively one may use also the volume integral for the full real potential J_V/A obtained by Johnson *et al.* adding the dispersive component to the Hartree-Fock one. The typical low-energy dependence implied by the use of the optical-potential dispersion relation (DR) yields in this case the form

$$V_0 = 32.8 - 0.207E_i \quad for\ 4 < E_i < 40 MeV \tag{5}$$

The predictions of Eqs. (4-5) are compared with various empirical values of V_0 from (n,n'), (p,xn), and (p,xp) reactions in Fig. 1 versus the incident energy. First, one general comment which should be made concerns the necessity pointed out by recent systematic studies of the effective-interaction strength V_0 [3–6,9], including the sensitivity of the respective FKK calculations to the input parameters [3], to carry out such analyses by using the same standard parameter set over a wide range of the target mass number and incident energy. The data shown in Fig. 1 satisfy this condition only in part while the additional dependence of V_0 on the target mass [11] and the neutron-proton distinguishability [3,4] increases the complexity of this figure. Second, the comparison should be completed with the formula derived by Cowley *et al.* [8]

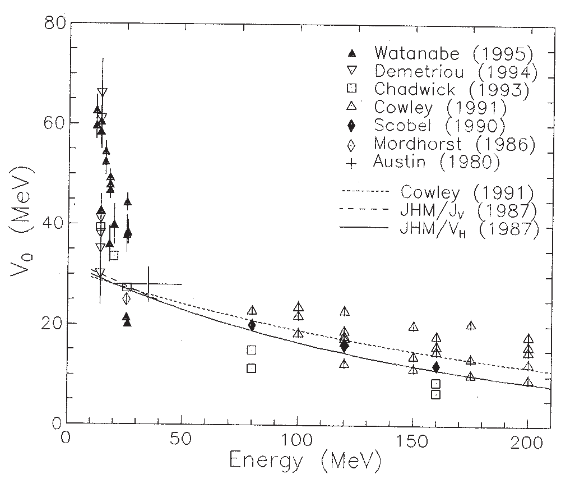

Fig. 1. Comparison of the effective NN-interaction strengths as functions of the incident energy obtained from FKK analyses of nucleon induced reactions using 1 fm range Yukawa form factor with the predictions for the target nucleus ^{94}Nb of the normalized energy-dependence of the nucleon optical potential obtained by Cowley *et al.* [8] (dotted curve), the Hartree-Fock component V_H of the real optical-potential depth (full curve) and the volume integral per nucleon J_V/A of the full real potential (dashed curve) of Johnson *et al.* [10]. The points are from: Watanabe *et al.* [3], Demetriou *et al.* [11], Chadwick *et al.* [12,13], NAC [8,14,15], Scobel *et al.* [16], Mordhorst *et al.* [17], and Austin [7].

$$V_0 \simeq 30.8 \exp(-0.15 E_i/30.8) \tag{6}$$

by using the Hartree-Fock component V_H of the real optical potential of Johnson *et al.* [10] with (i) a correction factor of $\frac{3}{4}$ for the gradual energy loss of the incident nucleon in the subsequent stages of the multistep process, and (ii) a normalization at E_i=20 MeV to the V_0 value found in the DWBA analysis of (p,p') reaction at 20-50 MeV [7]. However, the correction factor for the gradual energy loss in the subsequent reaction steps should be not involved at low energies where the two-step scattering in the MSD process is negligibly small [12]. It results that the optical-model provisos (4-5) agree with the normalized energy-dependence of Cowley *et al.* below e.g. 50 MeV. The low-energy phenomenological V_0 values are much more increased in comparison with any predictions, including the additional dependence on the target-mass and the neutron-proton distinguishability. It is shown in the following that the nuclear-density dependence of the effective NN interaction may account for this, while other effects are avoided by considering only (n,n') and (p,p') reactions on ^{93}Nb.

3. Nuclear-density dependence of effective NN interaction

First, Myers [18] described the density dependence of V_0 for a given incident energy by using a phenomenological factor which multiplies the effective NN interaction (see also [19])

$$f^E(\rho) = C_\rho(E_i)(1 - d\rho^{2/3}) \tag{7}$$

where d=2 fm^2. Bonetti and Colombo [20] have already used this form within FKK calculations by taking the density-independent parameter C_ρ=1.4 in order to obtain $f(\rho)$=1 for $\rho = \frac{1}{3}\rho_0$.

Next, Jeukenne *et al.* [24] showed that Eq. (1) is replaced in the frame of the local density approximation (LDA, e.g. [21]) by

$$\frac{V(r)}{\rho(r)} = \int d\mathbf{r}'\, v_0(r') \tag{8}$$

An immediate result of this relation, for the 1 fm range Yukawa interaction, it is a radial-dependent strength of the effective NN interaction

$$V_0(r, E_i) = \frac{1}{4\pi}\frac{V(r)}{\rho(r)} \tag{9}$$

determined by the real part of the optical model potential (OMP). In the following we illustrate the case by means of three potentials. The first is that obtained by Johnson *et al.* [10] with the DR constraint, namely the full potential for $E_i \leq$40 MeV and the Hartree-Fock component at higher energies where the respective volume integrals are similar. The second is the global OMP of Walter and Guss [22], which was used in the systematic analysis of Watanabe *et al.* [3] mainly due to the possibility to provide both neutron and proton optical potentials in which the asymmetry term has the same magnitude but opposite signs. The last aspect is specific also to the well-known OMP of Becchetti and Greenlees [23] obtained for energies up to 50 MeV.

On the other hand, Brueckner-Hartree-Fock nuclear-matter calculations performed also by Jeukenne *et al.* [24] showed that the contribution of the isoscalar component of the OMP to the left-hand side of Eq. (8) can be parametrized so that

$$\frac{V(r)}{\rho(r)} \approx F(E_i)\,[1 - d\rho^{2/3}(r)] \tag{10}$$

where d=2.03 fm^2 and $F(E_i)$=(903-7.67E_i+0.022E_i^2) MeV $\cdot$ fm^3, in the energy range [10,140 MeV]. From Eqs. (8-9) we may now obtain another form for the local density-dependent strength of the 1 fm range Yukawa interaction

$$V_0(r, E_i) = \frac{1}{4\pi}F(E_i)\,[1 - d\rho^{2/3}(r)] \tag{11}$$

corresponding to the Myers' expression (7) except the factor $C_\rho(E_i)$ which is normalized to the parametrization (9). The parametrization of Negele [25] has been used to describe the realistic nuclear matter distribution. Actually Kobos *et al.* [19] used a similar method firstly but a different radial part of the effective interaction as well as an exponential density dependence.

4. Average strength of the effective NN interaction

The comparison of results of the present analysis with the phenomenological V_0 values requires the derivation of an average strength of the effective NN interaction along the trajectory of the incident nucleon in a complex distorting optical potential. The method which has been used in this respect has its origin within the geometry-dependent hybrid (GDH) model of Blann [26] for preequilibrium emission, where l-dependent average Fermi energies have firstly been involved. The main point added by us concerns the calculation of the radial-dependent probability of the first two-body collision between the projectile and one of the target nucleons, and its further consideration to obtain average quantities of interest for the reaction description. The form of this probability $P(r)$ is given elsewhere [27] while hereafter are shown the basic assumptions.

We have mainly followed the incoming particle's path in the nuclear target by using the semiclassical method. The particle curved trajectory as well as the momentum of the particle at each point of the trajectory, i.e. the NN-collision localization [28,29], can be considered providing the semiclassical approach is expected to be quantitatively reliable. The applicability of the semiclassical approximation below 50-100 MeV is yet an open question. However, there are evidences in this respect [30,31] while Kawai *et al.* [28,29,32] pointed out the limits in the correctness of the respective results. On the other hand, we have obtained a radial dependence $P(r)$ (Fig. 2) which evidences the surface character of the first NN collision and thus supports this approach. The case is illustrated in Fig. 2 for nucleons of 20 MeV incident on ^{93}Nb, by means of global optical parameter sets with asymmetry terms of the same magnitude but opposite signs for the two kinds of fermions [22,23]. The widely used potentials of Wilmore and Hodgson [34] and Perey [35] are yet providing similar shapes, with additional surface peaking due to the pure surface character of these optical potentials.

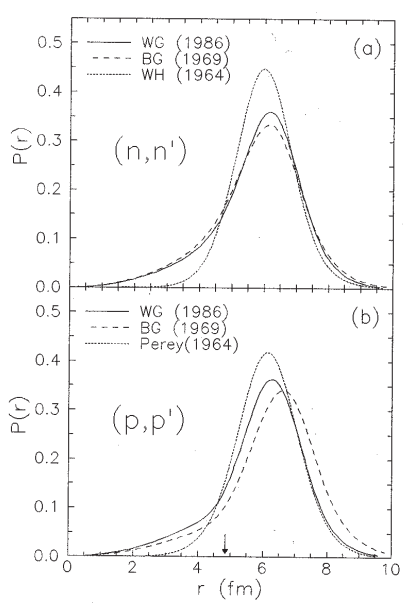

Fig. 2. Radial dependence of the first NN-collision probability, for incident nucleons on ^{93}Nb at the incident energy of 20 MeV. The OMP parameter sets of Walter-Guss (WG) [22], Becchetti-Greenlees (BG) [23], Wilmore-Hodgson (WH) [34], and Perey [35] are used. The arrow indicates the value of the half-density radius [25] of the nuclear matter density distribution for ^{93}Nb.

Under these circumstances, the effective NN-interaction strength averaged along the trajectory of the incident nucleon with respect to both the nuclear density and the first NN-collision probability becomes

$$\overline{V}_0(E_i) = \frac{\int d\mathbf{r}\,\rho(\mathbf{r})P(r)V_0(r,E_i)}{\int d\mathbf{r}\,\rho(\mathbf{r})P(r)} = \frac{\int_0^{R_s} dr\,r^2\rho(r)P(r)V_0(r,E_i)}{\int_0^{R_s} dr\,r^2\rho(r)P(r)} \tag{12}$$

where the integral upper limit is chosen to be equal to the radius R_s=$r_D A^{1/3} + 6a_D$ at which the surface part of the imaginary potential is one percent of its central depth. The present formalism makes it possible to integrate over the whole nuclear volume without any additional assumption on the localization of the first NN collision [33].

The average $\overline{V}_0$ values for the first NN collision corresponding to both the local strengths of the effective NN interaction given by Eq. (11) and the use of the three OMPs within Eq. (12) for the target nucleus ^{93}Nb are compared in Fig. 3 with the phenomenological V_0 values available for the (n,n') and (p,p') reactions. The comparison is done in the energy range of the Walter-Guss OMP. It is meaningful for low energies, due to the negligibly small two-step contribution to the MSD process. On the other hand that contribution could justify the correction factor of $\frac{3}{4}$ at the high energy limit, increasing the agreement with data. The V_0 values predicted by the optical potential of Johnson *et al.* corresponding to Eq. (5) for $E_i \leq$40 MeV and Eq.(4) at higher energies, as well as by the two global parameter sets are shown in Fig. 3(a,d) too. It is obvious the effect of taking into account the density dependence of the effective NN interaction. This behaviour is due to the well-known increase of the effective interaction as the nuclear density reduces [18] and to the increased surface localization of the first NN collision at lower energies (Fig. 2).

The V_0 values predicted by the optical potential of Johnson *et al.* are discussed due to the involvement of this potential within previous analyses. However, the calculation of the respective average values for the target nucleus ^{93}Nb has been carried out by using the probability $P(r)$ given by the global parameter sets [22,23], Fig. 3(b,e). It has been done similarly in the case of the average strengths obtained by using the parametrization based on the Brueckner-Hartree-Fock nuclear matter calculations [24], shown in Fig. 3(c,f). On the other hand, it results from the comparison of the $\overline{V}_0$-values corresponding to one set of V_0 values but different probabilities $P(r)$, as well as obtained with the same $P(r)$ for various $V_0(E_i)$, that the slope of $\overline{V}_0(E_i)$ is given mainly by the surface peaking of $P(r)$.

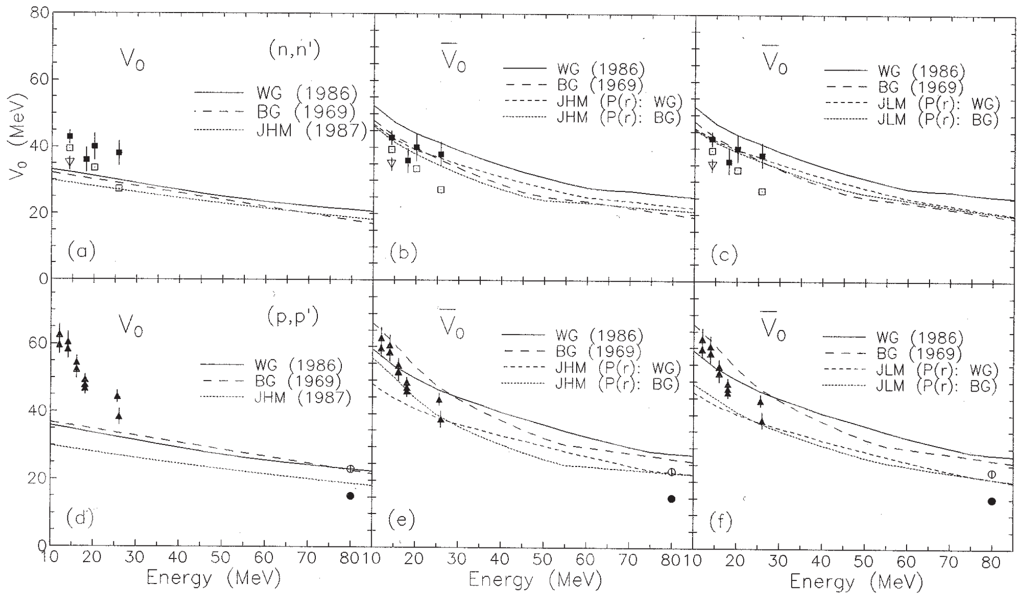

Fig. 3. The same as in Fig. 1 but for (a-c) (n,n') and (d-f) (p,p') reactions, and (a,d) the V_0 and (b,c,e,f) $\overline{V}_0$ values given by the optical potentials used also for Figs. 1,2. The points are from: Watanabe *et al.* [3] (full triangles and squares), Demetriou *et al.* [11] (open triangles), Chadwick *et al.* [12,13] (open squares, full circles), and Cowley *et al.* [8] (open circles).

Large differences between the various average $\overline{V}_0$ values correspond to the (p,p') reactions at lower energies. On the other hand, the agreement between the average strengths obtained with the Hartree-Fock potential plus the dispersive component [10] and by using the parametrization based on the nuclear matter calculations of Jeukenne *et al.* is very good. The underestimation of the absolute V_0 values at the lowest incident energies by the latter approach originates from the similar behaviour at small nuclear density of the expression $F(E_i)$ fitting the isoscalar real potential (Fig. 1 of [24]).

5. FKK calculations by using average interaction strength $\overline{V}_0(E_i)$

The effect of the $V_0(E_i)$-value replacement by the average interaction strength $\overline{V}_0(E_i)$ within FKK multistep reaction calculations is analyzed in this section for neutron-induced reactions on the target nucleus ^{93}Nb at four incident energies between 7 and 26 MeV. No other changes are made in already standard FKK calculations, while the V_0 values given by Eq. (5) following Johnson *et al.* [10] are involved since the good approximation of the widely-used formula (6) of Cowley *et al.* [8].

The first trial has concerned the calculated cross sections which could result if the effective-interaction strength V_0 is not considered as the only adjustable parameter of the MSD model but is taken thus just according to the V_0 systematics [9]. The one-step MSD process, known to contribute mainly in the nucleon-induced reactions at incident energies below 30 MeV, has been estimated by means of the Milano computer code MUDIR [36] enlarged by inclusion of the spherical optical model code SCAT2 [37]. The usual constant single-particle state density $g = A/14$ MeV^{-1} is adopted for calculation of the particle-hole state density in the frame of the Williams formula with additional corrections [38]. The other parameters used in the MSD/MSC calculations have been summarized elsewhere [39]. Similarly, the collective enhancement of the direct scattering cross section due to the low-energy surface vibrations of quadrupole and octupole multipolarity, which is not described by the FKK model, has been included by means of the DWBA method. The DWUCK4 code [40] and a conventional collective form-factor have been thus used, and deformation parameters β_L were derived from results of similar macroscopic DWBA analyses by imposing the condition of equal deformation lengths $\delta_L = R\beta_L$ (where R is the radius of the respective optical potentials).

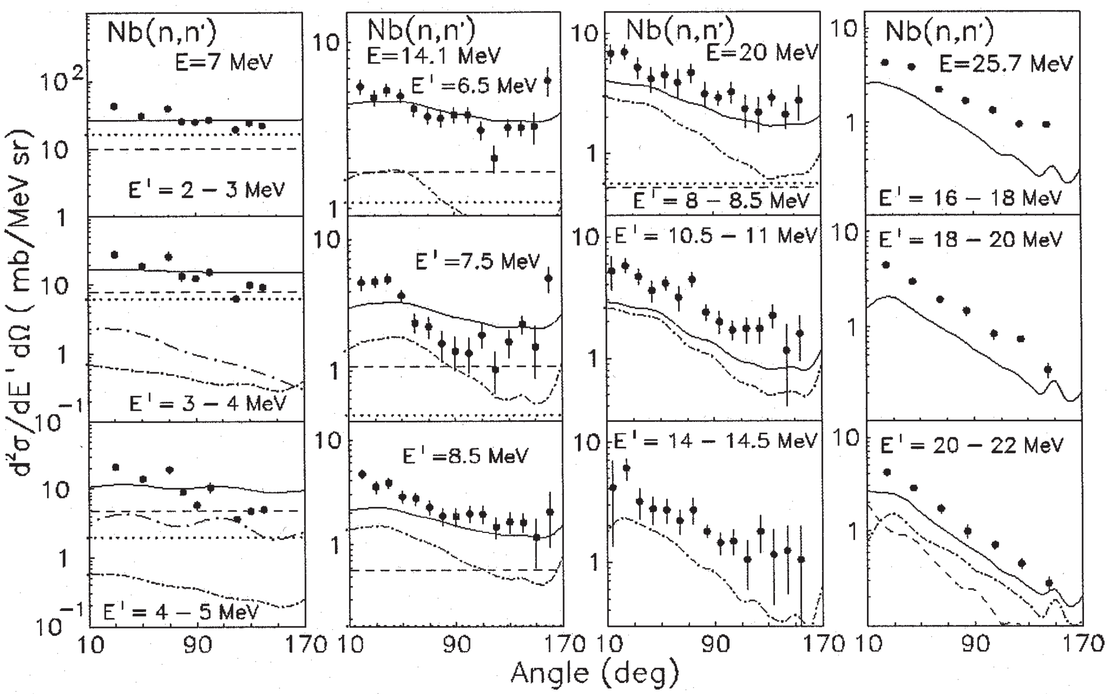

Fig. 4. Comparison of calculated (FKK) and experimental angular distributions of neutrons from 7, 14.1, 20, and 25.7 MeV neutron-induced reactions on ^{93}Nb. Total cross sections (solid curves) include contributions of direct collective excitation (long dashed-dotted), MSD (dotted-dashed) obtained by using the V_0 values given by the optical potential of Johnson *et al.* [10], MSC (dashed) and statistical r-stage (dotted) processes. For experimental data see [39].

The MSC emission from particle-hole bound states (Q space) has been described by the Marcinkowski *et al.* [41] modified FKK theory for gradual absorption of the reaction flux through $P \rightarrow Q$ transitions at the subsequent stages of the reaction. The MSC cross sections have been calculated with an enlarged version of the code GAMME [42] including [43] the optical model code SCAT2. Finally, the code STAPRE-H95 [44,45] is used for the r-stage and second-chance emission calculations.

The double-differential cross-section analysis at intermediate emission energies are generally used in order to determine or check the strength V_0, as it was also the case of our previous analyses [33,39]. Actually, at the incident energy of 7 MeV the MSD contribution is at most one order of magnitude smaller, while it accounts for nearly all emission cross section at incident energies of 20 and 25.7 MeV. However, the lower V_0 values of Eq. (5) used now at this point are leading to underestimated cross sections especially for these higher incident energies (Fig. 4). The change at various incident energies of the MSD and MSC calculated cross sections has been checked also by analyzing the angle-integrated spectra for neutron emission at the four incident energies (Fig. 6).

The calculated cross sections by using average interaction strengths $\overline{V}_0(E_i)$ are shown in Fig. 5 and the right side of Fig. 6. These results are actually obtained without any free model parameter. The average $\overline{V}_0$ values for the first NN collision are especially justifyed as only one-step MSD processes are involved. These $\overline{V}_0$ values, shown by the short-dashed curves in Fig. 3(b), correspond to (i) the local strengths of the effective NN interaction given by Eq. (9) and the same optical potential of Johnson *et al.* [10], and (ii) the probability $P(r)$ given by the global OMP parameter set of Walter and Guss [22]. The latter choice is recommended by the good overall description of the neutron-induced reactions on ^{93}Nb [3,39] in this energy range.

Figures 5 and 6 show a good agreement between the experimental data the FKK results obtained by using the $\overline{V}_0(E_i)$ values, i.e. carried out without free parameters. It is concludent mainly for the MSD component. The MSC processes have already no contribution above the emission energy of 10 MeV, at the incident energies of 20 and 25.7 MeV, so that the intermediate-energy region of respective spectra is given fully by the MSD cross section.

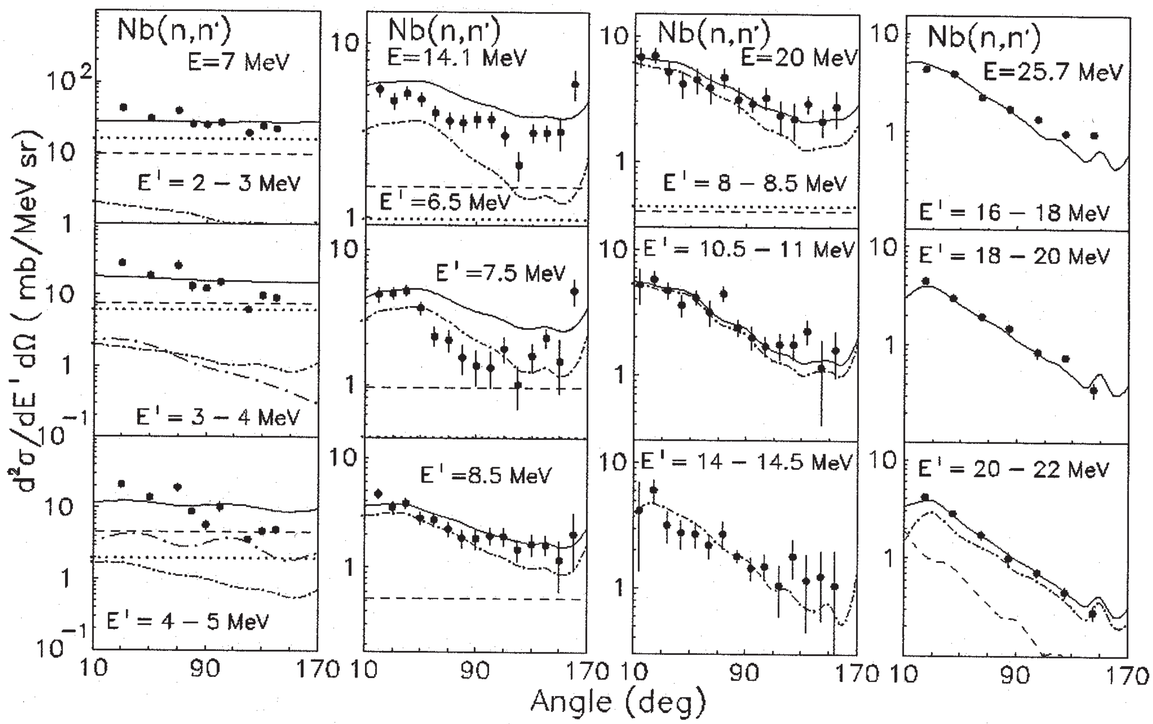

Fig. 5. The same as in Fig. 3, for the use in the FKK calculations of the average $\overline{V}_0$ values for the first NN collision, corresponding to the local strengths of the effective NN interaction given by the use of the optical potential of Johnson *et al.* [10] and the probability $P(r)$ given by the global OMP parameter set of Walter-Guss [22].

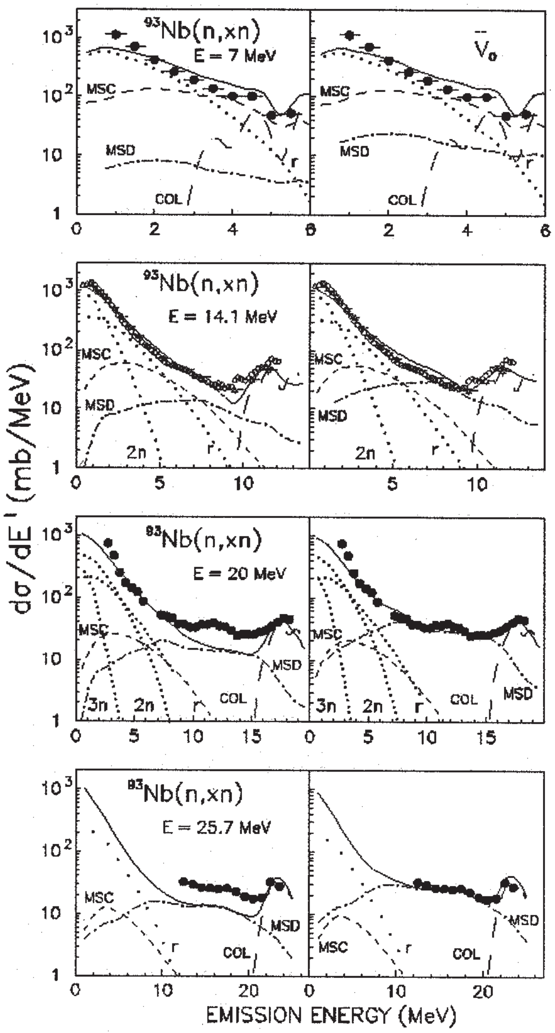

Fig. 6. Comparison of the calculated (FKK) and experimental angle-integrated spectra for ^{93}Nb(n, n') at 7, 14.1, 20, and 25.7 MeV. Calculations are carried out by using (i) the V_0 values given by optical potential of Johnson *et al.* [10] (left side), and (ii) the average $\overline{V}_0$ values for the first NN collision, corresponding to the local strengths of the effective NN interaction from the optical potential of Johnson *et al.* [10] and the probability $P(r)$ given by the global OMP parameter set of Walter-Guss [22]. The curve meaning is the same as in Fig. 5, with addition of the main sequential-decay cross sections (dotted curves). For experimental data see [39].

6. Conclusions and future work

This work has shown that nuclear-density dependence of the effective NN interaction may account for the low-energy phenomenological V_0 values. It may provide the higher strength values which are requested in order to obtain the agreement between the FKK multistep reaction theory and the experimental data, with no free model parameter.

This makes also possible investigaton of other effects which have been yet neglected [9]. The study should be completed by taking into account (i) the whole emission of neutrons and protons, (ii) at all emission energies and angles, (iii) for a number of incident energies, and (iv) for target nuclei of different asymmetry $(N-Z)/A$ since the MSC process becomes more important for (n, p) reactions on nuclei of lower asymmetry.

Acknowledgements. M.A. is grateful to the Soros Foundation for Open Society (Bucharest) for support of participation to the OECD NEA/NSC meeting. This work was carried out under the Romanian Ministry of Research and Technology Contract No. 34/A12 and the Bulgarian National Science Foundation Contract No. Phi-406.

References

[1] E. Gadioli and P.E. Hodgson, *Pre-Equilibrium Nuclear Reactions* (Oxford University Press, Oxford, 1992).

[2] H. Feshbach, A. Kerman, and S. Koonin, Ann. Phys. (NY) **125**, 429 (1980).

[3] Y. Watanabe, A. Aoto, H. Kashimoto, S. Chiba, T. Fukahori, K. Hasegawa, M. Mizumoto, S. Meigo, M. Sugimoto, Y. Yamanouti, N. Koori, M.B. Chadwick, and P.E. Hodgson, Phys. Rev. C **51**, 1891 (1995).

[4] Y. Watanabe, Acta Phys. Slovaca **45**, 749 (1995).

[5] W.A. Richter, Acta Phys. Slovaca **45**, 733 (1995).

[6] R. Lindsay, Acta Phys. Slovaca **45**, 717 (1995).

[7] S. M. Austin, in *The (p,n) Reaction and the Nucleon-Nucleon Force*, edited by C. D. Goodman *et al.* (Plenum, New York,1980), p.203.

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

[9] P.E. Hodgson, Acta Phys. Slovaca **45**, 673 (1995).

[10] C. H. Johnson, D. J. Horen, and C. Mahaux, Phys. Rev. C **36**, 2252 (1987).

[11] P. Demetriou, P. Kanjanarat, and P.E. Hodgson, J. Phys. G **19**, L193 (1993); *ibid.* **20**, 1779 (1994).

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

[13] M.B. Chadwick, P.G. Young, D.C. George, and Y. Watanabe, Phys. Rev. C **50**, 966 (1994).

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

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

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

[17] E. Mordhorst, M. Trabandt, A. Kaminsky, H. Krause, W. Scobel, R. Bonetti, and F. Crespi, Phys. Rev. C **34**, 103 (1986).

[18] W.D. Myers, Nucl. Phys. **A204**, 465 (1973).

[19] A.M. Kobos, B.A. Brown, P.E. Hodgson, G.R. Satchler, and A. Budzanowski, Nucl. Phys. **A384**, 65 (1982).

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

[21] A.N. Antonov, P.E. Hodgson, and I.Zh. Petkov, *Nucleon Momentum and Density Distributions in Nuclei* (Clarendon Press, Oxford, 1988), p. 22.

[22] R.L. Walter and P.P. Guss, Rad. Effects **95**, 73 (1986).

[23] F.D. Becchetti, Jr., and G.W. Greenlees, Phys. Rev. **182**, 1190 (1969).

[24] J.-P. Jeukenne, A. Lejeune, and C. Mahaux, Phys. Rev. C **16**, 80 (1977).

[25] J.W. Negele, Phys. Rev. C **1**, 1260 (1970).

[26] M. Blann, Phys. Rev. Let. **28**, 757 (1972); Nucl. Phys. **A213**, 570 (1973).

[27] M. Avrigeanu, A. Harangozo, V. Avrigeanu, and A. N. Antonov, Phys. Rev. C **54** (1995) *(in press).*

[28] M. Kawai, Prog. Theor. Phys. **27**, 155 (1962).

[29] Y.L. Luo and M. Kawai, Phys. Rev. C **43**, 2367 (1991).

[30] H.C. Chiang and J. Hüfner, Nucl. Phys. **A349**, 466 (1980).

[31] I.E. McCarthy, Nucl. Phys. **11**, 574 (1959); *ibid.* **10**, 583 (1959).
[32] M. Kawai and H.A. Weidenmüller, Phys. Rev. C **45**, 1856; Y. Watanabe and M. Kawai, Nucl. Phys. **A560**, 43 (1993); M. Kawai, Y. Watanabe, and H. Shinohara, Acta Phys. Slovaca **45**, 693 (1995).
[33] M. Avrigeanu, A. Harangozo, V. Avrigeanu, and A. N. Antonov, Acta Phys. Slovaca **45**, 617 (1995).
[34] D. Wilmore and P.E. Hodgson, Nucl. Phys. **55**, 673 (1964).
[35] F.G. Perey, Phys. Rev. **131**, 745 (1963).
[36] R. Bonetti and C. Chiesa, MSD code system, Universita di Milano (unpublished).
[37] O. Bersillon, *SCAT2: Un programme de modele optique spherique*, CEN-Bruyeres-le-Chatel, Note CEA-N-2227, 1981.
[38] C. Kalbach, Nucl. Sci. Eng. **95**, 70 (1987); Z. Phys. A **332**, 157 (1989).
[39] M. Avrigeanu, A. Harangozo, andV. Avrigeanu, Rom. J. Phys. **41**, 77 (1996).
[40] P.D. Kunz, DWUCK4 user manual, OECD/NEA Data Bank, 1984.
[41] A. Marcinkowski, J. Rapaport, R.W. Finlay, C. Brient, M. Herman, and M.B. Chadwick, *Nucl. Phys.* **A561**, 387 (1993).
[42] R. Bonetti, M.B. Chadwick, P.E. Hodgson, B.V. Carlson, and M.S. Hussein, Phys. Rep. **202**, 171 (1991); R. Bonetti and M.B. Chadwick, *GAMME Code*, Oxford University Report OUNP-91-16, 1991.
[43] M. Avrigeanu, A. Harangozo, and V. Avrigeanu, in *Proceedings of the 7th International Conference on Nuclear Reaction Mechanisms*, Varenna, 1994, edited by E. Gadioli (Ricerca Scientifica ed Educazione Permanente, Milano, 1994), p. 165.
[44] M. Uhl and B. Strohmaier, *STAPRE Computer Code for Particle Induced Activation Cross Sections and Related Quantities*, Institut für Radiumforschung und Kernphysik Report IRK 76/01, Vienna, 1976.
[45] M. Avrigeanu and V. Avrigeanu, *STAPRE-H95 Code*, Institute of Physics and Nuclear Engineering Report NP-88-1995, Bucharest, 1995.