Slope anomaly in neutron transfer reactions

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We study one- and two-neutron transfer probabilities in heavy-ion reactions within a semiclassical model. As in the case of the already studied proton transfer reactions, the interplay between absorption and tunneling effects qualitatively reproduces the overall properties of these probabilities and in particular the so-called slope anomaly observed in these reactions. [S0556-2813(98)07006-X]

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The study of nucleon transfer reactions at large internuclear distances is usually done assuming that the influence of the nuclear potential is very small (see, for example, Refs. [1–3]). The standard theoretical interpretation [4] considers a classical Rutherford trajectory and the transfer probability is determined by the tunneling of the transferred particle through an effective potential barrier created by the donor and acceptor core nuclei at the distance of closest approach. Within this semiclassical model the transfer probability is given by

$$P_{tr} \propto \sin(\theta/2) e^{-2\kappa D_{Ruth}}, \tag{1}$$

with

$$\kappa = \sqrt{2\mu B_{eff}/\hbar^2}, \tag{2}$$

where μ and B_{eff} are the reduced mass and the effective barrier height to be traversed by the transferred particle and D_{Ruth} is the distance of closest approach for a Rutherford trajectory at the given scattering angle θ. The decay constant κ is energy independent and it can be seen from Eq. (2) that its value of for two-nucleon transfer is approximately twice than that for one-nucleon transfer.

The experimentally observed transfer probabilities are usually plotted as a function of D_{Ruth}. When this is done, the plot presents an exponential falloff at large distances [1,5,6]. In the case of one-neutron transfer, these slopes are well approximated by Eq. (1) in most of the measured cases [1,7]. However, deviations from the expected values of the slopes have been reported in two-neutron transfer reactions, which in the literature are referred to as ''slope anomalies'' [8].

Recently we have proposed a model to analyze one- and two-proton transfer probabilities [9,10]. In this model we have assumed that the relative motion of the colliding heavy ions is governed by the real part of the total Coulomb plus nuclear optical potential. We have also taken into account the absorption due to the imaginary part of the optical potential and considered that the transfer process occurs via tunneling at the point of closest approach. Two-nucleon transfer reactions are assumed to proceed by simultaneous transfer of

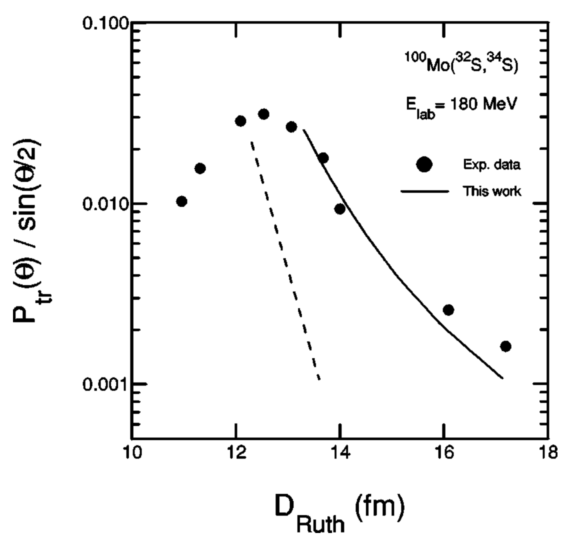

FIG. 1. Transfer probability divided by $\sin(\theta_{c.m.}/2)$, as a function of D_{Ruth} for the ^{100}Mo(^{32}S,^{34}S) reaction at E_{lab}=180 MeV. Filled circles are the experimental data of Ref. [7], solid lines are the theoretical results of this work normalized to the data, and the dashed line is an exponential with the decay constant of Eq. (2) and arbitrary normalization.

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TABLE I. Experimental and theoretical values of the decay constant κ.

Reaction	E_{lab} (MeV)	κ [Eq. (2)] (fm^{-1})	κ (Expt.) (fm^{-1})	κ (Theor.) (fm^{-1})
$^{100}Mo(^{32}S,^{33}S)$	180	0.63	0.54	0.48
$^{100}Mo(^{32}S,^{34}S)$	180	1.16	0.34	0.39
$^{96}Mo(^{32}S,^{33}S)$	180	0.67	0.48	0.50
$^{96}Mo(^{32}S,^{34}S)$	180	1.27	0.30	0.38
$^{208}Pb(^{28}Si,^{30}Si)$	152	1.16	1.34	1.16
$^{208}Pb(^{28}Si,^{30}Si)$	225	1.16	0.41	0.41
$^{92}Mo(^{36}S,^{34}S)$	180	1.27	0.23	0.29

the two nucleons [10]. We have shown that the competition between tunneling and absorption explains the apparently anomalous energy dependence of the slopes of the proton transfer probabilities.

For energies above the Coulomb barrier several trajectories can contribute to the same scattering angle, but only the two corresponding to the largest impact parameters survive the absorption process. Of these, one is essentially a Rutherford trajectory and the other ''feels'' more strongly the nuclear field. Since the Rutherford trajectory dominates because it feels no absorption, the slopes of the one-proton transfer probabilities are approximately given by the standard formula, Eq. (2). On the other hand, in the two-proton transfer case, the tunnneling probability in the Rutherford trajectory is hindered due to the larger mass of the cluster and the fact that the barrier is wider. In this case the second trajectory, even taking into account absorption, contributes significantly to the transfer probability because for it the actual distance of closest approach is smaller. The dependence of the transfer probability on D_{Ruth}, now only a parametrization of the scattering angle, is very different in this trajectory [9] and it follows that the addition of the two contributions explains the slope anomaly and the energy dependence of the slopes.

It is the purpose of this work to show that the model of Refs. [9] and [10] also qualitatively reproduces the behavior known as slope anomaly in neutron transfer reactions. In the calculations presented here, we have taken the prescriptions of Broglia and Winther [11] for both the real part of the nuclear optical potential and the potential to be traversed by the transferred nucleons, except that we have used a diffuseness $a = 0.65$ fm in the nuclear optical potential. For the imaginary part of the optical potential we considered the same geometrical parameters as for the real part and a strength $W_0 = 30$ MeV.

As an example of our calculations we take the $^{100}Mo(^{32}S,^{34}S)^{98}Mo$ reaction at 180 MeV of laboratory energy measured by Herrick *et al.* [7]. The experimental data are indicated by the filled circles with the error bars quoted by the authors in Fig. 1. The solid line is the calculation described above normalized to the data and the dashed line is an exponential with the decay constant of Eq. (2) with arbitrary normalization. It may be seen that our calculation predicts a significantly smaller slope, in qualitative agreement with the data.

In Table I we present a comparison of the measured and calculated values of the decay constant κ for a variety of neutron transfer reactions. The first column indicates the reaction considered, the second is the laboratory energy, and in column 4 are the experimental slopes taken from the compilation of Rehm *et al.* [1]. In columns 3 and 5 we write the theoretical values as calculated by Eq. (2) and the model of Refs. [9,10], respectively. The theoretical values were obtained by means of an exponential fit to the calculated results in the range of D_{Ruth} between 15 and 18 fm. The discrepancy between experiment and Eq. (2) in the case of two-neutron transfer is the slope anomaly. There is satisfactory agreement between our theory and the experimental data, especially taking into account that no attempt at parameter fitting was made. One should remark, however, that our calculations indicate only the general trend of the transfer data, which may be distorted by specific structure effects, such as deformation of one or both collision partners.

In conclusion, we have shown that the semiclassical model of heavy-ion transfer reactions is capable to explain the slope anomaly in neutron transfer if we consider the influence of the optical nuclear potential in the trajectory and in the absorption process.

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[1] K. E. Rehm, B. G. Glagola, W. Kutschera, F. L. H. Wolfs, and A. H. Wuosmaa, Phys. Rev. C **47**, 2731 (1993).

[2] J. F. Liang, L. L. Lee, Jr., J. C. Mahon, and R. J. Vojtech, Phys. Rev. C **50**, 1550 (1994).

[3] M. Wilpert, B. Gebauer, Th. Wilpert, W. von Oertzen, H. G. Bohlen, and J. Speer, Phys. Rev. C **47**, 2731 (1993).

[4] G. Breit and M. E. Ebel, Phys. Rev. **103**, 679 (1956).

[5] R. B. Roberts, S. B. Gazes, J. E. Mason, M. Satteson, S. G. Teichmann, L. L. Lee, J. F. Liang, J. C. Mahon, and R. J. Vojtech, Phys. Rev. C **47**, 1831 (1993).

[6] D. Tomasi, J. O. Fernández Niello, A. O. Macchiavelli, A. J. Pacheco, J. E. Testoni, D. Abriola, O. A. Capurro, D. E. Di Gregorio, M. di Tada, C. P. Massolo, and F. Penayo, Phys. Rev. C **48**, 2840 (1993).

[7] D. M. Herrick, F. L. H. Wolfs, D. C. Bryan, C. G. Freeman, K. L. Kurz, D. H. Mathews, P. A. A. Perera, and M. T. Zanni, Phys. Rev. C **52**, 744 (1995).

[8] C. Y. Wu, W. von Oertzen, D. Cline, and M. W. Guidry, Annu. Rev. Nucl. Part. Sci. **40**, 285 (1990).

[9] H. D. Marta, R. Donangelo, D. Tomasi, J. O. Fernández Niello, and A. J. Pacheco, Phys. Rev. C **54**, 3156 (1996).

[10] H. D. Marta, R. Donangelo, D. Tomasi, J. O. Fernández Niello, and A. J. Pacheco, Phys. Rev. C **55**, 2975 (1997).

[11] R. A. Broglia and A. Winther, *Heavy Ion Reactions* (Addison-Wesley, Redwood City, CA, 1991).