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ON MECHANISM OF THE PROTON TRANSFER REACTIONS

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1. Introduction

In surface collisions of the complex nuclei one, or several nucleons can transfer from target to projectile or vice versa. These transfer reactions are, usually, the typical direct interaction processes.

The theoretical discription of the single neutron transfer reactions, for energies below the Coulomb barrier, was developed by Breit and coworkers[x]. Information concerning the neutron reduced widths in the bound states of initial and final nuclei may be obtained by comparing the experimental data with predictions of this tunneling theory.

At energies above the Coulomb barrier, the presence of nuclear interaction makes the theoretical description of the transfer process more difficult and one is compelled, for the present, to the use of rather phenomenological models. The transfer reaction models for energies above the Coulomb barrier were proposed by Kammuri[2], Kalinkin and Grabowski[3], Greider[4], Strutinsky[5], Frahn and Venter[6], and Dar[7].

Most of the available data on transfer reactions have been obtained by investigating the neutron transfer. Experiments have been performed on many targets and in relatively wide energy range. On the contrary, the data on the proton transfer are scanty and they contain only the results obtained on light nuclei[8-13].

The present work has been undertaken to get information concerning the general behaviour of the proton transfer reactions, and in particular, about the influence of the Coulomb interaction on the proton transfer process.

Our earlier experiments showed that this influence is of great importance. When the reactions (^{12}C, ^{13}N) on ^{209}Bi and ^{197}Au nuclei were investigated ($E_{lab.} = 82$ MeV), no ^{13}N products were observed above the background level. The upper limit of the cross section, obtained in these experiments had been about 0.005 mb. On the other hand, our results concerning the same reaction (^{12}C, ^{13}N) on ^{27}Al and ^{12}C nuclei[14] showed that in the region of light nuclei the corss sections become significantly larger, of the order of 10^{-27} cm^2. Moreover, a comparison of these results with the neutron transfer data shows distinct differences in the general behaviour of the excitation functions.

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[x] See ref.[1], and earlier papers cited there.

These facts have encouraged us to perform experiments in the region of the intermediate nuclei. In the present work the angular distributions of the proton transfer reaction (^{12}C , ^{13}N) were investigated for several targets, covering a wide range of Z . The experiments were performed at different energies of the ^{12}C ions.

In order to see what is the influence of the proton binding energy in the final nucleus on the cross section of the transfer process, the angular distribution in the reaction $^{181}Ta(^{14}N, ^{15}O)^{180}Hf$ was also measured.

The experiments were performed with the external beam of the 150 cm cyclotron of the Laboratory of Nuclear Reactions, JINR. The maximum energy of the ^{12}C ions was 82 MeV, and the ^{14}N ions energy was 108.5 MeV.

A method of the radioactive products detection was used. The particles, coming from the target were collected on the aluminium catcher foils at different angles. The ^{13}N and ^{15}O reaction products are the β^+ emitters with 10 min and 2 min half-life, respectively. The β^+ activity of the catchers was measured by registration of the annihilation gammas in two scintillation counters, connected to the coincidence circuit. A more complete description of the experimental procedure has been published previously/14/.

When the $^{181}Ta(^{14}N, ^{15}O)^{180}Hf$ reaction was investigated, a reaction chamber with the ring Mylar window was used . This made it possible to collect the ^{15}O reaction products outside the chamber and pass the catchers quickly to the detector after irradiation.

The energy distributions of the reaction products were not analysed in detail. The measured activities of the catchers corresponded to the total reaction yields. In the (^{12}C , ^{13}N) reactions the final products were registered in the ground state only, because all the ^{13}N excited states are unstable with respect to particle decay. Therefore, the measured reaction yield corresponded to the all possible excitations of the final target nucleus. In the $^{181}Ta(^{14}N, ^{15}O)^{180}Hf$ reaction both the ^{180}Hf and ^{15}O could be detected in the excited states.

2. Results and Discussion

The (^{12}C , ^{13}N) reaction on the ^{12}C, ^{27}Al, ^{51}V, ^{93}Nb, $^{107,109}Ag$ and ^{181}Ta nuclei was investigated. Targets with natural content of isotopes were used. The proton transfer $^{12}C(^{12}C, ^{13}N)^{11}B$ and $^{27}Al(^{12}C, ^{13}N)^{26}Mg$ data were published in our previous paper/14/, in which the diffraction effects in the transfer reactions were discussed. These results are used here in the discussion of the total cross section magnitudes.

The angular distributions in the (^{12}C , ^{13}N) reaction on the ^{51}V, ^{93}Nb, Ag and ^{181}Ta nuclei are shown in figs. 1,2,3 and 4 , respectively. Fig. 5 presents the results obtained for the $^{181}Ta(^{14}N, ^{15}O)^{180}Hf$ reaction. The angular distribution are generally similar to the neutron transfer data. Most of the reaction products are emitted in a relatively narrow angular interval, forming a typical peak. In all cases the position of the maximum corresponds approximately to the surface collision trajectory.

A distinct difference between the neutron and proton transfer occurs in the cross section magnitudes and in their dependence on energy. The excitation functions for the investigated proton transfer reactions are shown in fig. 6. The experimental points are obtained by an integration of the angular distributions. The cross sections are plotted versus $(E_{c.m.} - E_B + \frac{1}{2}Q)/A_i$, where $E_{c.m.}$ is the initial centre-of-mass energy, E_B is the height of the Coulomb barrier and A_i is the mass number of the incident ion. Therefore, the data are referred to the same relative velocities at the moment of the transfer process. The Coulomb barrier heights were taken for the interaction radius values, obtained from analysis of the angular distributions by means of the Frahn-Venter model/6/ (Table 1).

The results, shown in Fig. 6, lead to the following conclusions: (1) The cross section of the proton transfer reaction (^{12}C , ^{13}N) falls down quickly with increasing Z of the target. Passing from aluminium to tantalum, the cross section decreases to about $\frac{1}{100}$ of the initial value (for equivalent energies). This effect does not occur in the neutron transfer reactions, in which the cross

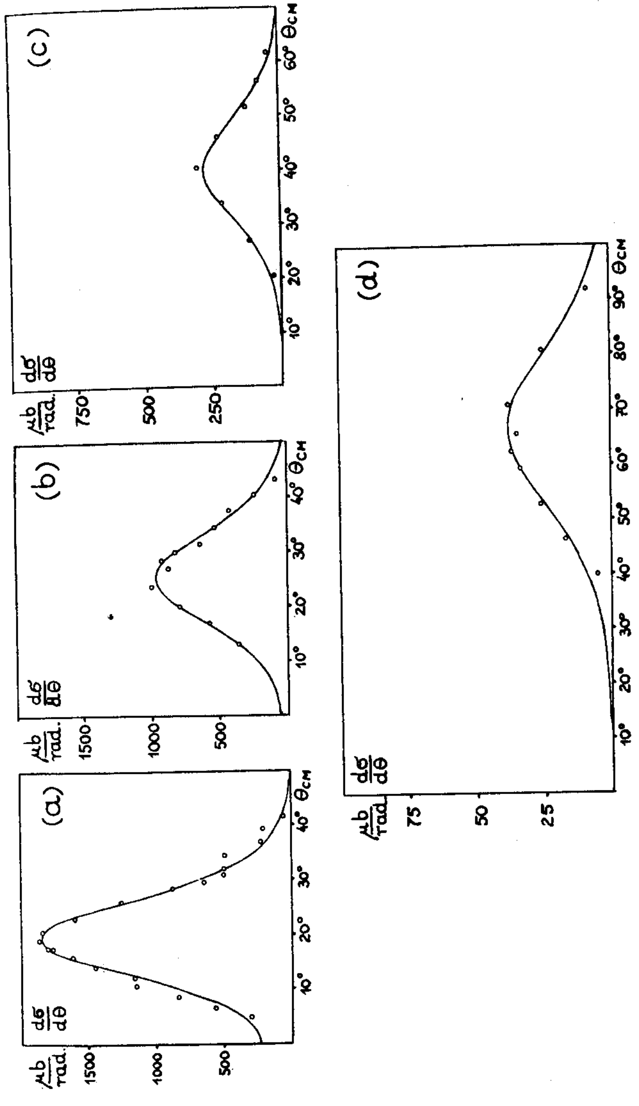

Fig. 1. Angular distributions in the reaction $^{51}V(^{12}C, ^{13}N)^{50}Ti$. Solid lines are calculated on the basis of the Frahn-Venter model. (a): E = 65.6 MeV, T′ = 48.7, Δ′ = 3.10, r = 0.340; (b): E = 55.4 MeV, T′ = 40.6, Δ′ = 2.73, r = 0.246; (c): E = 43.2 MeV, T′. = 28.1, D. = 2.43, r = 0.141; (d): E = 31.7 MeV, T′ = 18.4, Δ′ = 1.54, r = 0.055.

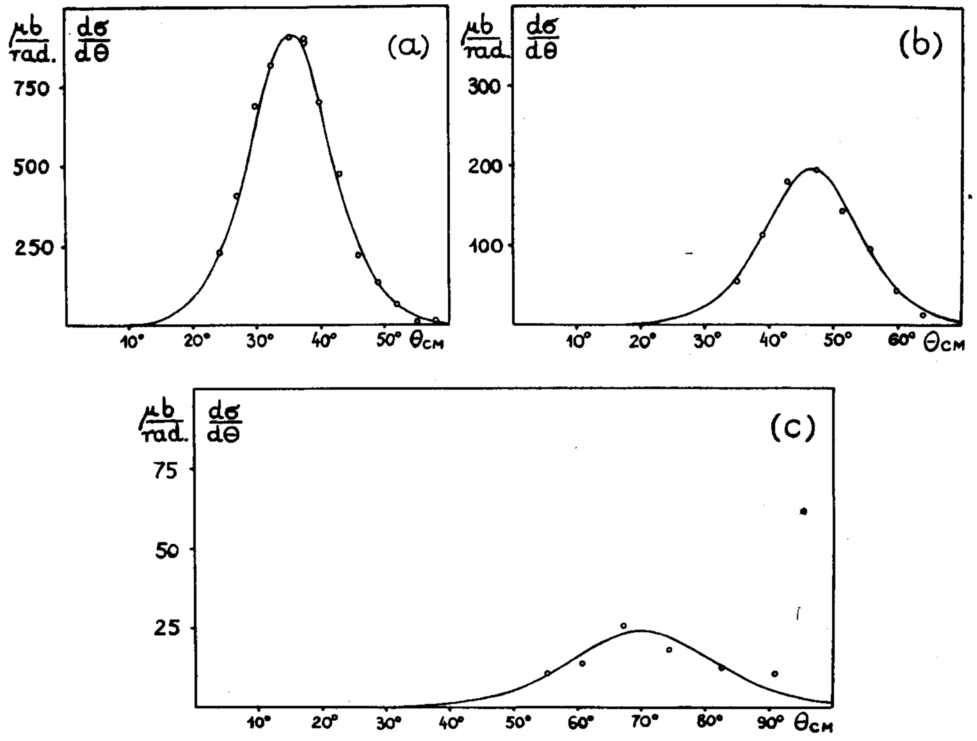

Fig. 2. Angular distributions in the reaction $^{93}Nb(^{12}C, ^{13}N)^{92}Zr$. Solid lines are calculated on the basis of the Frahn-Venter model (a): E = 71.0 MeV, T′ = 47.0, Δ′ = 3.56, r = 0.264; (b): E = 59.7 MeV, T′ = 38.0, Δ′ = 3.13, r = 0.125; (c): E = 46.8 MeV, T′ = 26.4, Δ′ = 2.06, r = 0.046.

Fig. 2.

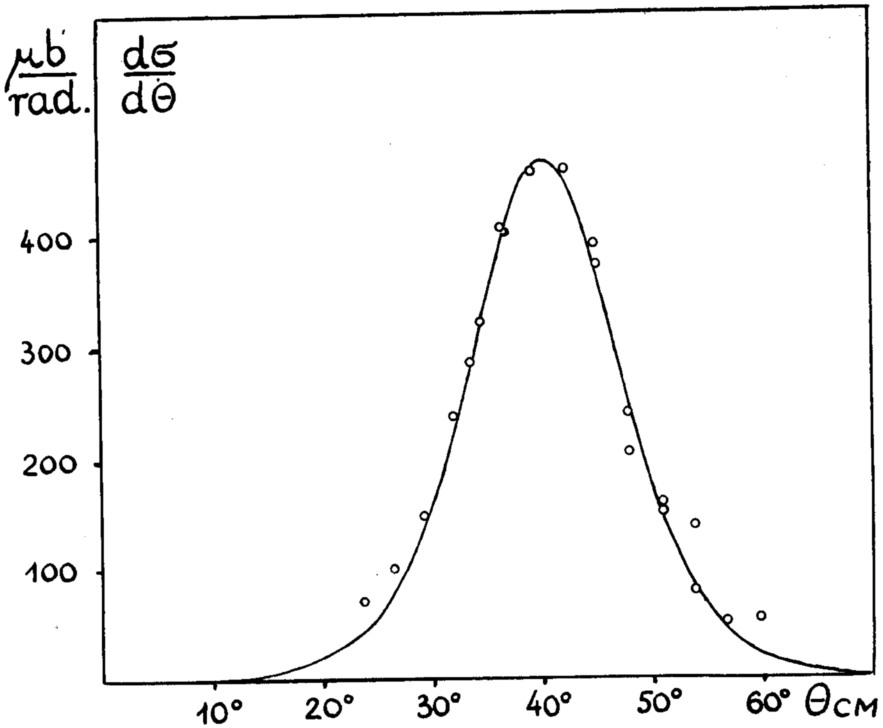

Fig. 3. Angular distribution in the reaction Ag(^{12}C, ^{13}N) Pd at energy E = 72.3 MeV. Solid line is calculated on the basis of the Frahn-Venter model: T′ = 46.8, Δ′ = 3.37, r = 0.193.

Fig. 3.

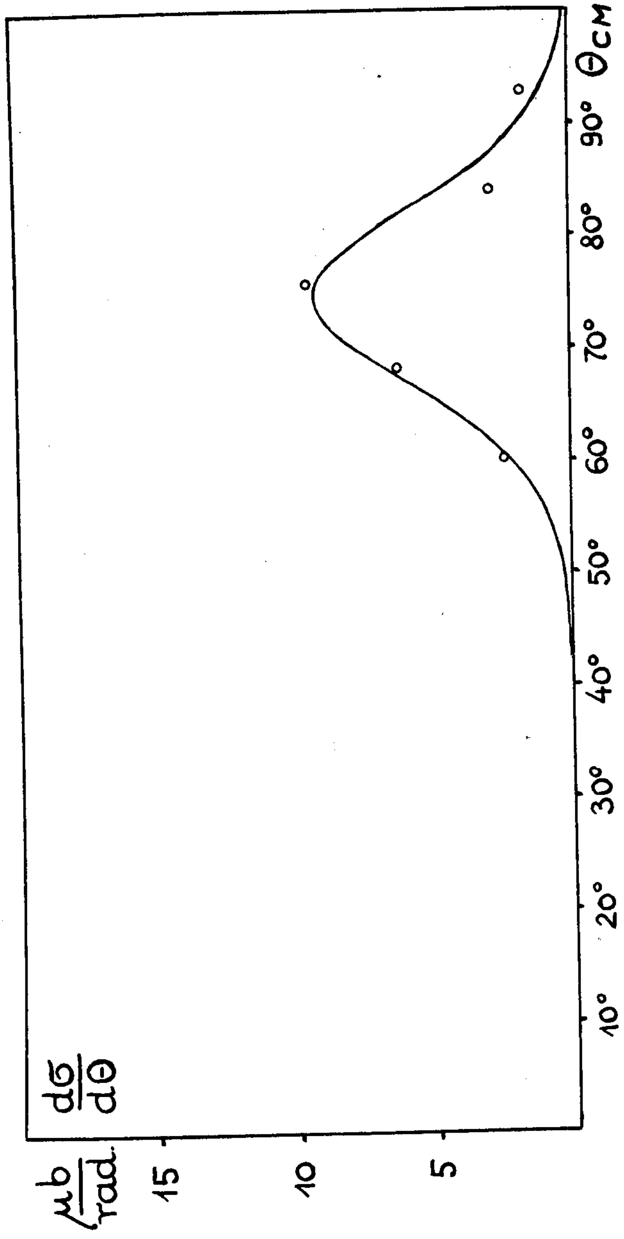

Fig. 4. Angular distribution in the reaction ^{181}Ta(^{12}C, ^{13}N) ^{180}Hf at energy E = 74.4 MeV. Solid line is calculated on the basis of the Frahn-Venter model: T′ = 35.5, Δ′ = 2.84, r = 0.032.

Fig. 4.

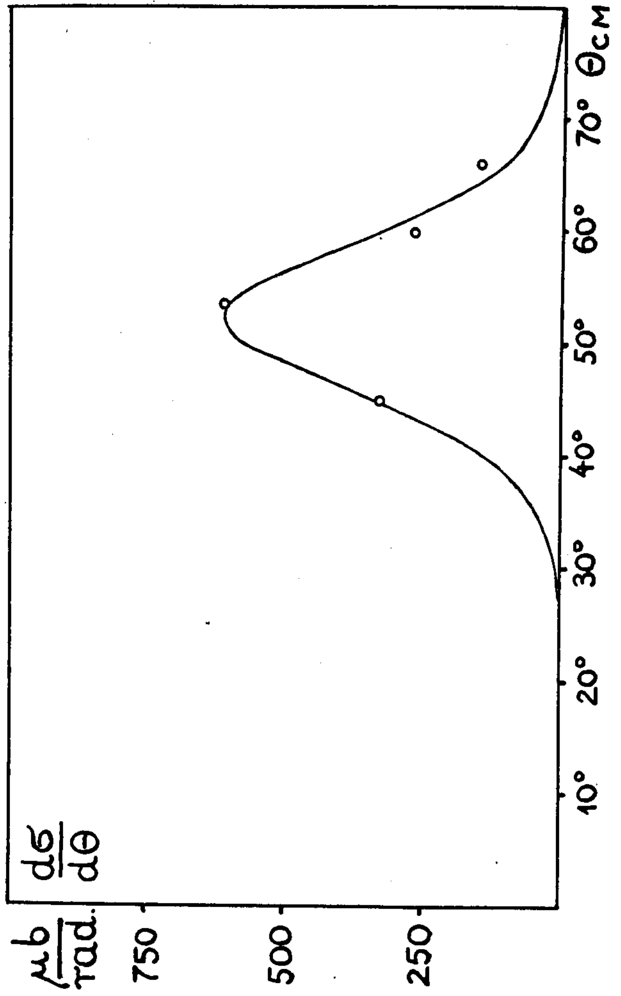

Fig. 5. Angular distribution in the reaction $^{181}Ta(^{14}N,\ ^{15}O)^{180}Hf$ at energy E = 98.4 MeV. Solid line is calculated on the basis of the Frahn-Venter model: T′ = 59.6, Δ′ = 3.41, r = 0.253.

Fig. 5.

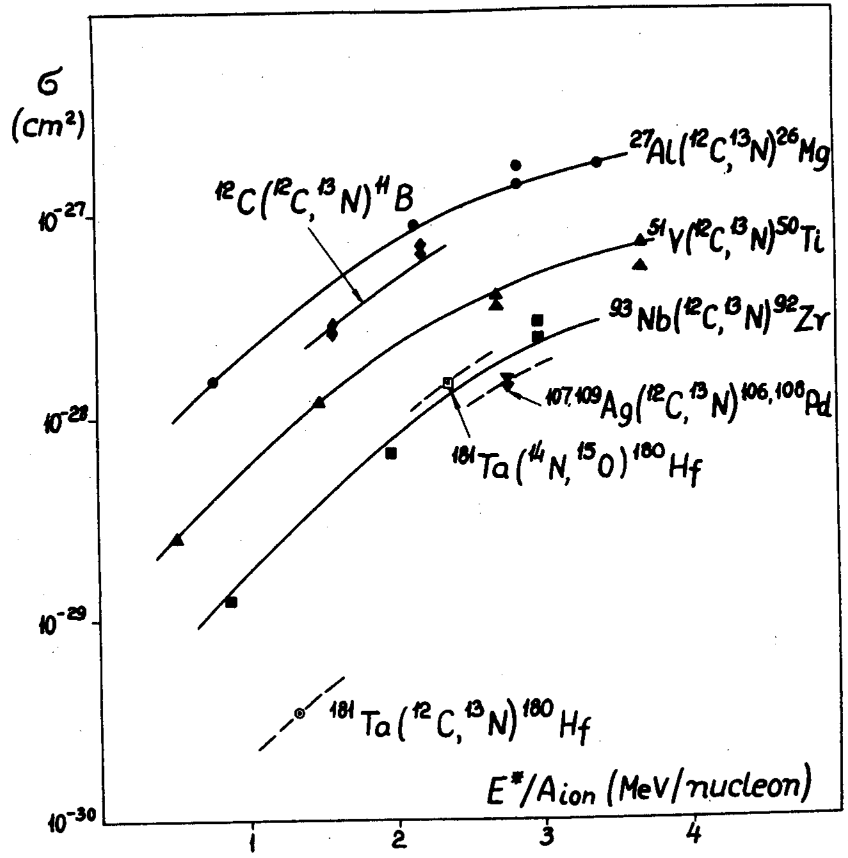

Fig. 6. Total cross sections plotted against energy $E^* = (E_{c.m.} - E_B + \frac{1}{2}Q)/A_i$, where $E_{c.m.}$ is the initial energy, E_B the height of the Coulomb barrier and A_i is the mass number of the incident ion.

Fig. 6.

section slowly grows large, when the value Z increases. (2) When the incident energy decreases, the cross section of the proton transfer reaction reduces more rapidly than in the neutron transfer case. This effect will be shown more distinctly later on. (3) A comparison of the reactions (^{12}C , ^{13}N) and (^{14}N ^{15}O) on ^{181}Ta seem to show that the change in the proton binding energy in the final nucleus (1.943 MeV in ^{13}N , 7.291 MeV in ^{15}O) has a great effect on the cross section of the transfer. One must remember however that in the reaction (^{14}N , ^{15}O) the excited states of the ^{15}O nuclei contribute to the reaction yield, and this may account largely for the increase of the cross section. A high background due to the ^{13}N nuclei, produced in the neutron stripping reaction (^{14}N , ^{13}N) , made it impossible to make a fair estimate of the contribution from the excited state of ^{15}O reaction channels.

For a more detailed analysis of the obtained results we have used the Frahn-Venter model/6/. The angular distributions of the single nucleon transfer reactions can be analysed in the framework of this model by means of three phenomenological parameters: T' , Δ', and τ . The parameter T' is the value of the variable $t = \ell + ½$, for which the amplitudes distribution of the partial waves has a maximum. The value T' is connected with the interaction radius $R' = r'_0 (A_1^{1/3} + A_2^{1/3})$ and is determined by the position of maximum in the angular distribution- θ'_0 and by the value of the Coulomb parameter $n = mZ_1Z_2e^2/\hbar^2 k$, where m is the reduced mass, Z_1 and Z_2 the atimic numbers of projectile and target, respectively, and k is the wave number. The parameter Δ' determines the width of the amplitudes distribution in ℓ space. This parameter is related to the surface width d' of the interaction region. The relative strength of the transfer interaction is determined by the parameter τ . The maximum value of the amplitudes distribution is equal $\tau/4\Delta'$, and should not depend upon the kinematic conditions. Frahn and Venter had analysed the neutron transfer reactions data/15-17/and showed, that the value $\tau/4\Delta'$ does not depend significantly upon energy and is practically constant for different targets; in all analysed cases these values lay in the interval 0.1- 0.2.

The angular distributions presented in figs. 1-4 and 5 were analysed by means of the Frahn-Venter model. The solid lines are calculated on the basis of this model, under the assumption that the diffraction oscillations, inessential

in this analysis, are completely damped. The obtained values of the parameters are presented in Table 1. The results of analysis for the reactions (^{12}C , ^{13}N) on the ^{12}C and ^{27}Al nuclei/14/ are also included.

The values of the parameters T' and Δ' , giving the "geometry" of a proton transfer process, appear close to those which have been obtained in case of the neutron transfer reactions for equal kinematic conditions. One can therefore conclude that the proton- and neutron transfer processes do not differ in the effective interaction radius and in a surface width of the interaction region.

A significant difference between these two reactions appears in the probabilities of the transfer process, expressed by the $\tau/4\Delta'$ values. The dependence of the value $\tau/4\Delta'$ for the investigated proton transfer reactions upon the target Z number and upon the kinetic energy at the moment of collision is shown in fig. 7. The probability of the proton transfer in the reaction (^{12}C, ^{13}N) rapidly reduces with the increasing of Z . For the fixed Z , the value $\tau/4\Delta'$

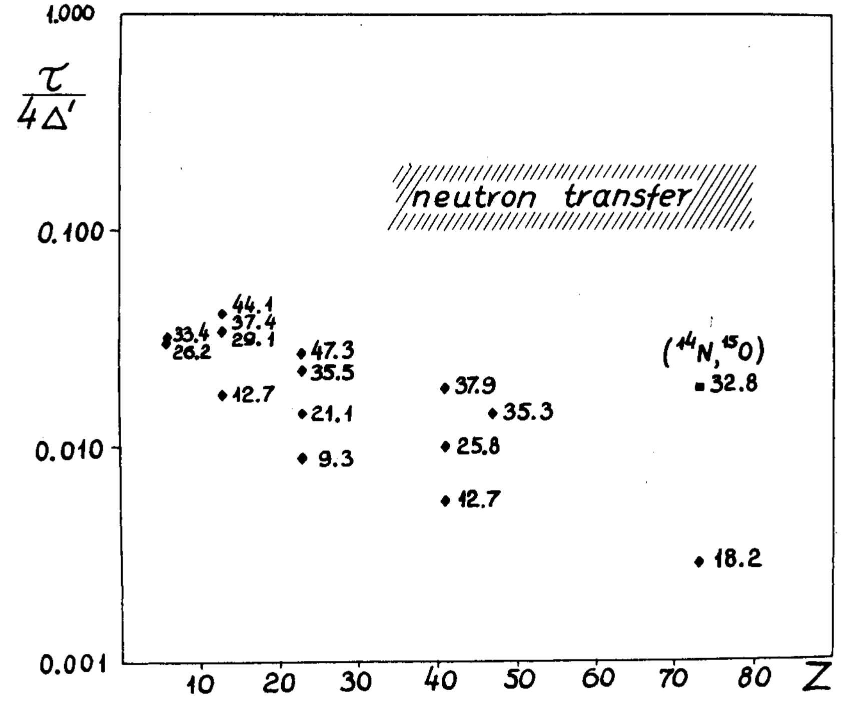

Fig. 7. Values of the parameter $\tau/4\Delta'$ plotted against the target atomic number Z . The kinetic energies at the moment of collision, $E_{c.m.} - E_B$, are noted at the corresponding experimental points. The dashed area denotes the region, within which lay all the experimental points, corresponding to the neutron transfer data/16-18/.

decreases when energy becomes smaller. The effect is more distinct at low energies. These results are different from those for neutron transfer reactions, for which the parameter $r/4\Delta'$ shows no systematic dependence on the atomic number and on the energy. The dashed area in fig. 7 indicates the region of change of $r/4\Delta'$ for neutron transfer reactions.

A relatively large value of the parameter $r/4\Delta'$ in the case of the reaction $^{181}\mathrm{Ta}\,(^{14}\mathrm{N},\,^{15}\mathrm{O})\,^{180}\mathrm{Hf}$ shows, perhaps, that the change of the proton binding energy in the final transfer product influences the cross section magnitude. However, as it was pointed out before, these data cannot be treated as conclusive.

The experimental results for the reaction $(^{12}\mathrm{C},\,^{13}\mathrm{N})$ on the $^{51}\mathrm{V}$ and $^{93}\mathrm{Nb}$ were analysed by Gareyev and Kalinkin in the framework of the Kalinkin-Grabowski model[3]. An analysis of the angular distributions for the reaction $^{51}\mathrm{V}\,(^{12}\mathrm{C},\,^{13}\mathrm{N})\,^{50}\mathrm{Ti}$ at energies 65.6, 55.4, and 43.2 MeV and the reaction $^{93}\mathrm{Nb}\,(^{12}\mathrm{C},\,^{13}\mathrm{N})\,^{92}\mathrm{Zr}$ at energies 71.0 and 59.7 MeV gives the value of the a parameter equal to 0.8 fm^{-1}, for all cases (a is a parameter related to the matrix element of the transition). This value is close to those which one obtains in the analysis of the neutron transfer data[15-17]. However, a large disagreement appears between the calculated excitation functions (normalized to the experimental data for the highest energy) and our results. The cross section in the proton transfer reactions reduces more rapidly with the descreasing energy than one can expect on the basis of the Kalinkin-Grabowdki model. This fact and the good agreement with the model predictions the case of the neutron transfer reactions show that in the proton transfer new effects occur, which are not taken into account by this model.

The observed specific behaviour of the proton transfer reactions may be caused by the Coulomb interaction in the proton transfer process. In reactions with the heavy nuclei, a relatively large "polarization" of the proton wave function in the final nucleus is possible, especially, when the proton binding energy in this nucleus is small. The "polarization" of the proton wave function would reduce the value of the matrix element of the transition. This effect should increase with the target Z number. At the higher energies the conditions of the transfer process become more adiabatic and then the polarization effect decreases. This fact may be the cause of the differences in the shapes of the excitation functions in the proton and neutron transfer reactions.

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Frahn-Venter Model Parameters for Proton Transfer Reactions

Reaction	Q value (G.G.) (MeV)	$E_{c.m.}$ (MeV)	n	θ'_0 (deg.)	T′	r'_0 (fm)	Δ′	d′ (fm)	r	$\frac{r}{4\Delta'}$	σ_{tot} (μb)
$^{12}C(^{12}C,{}^{13}N)^{11}B$	-I4.0I3	40,5	2.I8	II,0	22,6	I,59	I,76	0,5I	0,227	0,0322	670
		34.I	2.38	I5.0	I8.I	I.44	I.0I	0.32	0.I2I	0,0305	270
$^{27}Al(^{12}C,{}^{13}N)^{26}Mg$	-6,329	55.4	4.76	I3.0	4I.8	I.88	2.57	0.54	0.424	0,04I3	I720
		48.7	5.07	I5.0	38.5	I.88	2.3I	0.52	0.378	0.04I0	I550
		40.8	5.54	I9.2	32.8	I.8I	2.I3	0.52	0.295	0.0346	880
		26.4	6.88	40.7	I8.4	I.54	I.75	0.50	0.I22	0.0I74	I54
$^{51}V(^{12}C,{}^{13}N)^{50}Ti$	-6.I0I	65.6	8.36	I9.5	48.7	I.8I	3.I0	0.55	0.340	0.0274	625
		55.4	9.II	25.3	40.6	I.67	2.73	0.53	0.246	0.0226	368
		43.2	I0.30	40.3	28.I	I.50	2.43	0.5I	0.I4I	0.0I46	I20
		3I.7	I2.02	66.5	I8.4	I.48	I.54	0.34	0.055	0.0089	26
$^{93}Nb(^{12}C,{}^{13}N)^{92}Zr$	-4.0I5	7I.0	I5.0	35.4	47.0	I.57	3.56	0.56	0.264	0.0I85	268
		59.7	I6.4	46.6	38.0	I.54	3.I3	0.52	0.I25	0.0I00	65
		46.8	I8.5	70.0	26.4	I.53	2.06	0.35	0.046	0.0056	I2,4
$Ag(^{12}C,{}^{13}N)Pd$	-4.I40	72.3	I7.2	40.3	46.8	I.56	3.37	0,52	0.I93	0.0I43	I46
$^{181}Ta(^{12}C,{}^{13}N)^{180}Hf$	-4.256	74.4	26.8	74.2	35.5	I.4I	2.84	0,36	0.032	0.0029	3,5
$^{181}Ta(^{14}N,{}^{15}O)^{180}Hf$	+I.092	98.4	29.2	52.2	59.6	I.39	3.4I	0.38	0.253	0.0I86	I43