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# ALIGNMENT AND POLARIZATION IN ($^{14}N$, $^{12}B$) REACTIONS

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## 1. INTRODUCTION

In a series of papers Takahashi et al. (see ref.[1] for a summary) reported on measurements of the $^{12}B$ -polarization in ($^{14}N$, $^{12}B$) transfer reactions on heavy targets (Mo, Th) by means of detecting the anisotropy of $\beta$-rays emitted in the decay of the ground state of the final $^{12}B$ nucleus. For various incident energies ($E_{Lab}$=90 MeV, 125 MeV, 200 MeV) the kinetic energy spectra and the Q-dependence (Q being the energy loss) of the polarization P have been determined at a fixed detection angle. In the quasielastic region the regularities of $P(Q, \Theta=\mathrm{const})$ observed in the experiment have been interpreted by Ishihara[2] within a semiclassical theory of single-step transfer processes proposed by Brink[3]. For the deeper inelastic region the basic trends of the polarization as a function of Q, in particular the change of the sign of the polarization, can be followed within a two-dimensional classical friction model including statistical fluctuations. Such a conclusion can be drawn from a simple balance of the cross sections for positive and negative angle scattering[4] as well as from investigations utilizing a somewhat more involved averaging procedure[5]. But, it should be stressed, that the degree of polarization predicted by such a classical model for deep-inelastic collisions is in general too high, by a factor up to about four.

Recently, new experimental data on the $^{12}B$ polarization in ($^{14}N$, $^{12}B$) reactions are available for $^{14}N$ (200 MeV)+$^{232}Th$($\Theta_{Lab}$=30°)[1] and for much lighter targets, $^{14}N$ (120 MeV)+$^{27}Al$, $^{14}N$(120 MeV)+$^{nat}Cu$($\Theta_{Lab}$=20°)[6]. In addition, information on the alignment of $^{12}B$, extracted from $\beta$-anisotropy by means of M-substate interchange using NMR, are offered for $^{14}N$(200 MeV)+ + Mo, Th[1].

The present paper contains an analysis of these data in the framework of the classical friction model described in detail in refs.[4,5]. For the sake of simplicity mass transfer and deformation effects are neglected. The numerical calculations have been performed with the code TRAJEC 2[7]. In conclusion it is pointed out that for smaller Q-values (higher energy loss) the tendencies in the behaviour of the polarization as a function of incident energy, target nucleus, observation angle, and Q can be interpreted on the same level of agreement between theory and experiment as in previous investigations, using only one set of friction parameters. In particular, the investigations demonstrate that the small alignment does not contradict the classical friction concept for a basic element of the underlying interaction mechanism.

## 2. FRICTION PARAMETERS

The calculations have been performed with one set of strength parameters for the radial and tangential components of the friction tensor

$$a_r = 17{,}0 \text{ fm/c MeV}, \qquad a_\Theta = 0{,}523 \text{ fm/c MeV}. \tag{1}$$

These values are somewhat higher than those used in ref. /4/ for $^{14}$N+Mo and $^{14}$N+Th at 90 MeV and 125 MeV

$$a_r = 15{,}0 \text{ fm/c MeV}, \qquad a_\Theta = 0{,}389 \text{ fm/c MeV}. \tag{2}$$

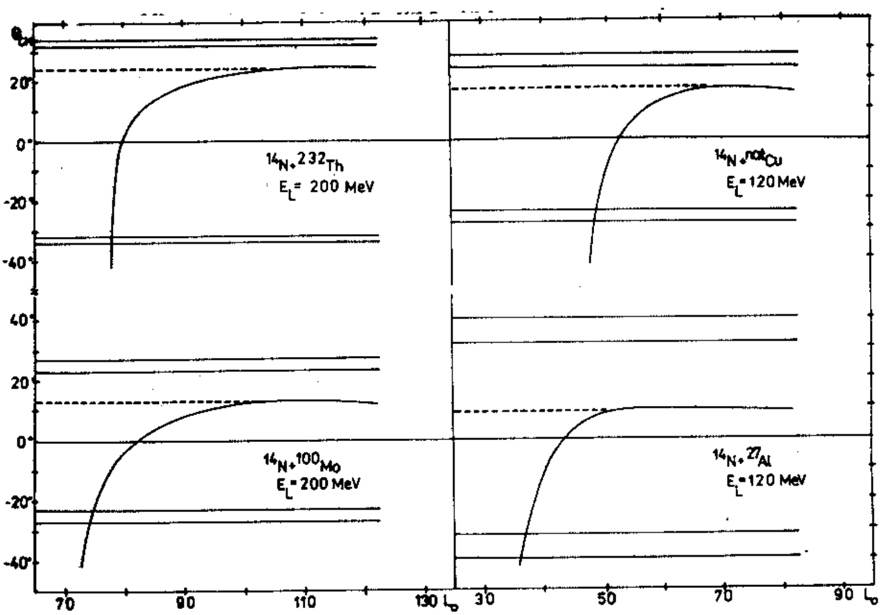


Fig. 1. Deflection function $\Theta(\ell)$ for various ($^{14}$N, $^{12}$B) reactions investigated in the present paper. Dashed line: grazing angle $\Theta_{gr}$. Shadowed area: centre of mass angle regions corresponding to detector positions at which polarization (and alignment) has been measured.

Choosing the parameter set (1) instead of (2), the critical $\ell$-value for fusion remains unchanged because the empirical constraint on $a_r$, $a_\Theta$ suggested in ref. [8] has been taken into account. This was checked again for the $^{14}N(120$ MeV)+ +$^{27}Al$ reaction, for which $\ell_{cr}=32\hbar$ has been obtained, corresponding to a fusion cross section of $\sigma_{Fu}^{(theor)}=0{,}92$ b. This value can be related to $\sigma_{Fu}^{(exp)}=1{,}36\pm0{,}2$ b measured at somewhat higher incident energies ($E_{Lab}=157$ MeV) [9].

The results of the calculations are presented in figs. 1-7, partly in comparison with available experimental data.

## 3. POLARIZATION

Al (fig. 2): For lighter systems as N+Al and N+Cu the classical friction concept for deep-inelastic collisions becomes more questionable in the energy range under discussion. Only a small band of about 20 initial partial waves contributes to the deep-inelastic cross section ($^{14}N(120$ MeV)+ $^{27}Al$: $\ell_{max}=50\hbar$, $\ell_{cr}=30\hbar$). In the experimental kinetic energy spectra of $^{12}B$ the quasi-elastic and the deep-inelastic collisions are not clearly separated (see bottom parts of figs.). The energy dissipation amounts about 50 MeV which is perhaps too low to reach level densities in the fragments which allow a description of the excitation in a global fashion as a friction mechanism. On the average the light ejectile carries a relatively large fraction of the mean dissipated energy so that events with one final fragment being in its ground state are reached only by strong fluctuations. The estimated fraction of the mean dissipated angular momentum transferred to the light fragment goes up to about $1\hbar$, but staying within the limits of allowed angular momentum transfer in $1^+\to1^+$ transitions. The fluctuations in the z-component of the dissipated angular momentum are reaching the same amounts as the mean value itself. In the N+Al reaction the detection angle corresponds to approximately 15 degrees backward from the grazing angle $\Theta_{gr}$. In the experiment a small positive polarization is observed for $Q\approx Q_{gg}$ while a large negative polarization, $|P|\approx 0{,}2$, is found for all larger energy losses. From a classical reaction model one expects a dominating negative angle scattering for $\Theta\gg\Theta_{gr}$ which explains the negative polarization for $Q\lesssim-30$ MeV. The decrease of $|P|$ for $Q\gtrsim-30$ MeV results from positive angle scattering because of fluctuations of the trajectory in angle. The decrease of $|P|$ for $Q\lesssim-60$ MeV may be attributed to orbiting trajectories (see also ref. [5]). The calculations are rather sensitive to parameter variations (compare fig. 2). For a weaker friction force $a_r=15{,}0$ fm/c MeV,

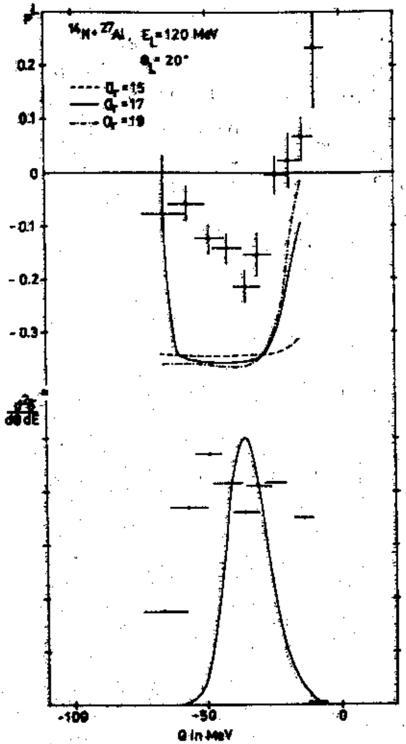


Fig.2. Kinetic energy spectrum and polarization for the reaction $^{14}N + ^{27}Al$, $E_{Lab}$ = =120 MeV. The experimental data are taken from ref. /6/. $a_r$, $a_\Theta$: strength parameters of the components of the friction tensor ($a_r$ =15,0; 17,0; 19,0 fm/c MeV; $a_\Theta$=0,389; 0,523; 0,676 fm/c MeV).

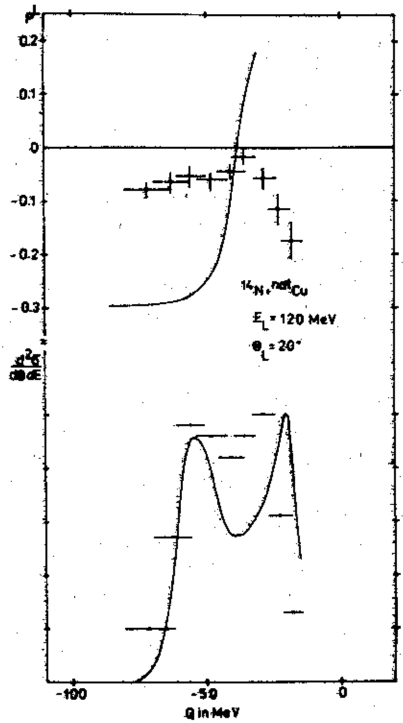


Fig.3. Kinetic energy spectrum and polarization for the reaction $^{14}N + ^{nat}Cu$, $E_{Lab}$=120 MeV. The experimental data are taken from ref. /6/. Strength parameters of the components of the friction tensor: $a_r$ = =17,0 fm/c MeV, $a_\Theta$=0,523 fm/c MeV.

$a_\Theta$ =0,389 fm/c MeV the fluctuations in the positive scattering angles are reduced so that the polarization remains large and negative also for $Q \gtrsim -30$ MeV. Enlarging the friction force, $a_r$ =19,0 fm/c MeV and $a_\Theta$ =0,676 fm/c MeV, or taking into account deformation effects leads to a trapping of those trajectories exhibiting an orbiting situation in the former calculations. The same result appears if one takes a stronger tangential friction only, $a_r$ =17,0 fm/c MeV and $a_\Theta$ =0,6 fm/c MeV.

Cu(fig.3): The polarization in N+Cu has been measured near the grazing angle, with a Q-dependence of the polarization

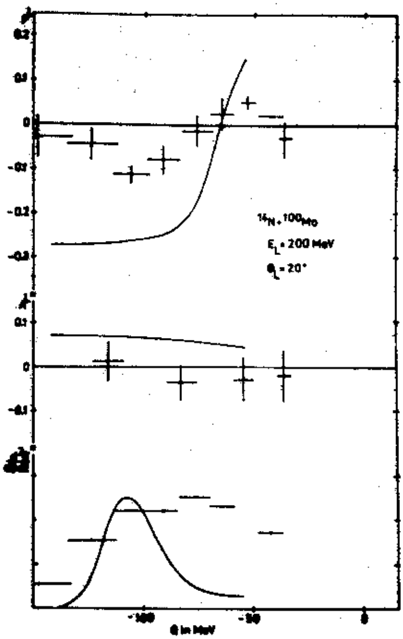


Fig.4. Kinetic energy spectrum, polarization and alignment of the light fragment for the reaction $^{14}N+^{100}Mo$, $E_{Lab}$=200 MeV at an observation angle of $\Theta_{Lab}$ =20°. The experimental data are taken from ref./1/. Strength parameters of the components of the friction tensor: $a_r$ =17,0 fm/c MeV, $a_\Theta$ =0,523 fm/c MeV.

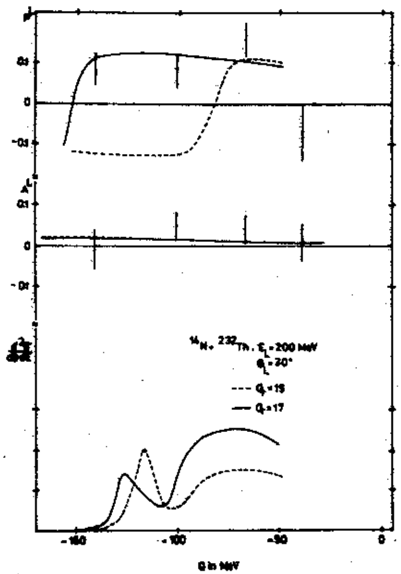


Fig.5. Kinetic energy spectrum, polarization and alignment of the light fragment for the reaction $^{14}N+^{232}Th$, $E_{Lab}$= =200 MeV at an observation angle of $\Theta_{Lab}$=30°. The experimental data are taken from ref./1/. Strength parameters of the components of the friction tensor: $a_r$ =15,0; 17,0 fm/c MeV, $a_\Theta$=0,389; 0,523 fm/c MeV.

similar to that obtained for N+Mo. The classical model explains the negative polarizations for $Q \lesssim -30$ MeV but predicts a positive polarization for $Q \gtrsim -30$ MeV. Apparently, in the latter region a different reaction mechanism becomes effective.

Mo (fig.4): The polarization shows a regular behaviour as is seen in previous experiments. The predicted maximum polarization degree in the deep-inelastic region is twice the experimental value only.

Th (fig.5): The sign of the measured polarization remains positive for $Q \lesssim -50$ MeV down to about − 150 MeV. This behaviour is predicted within the friction model which gives an appreciable negative angle scattering for $Q \lesssim -100$ MeV only. As indicated by the experimental data, this effect diminishes $|P|$ for higher energy losses (see also the deflection function depicted in fig. 1). Also the degree of polarization is reproduced by the calculations. A weaker friction force, $a_r = 15{,}0$ fm/c MeV, $a_\Theta = 0{,}389$ fm/c MeV would lead to negative polarization for $Q \lesssim -80$ MeV.

## 4. ALIGNMENT

The alignment $A = 1 - 3a_0$ $(-2 \leq A \leq +1)$ measures the population $a_0$ of the magnetic substate M of the I = 1, M = 0, ±1 ground state of $^{12}B$ $(a_0 + a_1 + a_{-1} = 1,\ P = a_1 - a_{-1})$. In the experiment [1] it turns out to be as small as +0,1 in the whole Q-range for N+Th while it is practically zero (within the error bars) for N+Mo.

Matsuoka et al. [10] calculated the alignment of $^{12}B$ as a function of the excitation energy E*of the heavy residual nucleus for N (90 MeV)+Mo using the semiclassical transfer model of refs. [2,3]. In this approach the probability for the cluster transfer is optimized if the kinematical conditions for the conservation of linear momentum and angular momentum are satisfied. The population of the magnetic substate M is calculated from the approximate form of the cross section in which the kinetical conditions are properly incorporated.

In such calculations Matsuoka et al. [10] found $A = +0{,}84$ for the ground state transition, negative A-values of $A \approx -0{,}4$ for $E^* \approx 10$ MeV; then the alignment increases up to $A \approx +0{,}75$ for $E^* \approx 30$ MeV. Definitely, from the semiclassical model for quasi-elastic transfer reactions one expects an alignment, which for smaller Q-values is too large compared with experiment. In the friction model the population of the M = 0 substate proceeds via fluctuations of the in-plane components $I_x, I_y$ of the dissipated angular momentum $\vec{I} = (I_x, I_y, I_z)$. The predicted alignment is always positive because of the vanishing expectation values of the x, y-components of $\vec{I}$; $\langle I_x \rangle = \langle I_y \rangle = 0$ ($\langle I_z \rangle = \Delta\ell$: mean dissipated orbital angular momentum, out of reaction plane). Distributing the expectation value $\langle I_z \rangle$ (and the fluctuations) between the fragments according to

$$\langle I_z \rangle_i = \langle I_z \rangle \frac{J_i}{J_1 + J_2} \quad \text{and} \quad \langle \sigma_z^2 \rangle_i = \langle \sigma_z^2 \rangle \frac{J_i}{J_1 + J_2}\left(1 + \frac{J_k}{J_{rel}}\right) \text{ for } i,k = 1,2 \qquad (3)$$

(see eq. (4) and (5) of ref. [5]) the light (heavy) fragment L(H) gets a rather small (large) mean z-component of the angular momentum ($^{14}N$ (200 MeV)+ $^{232}Th$: $\langle I_z^{(L)} \rangle \approx 0{,}1\hbar$, $\langle I_z^{(H)} \rangle \approx 13{,}9\hbar$ for a partial wave with $\ell = 92\hbar$). Assuming for each fragment the

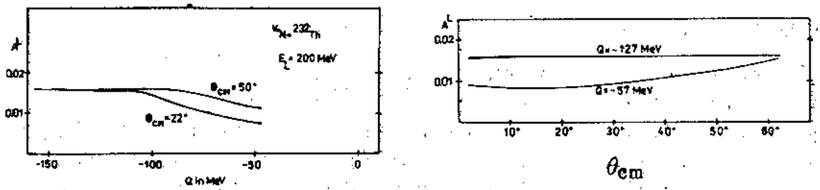


Fig.6. Reaction $^{14}N + ^{232}Th$, $E_{Lab}$=200 MeV. Calculated alignment $A^{(L)}$ of the light fragment as a function of observation angle $\Theta$ and Q-value.

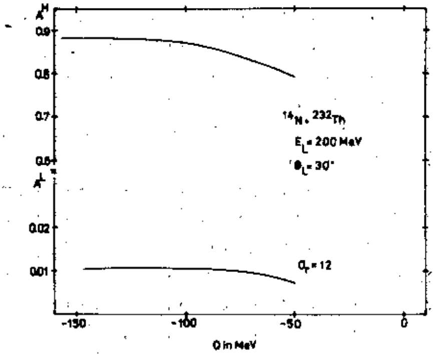


Fig.7. Calculated alignment $A^{(H)}$ of the heavy fragment in the reaction $^{14}N+^{232}Th$, $E_{Lab}$= =200 MeV at ($\Theta_{Lab}$=30°. Friction parameters: $a_r$=17,0 fm/c MeV, $a_\Theta$ =0,523 fm/c MeV. Alignment $A^{(L)}$ of the light fragment in the same reaction calculated for a weaker friction force: $a_r$=12,0 fm/c MeV, $a_\Theta$= =0,233 fm/c MeV.

same fluctuations for the in-plane components $I_x, I_y$ as for the z-component, the alignment will be small (large) for the light (heavy) fragment. In contrast to the semiclassical transfer model, this handling of expectation values and fluctuations within a classical friction model makes the statistical population of the M=0 substate in the fragment highly probable. The calculated alignment $A(\Theta, Q)$ shows a rather weak and smooth dependence on the observation angle and Q, as can be seen from fig.6. For both reactions, N+Mo and N+Th, we find the alignment of $^{12}B$ to vary between ≈ +0,05 and +0,07 in the range of small Q-values, in rather good agreement with the experimental data (see figs. 4,5). Because $\langle I_z^{(H)} \rangle$ is large compared to the fluctuations, the heavy fragment exhibits a strong alignment increasing with the energy loss from ≈0,8 to ≈ 0,9 (fig.7). The influence of reasonable changes in the friction parameters on the calculated alignment of the light fragment is negligible (fig.7).

For the reaction $^{14}N+^{100}Mo$ at $E_{Lab}$=90 MeV an alignment of A≈+0,04 comes out in the range of Q≈-30 MeV which is much smaller than the value expected by Matsuoka et. al. /10/.

## 5. CONCLUDING REMARKS

The main features in the Q-dependence of the $^{12}B$ ground state polarization observed in $(^{14}N, ^{12}B)$ reactions for various targets and incident energies can be interpreted crudely in a classical friction model including statistical fluctuations. In particular, the small alignment detected in the whole Q-range is reproduced while a semiclassical transfer model predicts large values of the alignment in the transition region from quasi-elastic to deeper inelastic collisions. The inclusion of deformation effects and mass transfer could improve the agreement between measured and calculated energy spectra but would not change qualitatively the above statements on orientation effects. However, one can state that the assumption of a single-step direct transition and a global friction mechanism separately do not give a consistent interpretation of the orientation phenomena for the whole Q-range. A more refined picture for the reaction has to be suggested, especially for kinematic regions, where none of the simple mechanisms is clearly dominating. So, for a collision with high energy transfer to the heavy residual nucleus one could expect several phases. (i) Inelastic excitations in the entrance and exit channel, which can be treated statistically as a frictional damping of the relative motion, at least for the heavier targets, while for the light fragments nonstatistical and quantal effects have to be admitted. This interaction would lead likely to a partial polarized state of the system, with fairly large degrees of polarization. (ii) A two-particle transfer is superimposed, which can change the orientation of the fragments appreciably. Such a more-step mechanism could also explain the low polarization degree observed if interference effects become effective. (Even for high energy losses the discrepancy between the measured and calculated degree of polarization is especially large for the reaction N+Cu for which the measurements have been done near to the grazing angle.)

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