сообщения
объединенного
института
ядерных
исследований
дубна

E4-81-26

R.Schmidt*, R.Reif*

STATISTICAL FLUCTUATIONS AND POLARIZATION IN DEEP INELASTIC HEAVY ION COLLISIONS

* Present address: Technische Universität Dresden, Sektion Physik Dresden, DDR.

1981

1. Introduction

The reaction mechanism of deep inelastic heavy ion collisions (DIC) can be further explored by investigating the orientation properties of the reaction products, which for a given intrinsic spin I may be specified by the expection values (ensemble average) of a complete set of 2I spherical tensor operators. In particular, extended information on the lowest moments of the fragment spin, e.g., the vector polarization and the alignment, would lead to a more detailed understanding of the process of angular momentum dissipation. But the determination of the nuclear orientation from observing the angular distribution, angular correlation or polarization of the subsequent radiation, emitted from the decaying system, encounters considerable experimental difficulties. So, up till now only few measurements of the alignment or the sign and the degree of the fragment polarization have been reported for DIC.

In the reaction ^{40}Ar(284 MeV and 303 MeV) + Ag Trautmann et al.[1] determine the circular polarization of γ-Rays emitted from both products as a function of the kinetic energy loss. For quasi-elastic and deep inelastic events the sign of the polarization turned out to be opposite. In the deep inelastic region the polarization was directed along the axis $\vec{k}_i \times \vec{k}_f$, where $\vec{k}_i$ and $\vec{k}_f$ denote the incoming and ougoing wave vector, respectively.

The polarization of the projectile-like fragment has been deduced by Takahashi et al.[2] for the reaction $^{100}Mo(^{14}N,^{12}B)\,^{102}Ru$, E_{Lab} = 90 MeV, 125 MeV, and 200 MeV at definite reaction angles. In this specific collision the polarization follows from the anisotropy of ß-rays emitted in the ß-decay of the ^{12}B ground state ($I^{\pi} = 1^{+}$, $T_{1/2}$ = 20.3 ms, $E_{\beta max}$ = 13.4 MeV). Selecting certain regions of the kinetic energy spectra of ^{12}B by a range--energy method, a systematic trend in the Q-value dependence of the polarization has been observed: (i) In the quasielastic part of the spectrum an appreciable amount of polarization (up to about 50°/o) is detected. The degree of polarization decreases for decreasing Q-value with a change in sign from negative to positive near the Coulomb energy. (ii) In the deep inelastic region the degree of polarization remains small, never exceeding 15 °/o. The behaviour of the polarization as a function of Q depends on the bombarding energy. For incident energies of 125 MeV and 200 MeV the polarization changes the sign again, becoming negative for $Q \lesssim -70$ MeV, while for $E_{Lab} = 90$ MeV the polarization stays at positive values in the whole measured range of Q-values below $Q \approx -25$ MeV. From complementary measurements for the reaction $^{14}N(129\ MeV) + {}^{232}Th$ Takahashi et al.[3] obtained a positive polarization (up to about 20 °/o) in a broad range of low Q-values between - 40 MeV and - 90 MeV.

Several attempts have been made to give an at least qualitative interpretation of the characteristic features of the polarization data on heavy ion reactions. In a more general consideration Ellis[4] discussed the polarization phenomena by employing the formal expression for the transition amplitude. In order to find simple formula the asymptotic forms of the Clebsch-Gordan coefficients involved as well as a parametrization of the matrix element in the l-space have been introduced. The applicability of the model for transfer reactions has been demonstrated by comparing with exact DWBA-calculations. Furthermore, particular models have been used to explain specific observations. For large Q-values (quasielastic region) the polarization data can be understood in terms of the kinematical matching conditions for a direct two-particle transfer mechanism as suggested by Brink[5] and pointed out in refs.[6,7] for the reaction $^{100}Mo(^{14}N, ^{12}B)$. In the deep inelastic region the sign of the measured polarization is consistent with the predictions of the macroscopic friction model[8]. But the amount of polarization found in the experiments of Takahashi et al. are far below the classical limit. In a recent paper, Dünnweber and Hartmann[9] emphasized the importance of the dispersion around the mean classical path for this strong depolarization. This effect was discussed by expressing the polarization observed for certain values of reaction angle and energy loss in terms of the corresponding cross sections for positive and negative deflection, the angular spreading of which is parametrized in Gaussian form.

The special aim of this note is to consider quantitatively the importance of statistical fluctuations and correlations in the collective variables of the relative motion for the fragment depolarization in the framework of the statistical theory of Hofmann and Siemens[10] and a classical friction model[11] with friction parameters adjusted to independent experimental data. In accordance with this macroscopic picture the polarization for given reaction angle and Q-value is calculated from the partial double differential cross sections for positive and negative angle scattering, as already suggested in ref. [9]. Numerical calculations have been performed for the ^{14}N induced reactions, in which the polarization of the fragment ^{12}B has been measured by the Japanese group. These experiments (mainly on a non-symmetrical light system) project on a final situation, which from the point of view of a macroscopic model with statistical fluctuations should be regarded as some extreme case: transfer of two particles, zero excitation energy and low spin of the projectile-like fragment. So, one cannot expect a complete interpretation of all experimental details by such calculations. But a comparison of the theoretical predictions with the polarization observed for different target-projectile combinations, as a function of the incident energy and the Q-value, should give some insight to what an extent the basic features of the phenomena, as derived from a classical friction model including statistical fluctuations of the deflection angle and kinetic energy, are reflected in the experimental data available. Moreover one can draw conclusions on the importance of further depolarization mechanisms as statistical fluctuations of the transferred angular momentum [12,13,14] as well as the manifestation of quantal fluctuations, which should be of importance for the excitation of discrete lowlying fragment states.

2. Classical Friction Model and Polarization.

We treat the heavy ion reaction within a two-dimensional friction model [11] with polar coordinates R, Θ as collective variables for the relative motion of both nuclei. All basic quantities of the model are described in ref. [11]. For the reaction under discussion we use the values

$$a_R = 15.0 \text{ fm/c MeV} \qquad a_\Theta = 0.38879 \text{ fm/c MeV} \tag{1}$$

for the radial and tangential friction strengths, and in addition we neglect the deformation energy ($\alpha = 0$). This choice of parameters has been taken for the following reasons:

(i) The parameters (1) fit very well the fusion cross sections in a broad range of target-projectile combinations, because they have been calculated according to the empirical relation between these quantities as introduced in [11]. Particularly, for the reactions $^{14}N + ^{103}Rh$, Elab = 81 MeV and E_{Lab} = 121 MeV, i.e., for a similar target-projectile combination at comparable incident energies as discussed in the present paper, the theoretical values of the critical angular momentum for fusion l_{cr}^{exp} = 39 and 51 are in excellent agreement with $l_{cr}^{exp} = 40 \pm 5$ and 52 ± 5 deduced from experimental data by Galin et al.[15].

(ii) The parameters (1) reproduce the double humped shape of the experimental kinetic energy spectrum in the reaction ^{14}N(125 MeV) + ^{100}Mo with two peaks at $Q \approx -20$ MeV and $Q \approx -40$ MeV corresponding to **predominant positive and negative angle scattering**, respectively (see fig. 1). The theoretical double differential cross section $d^2\sigma/d\theta\, dQ$ is calculated as described in ref.[16] but neglecting the mass diffusion because the mass transport as approximately considered in [16] does not influence the statistical fluctuations of the relative motion.

(iii) The friction constants (1) give an appreciable amount of angular momentum transferred from relative to intrinsic motion, which is close to the sticking limit for rigid rotation of the double nuclear system.

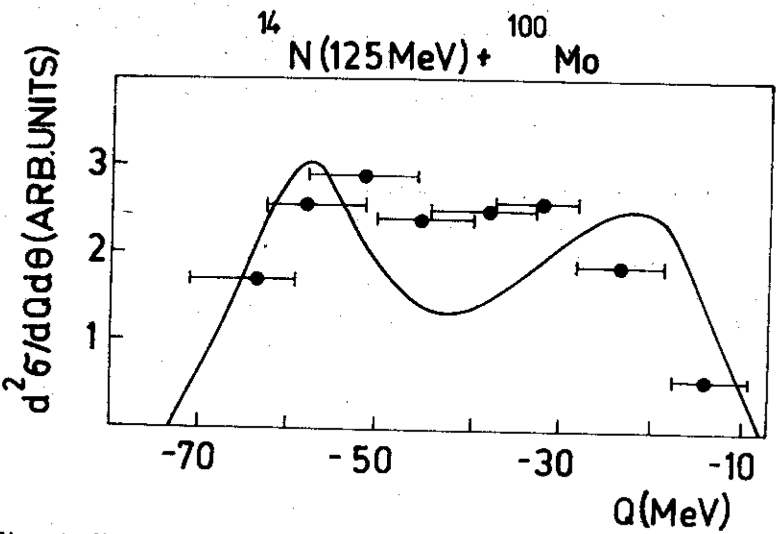


Fig. 1 Measured and calculated energy spectrum of ^{12}B as function of the reaction Q-value for the reaction ^{14}N (125 MeV) + ^{100}Mo at $\Theta_L = 25^\circ$.

in a classical picture the dissipated angular momentum is oriented perpendicular to the reaction plane, and in the final state both primary fragments are completely polarized with equal sign. But the polarization differs in sign for scattering events from opposite sides of the interaction region. With the convention that the polarization is positive if it is directed along $\vec{k}_i \times \vec{k}_f$, one has positive (negative) polarization for positive (negative) angle scattering. Consequently, from this classical picture for a given reaction angle one expects complete positive (negative) polarization for events with small (high) energy loss. If statistical fluctuations in the collective variables occur because of a coupling of the relative motion to intrinsic excitations the degree of polarization for given θ and Q can go below 100°/o, related to the relative contributions of positive $(\sigma(+\theta, Q))$ and negative angle scattering $(\sigma(-\theta, Q))$ to the double differential cross section $d^2\sigma/d\theta dQ$

$$\frac{d^2\sigma}{d\theta\, dQ} = \sigma(+\theta, Q) + \sigma(-\theta, Q) , \tag{2}$$

$$P(\theta, Q) = \frac{\sigma(+\theta, Q) - \sigma(-\theta, Q)}{\sigma(+\theta, Q) + \sigma(-\theta, Q)} . \tag{3}$$

For a given scattering angle the polarization P as a function of Q changes from P = + 1 for high Q-values to P = - 1 for low Q-values, with a vanishing polarization for those regions of the kinetic energa spectrum, in which equal numbers of particles are reaching the detector from both sides of the interaction region. So, the position and the range of the Q-value, in which the transition from P = + 1 to P = - 1 occurs reflects the fluctuations and correlation in energy and angle, inherent in the collision model.

3. Polarization in the Reaction $^{14}N + ^{100}Mo$ and $^{14}N + ^{232}Th$

The systematic dependence of the polarization on reaction angle and energy loss is demonstrated for the reaction ^{14}N(200 MeV) + ^{100}Mo in fig. 2. Deviations from a complete polarization appear only for reaction angles $\theta \lesssim 50^0$. As a function of the polarization for large (small) Q-values remains positive (negative) at all reaction angles, while for a medium energy loss the polarization changes from positive to negative sign at $\theta \approx 40^0$. The range of Q-values in which the polarization as function of Q goes from P = + 1 to P = - 1 depends on the reaction angle, beeing rather narrow for large deflection.

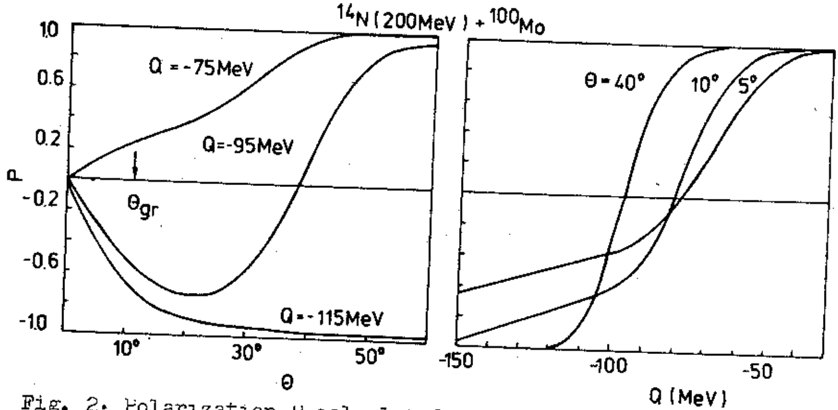


Fig. 2. Polarization P calculated as function of deflection angle θ and reaction Q-value for the reaction $^{14}N(200\ MeV) + ^{100}Mo$.

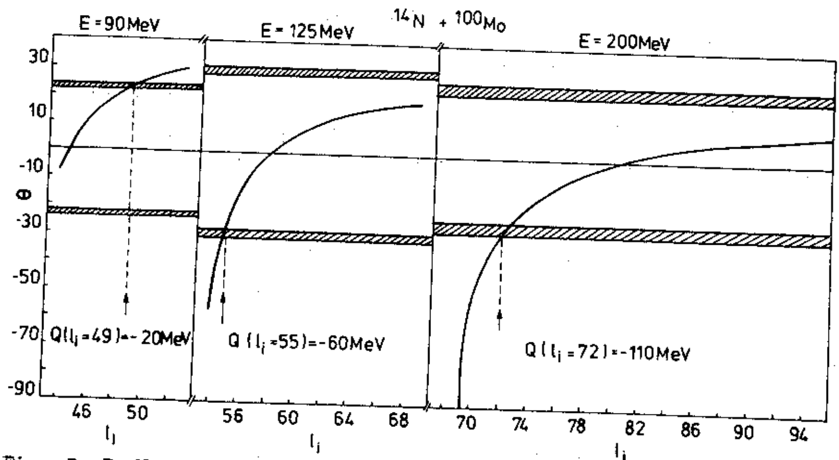


Fig. 3. Deflection angle θ calculated as function of initial relative angular momentum l_i for the reaction $^{100}Mo(^{14}N, ^{12}B)$ at different incident energies E. Shadowed areas: centre of mass angle region corresponding to detector positions in the laboratory system of 20°, 25°, and 20°, respectively, realized in the experiment. The Q-values calculated for the relevant partial waves are indicated.

The change in the direction of the experimental polarization (cf. fig. 5) as the incident energy in the reaction ^{14}N + ^{100}Mo is raised from 90 MeV to 125 MeV or 200 MeV can be explained already from the deflection functions shown in fig. 3. The angular range detected in the experiment is markes by shadowed areas. The main contribution to the double differential cross section results from partial waves in the region, where the deflection function crosses these shadowed areas. With these partial waves definite Q-values are connected, which belong to the maximum in the kinetic energy spectrum of ^{12}B. The Q-values Q $\approx$ - 20 MeV, - 60 MeV, and - 110 MeV obtained in the friction model for the incident energies 90 MeV, 125 MeV, and 200 MeV, respectively, agree **reasonably** well with the maximum in the experimental spectra at Q $\approx$ - 25 MeV, - 55 MeV, and - 90 MeV, respectively. In this region of the spectrum the sign of the polarization should be positive (negative), if the deflection function crosses the intervall of detection angles for positive (negative) reaction angles. So, from fig. 2 one expects positive polarization for 90 MeV incident energy, but negative polarization for 125 MeV and 200 MeV, in agreement with the measurements (see fig. 5). The same situation as for ^{14}N + ^{100}Mo at E_{Lab} = 90 MeV holds for ^{14}N (129 MeV) + ^{232}Th, as can be deduced from figs. 4 and 6.

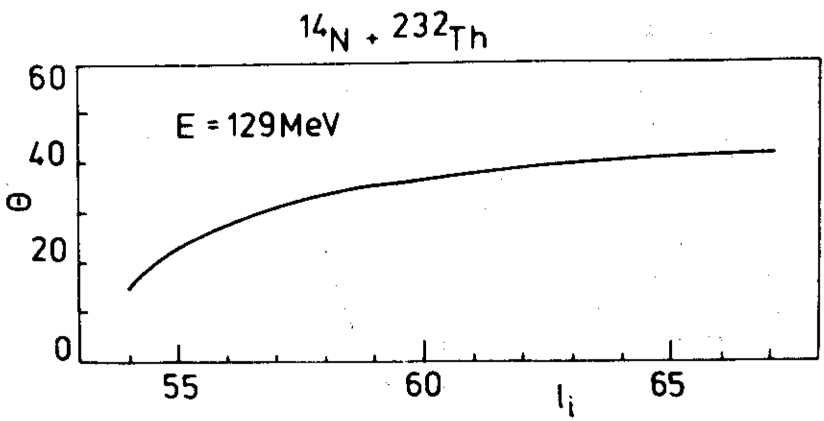


Fig. 4. Deflection angle Θ calculated as function of initial relative angular momentum l_i for the reaction ^{14}N(129 MeV) + ^{232}Th.

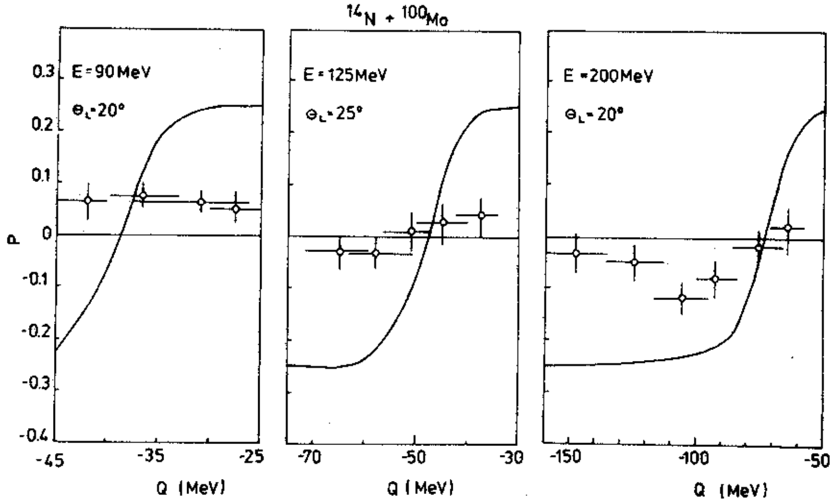
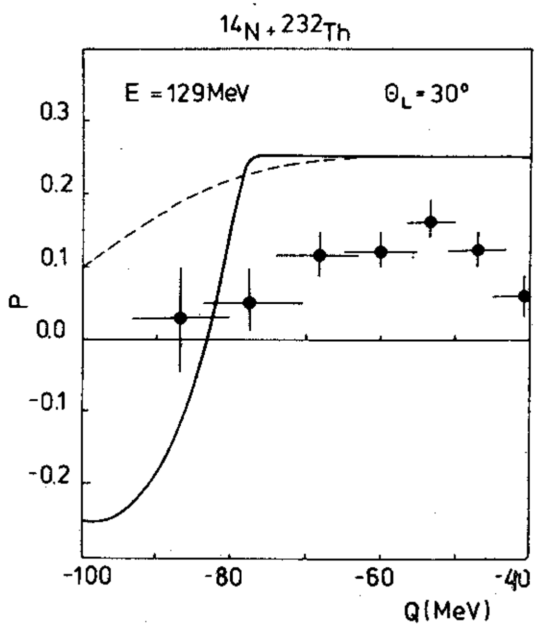


Fig. 5. Measured and calculated polarization P as function of Q-value for the reaction $^{14}N + {}^{100}Mo$ at three incident energies E and observation angle Θ . The theoretical curves are normalized with a factor of 1/4.

Fig.6. Measured and calculated polarization P as function of Q-value for the reaction $^{14}N(129\ MeV) + {}^{232}Th$ at an observation angle $\Theta_L = 30^\circ$. The dashed curve is calculated by taking into account the fluctuation in energy and angle, but neglecting their correlation. The theoretical curves are normalized with a factor of 1/4.



The polarization calculated at a certain detection angle as a function of Q is compared with the experimental data for ^{14}N + Mo in fig. 5 and for $^{14}N + ^{232}Th$ in fig. 6. While the region of Q-values in which the polarization vanishes is well reproduced in all cases, it is obvious, that the friction model is far from reproducing the small maximum polarization. The dashed curve in fig. 6 refers to a calculation, in which the fluctuations in energy loss and deflection angle are taken into account, while the energy-angle correlation is neglected. Disregarding the correlation effects weakens the agreement with experiment $P \approx 0$ is predicted for too small Q-values.

4. Conclusions

A classical friction model including statistical fluctuations and correlations is insufficient to interprete all observed features of the ground state polarization of the light fragment in the reactions $^{100}Mo(^{14}N, ^{12}B)$ and $^{232}Th(^{14}N, ^{12}B)$. While the sign of the polarization in the maximum of the ^{12}B spectrum and the range of Q-values, in which the directions of the polarization changes, are predicted correctly, the calculated degree of the polarization by far exceeds the measured data. From these results one can conclude that the mean characteristics of the collision as well as the fluctuations and correlations in energy loss and angle are satisfactorily described within macroscopic model, but a more detailed theory of the angular momentum dissipation in DIC should be necessary to explain the orientation phenomena in the reactions discussed in this paper.

References

1) W. Trautmann et al. Phys.Rev.Lett. 39 (1977) 1062)
2) N. Takahashi et al. Phys.Lett. 78B (1978) 397
3) N. Takahashi et al. Proc.Int.Conf. on Nuclear Interactions, Canberra, 1978
4) P.J. Ellis. Nucl.Phys. A302 (1978) 257
5) D.M. Brink, Phys.Lett. 40B (1972) 37
6) K. Tanaba et al., Proc.Conf. on Nuclear Structure, Tokyo, 1977
7) P.D. Bond. Phys.Rev.Lett. 40 (1978) 501
8) J. Wilczynski. Phys.Lett.47 B (1973) 484
9) W. Dünnweber and K.M. Hartmann. Phys.Lett. 80B (1978) 23
10) H.Hofmann and P.J. Siemens. Nucl.Phys. A 275 (1977) 464

11) R. Schmidt and R.Reif. Journ.of Phys. G5 (1979) L181
12) G. Wolschin. Nucl.Phys. A 316 (1979) 146
13) L.G. Moretto and R.P. Schmitt. Phys.Rev. C21 (1980) 204
14) R. Schmidt and R.Reif. Submitted to Journ.of Phys. (1980)
15) J. Galin et al. Phys.Rev. C9 (1974) 1113
16) R. Schmidt, V.D. Toneev and G. Wolschin. Nucl. Phys. A311 (1978) 247

Received by Publishing Department
on January 14 1981.