Fragment Spin Distribution in 400 MeV $^{40}$Ar + $^{93}$Nb Collisions
Investigated by Light-Particle Anisotropies

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In and out-of-plane angular correlations between light particles and projectile-like fragments from deeply inelastic collisions of 400 MeV $^{40}$Ar + $^{93}$Nb were measured. At backward angles, the equilibrium emission of $\alpha$ particles and protons from the target-like fragment was identified. By analysing the out-of-plane angular correlations in the framework of a semi-classical statistical model, an average spin of $30 \pm 2h$ and an average alignment of $P_z = 0.80 \pm 0.15$ for the target-like fragment were deduced.

1. Introduction

Angular momentum transfer in deep-inelastic reactions from the relative motion of two colliding ions into intrinsic spin of the two separated fragments has been established in many $\gamma$ ray multiplicity experiments [1-7] and has been described in the framework of transport theories [8-10]. The spin values deduced from these experiments tend to be close to the sticking value, inviting for a macroscopic interpretation in terms of a tangential friction force. The $\gamma$ multiplicity method, however, involves considerable uncertainties and specific deficiencies so that quantitative results should be taken with some caution. In short, these uncertainties arise from insufficient knowledge of (i) the multipolarity of the radiation, (ii) of the ratio of stretched to unstretched $\gamma$ transitions, (iii) the sizeable amount of angular momentum carried away by light particle emission prior to $\gamma$ decay. Although problem (i) and (ii) have been studied carefully for $\gamma$ decay following compound nucleus formation [11], there is little hope to apply those results in a straight-forward manner to fragments emerging from deep-inelastic collisions: in most cases it is impractical to produce the fragment species with distributions in angular momentum and excitation energy typical of deep-inelastic collisions in a compound nucleus reaction for calibration purposes.

To improve the situation, methods more directly related to the primary spin distribution are necessary. In very heavy systems where the heavy fragment may undergo fission, angular correlations between one of the fission fragments and the deep-inelastic scattered light fragment have been employed to deduce average fragment spin and spin alignment [12, 13]. In these experiments, large anisotropies with respect to the reaction plane were observed which led to the conclusion that the fragments carry large spins with average orientation perpendicular to the reaction plane. As this result is predicted by different models [14, 15], the average spin is not very sensitive to the underlying mechanisms for angular momentum.

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transfer in deep-inelastic collisions. The alignment – or more general – the width of the spin vector distribution is more sensitive to the microscopic features of the angular momentum transfer process. The alignment is related to the size of the spin fluctuations which may be of statistical or of quantal nature. However, the presence of fluctuations inherent in the fission process itself complicates the interpretation of the sequential fission data. The method to employ sequential fission is not applicable in light and medium-heavy systems, where the excited fragments decay mainly by light particle and γ emission. In lighter systems, alignment measurements have been performed by observing discrete γ lines [16, 17] and continuum γ ray anisotropies [18, 19]. Trautman et al. [20] and Sugimoto et al. [21] have measured the fragment spin polarization. Light particle anisotropies observed in deep-inelastic reactions have been shown to probe both the alignment and the average spin of the heavy fragments [22, 23]. It was found that the fragments carry highly aligned angular momenta with absolute values close to the sticking limit. Recently, Lefort and Ngô [24] have reviewed the experimental and theoretical aspects of angular momentum transfer in deep-inelastic reactions.

In this paper, we would like to report on a study of light particle emission in the system 40Ar + 93Nb. The present experiment was set out to investigate whether the results presented in [22] apply in general to DIC or to the specific structure of light systems. In Sect. 2 of this paper, we shall discuss the relation between the angular momentum distribution and the out-of-plane angular correlation of light particles in the framework of a semiclassical statistical model. Experimental details are described in Sect. 3. Since our analysis is based on the assumption of equilibrium emission, Sect. 4 deals with the identification of equilibrium emission from the target-like fragments. Preequilibrium aspects are discussed elsewhere [25]. Section 5 presents the analysis of the experimental out-of-plane correlations. Section 6 summarizes the results.

2. Angular Momentum Transfer
and Statistical Description of Light-Particle Decay
from Equilibrated Fragments

In a semi-classical description of light-particle decay from equilibrated fragments spinning around an axis one expects maximum yield in the plane perpendicular to this axis, in our case, maximum yield in the reaction plane. The early paper of Erikson and Strutinski [26] has been extended by Dossing [27] and Ho et al. [28] to describe the 16O + 59Ni fragment-푥 correlation experiments. Reference 27 presents also full statistical-model calculations confirming the trends of the semi-classical analysis. Catchen et al. [29] have recently reviewed the various approaches to light particle emission in the framework of the statistical model.

In the following, we give a simple parametrization of the fragment spin distribution, which in turn is determined by the measured quantity, the anisotropy, or more general, the out-of-plane angular correlation of light particles. We describe the fragment spin \( \mathbf{J} \) as to be composed of a “macroscopic” spin \( \mathbf{J}_0 \) oriented perpendicular to the reaction plane, and a fluctuating spin \( \mathbf{J}_\perp \) whose components are Gaussian distributed around zero with standard deviation \( \sigma_J \) which for simplicity reasons is assumed to be the same in all three directions. In consequence, the fragment spin \( \mathbf{J} = \mathbf{J}_0 + \mathbf{J}_\perp \) is also a Gaussian with mean values \( \langle J_x \rangle = \langle J_y \rangle = 0; \langle J_z \rangle = J_0 \).

\[
P(\mathbf{J}) \sim \exp \left\{ -\frac{(\mathbf{J} - \mathbf{J}_0)^2}{2 \sigma_J^2} \right\}.
\]

The \( z \) axis is chosen to be perpendicular to the reaction plane.

The experimental data will be parametrized in terms of \( J_0 \) and \( \sigma_J \). This procedure has its natural origin in a transport description [14] where the angular momentum transfer from orbital angular momentum to intrinsic spin of the two fragments is a random walk process involving the angular momenta of many nucleons exchanged or nuclear modes excited during the fragments being in contact. \( J_0 \) and \( \sigma_J \) could be visualized as being due to dissipation and fluctuations effected by tangential friction. However, other interpretations as the one of Broglia et al. [15] would not invalidate our analysis since the assumption of a Gaussian distribution is probably sufficiently general.

In case the spin dissipation reaches equilibrium while the fragments are still in contact, Wolschin [14] obtains the simple asymptotic relation for the average spin of one fragment (“sticking value”):

\[
J_0 = \frac{\ell_1}{1 + (\theta_1 + \theta_2 + \mu R^2)}
\]

and suggests for the variance

\[
\sigma_J^2 = T \theta_1 \mu R^2/(\theta_1 + \theta_2 + \mu R^2).
\]

\( \theta_1, \theta_2 \) are the intrinsic moments of inertia of fragment 1, 2, \( \mu R^2 \) is the relative moment of inertia of the two fragments, and \( \ell_1 \) is the orbital angular momentum in the entrance channel. The thermodynamic temperature \( T \) is given approximately by

\[
T = \{E^*/(J_1)+a\}^{1/2}
\]