Proton and α sequential emission in the ^{16}O + ^{58}Ni deep inelastic reaction: a semi-classical approach.

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Abstract

(132 MeV)$^{16}O+^{58}Ni$ reaction have been experimentally investigated by using coincident charged particle techniques. A closed-form theoretical approach, describing in a simple picture the nonequilibrium component and the evaporative component of the angular correlation between light particles and reaction residues emitted in a peripheral heavy-ion collision, is applied - in the hypotesis of sequential process- to the (C,N,O)-α and (C,N,O)-p differential multiplicities for the $^{16}O+^{58}Ni$ at 8.25 MeV/A deep inelastic collision. From this analysis some reaction mechanism information is deduced.

1 Introduction

The study of light particle emission in heavy ion deep inelastic collisions is a very powerful experimental tool to investigate different reaction stages and to better understand the various mechanisms leading to the strong energy dissipation typical of this kind of nuclear reactions.

In this framework, information can be obtained by studying a reaction mechanism appearing as an important decay channel at incident energies below 20 MeV/A, i.e. that of *sequential reactions.*
The typical reaction mechanism is the following:

$$\mathrm{a + A \rightarrow b + B \rightarrow b + c + C}$$

where the three bodies in the final state are not produced in a unique step, but they result from two subsequent sequences.
During the first sequence, i.e. the two body reaction:

$$\mathrm{a + A \rightarrow b + B}$$

a projectile-like fragment (PLF) b is produced, together with an excited target-like nucleus (TLN) B, subsequently decaying, from a continuum state, through the second sequence:

$$\mathrm{B \rightarrow c + C}$$

to the nucleus C, by emitting a light particle c (usually not heavier than an α-particle).

An experimental evidence of deep inelastic reactions is a large transfer of angular momentum from the entrance channel to the intrinsic spin of the reaction products. The amount of the momentum transferred, and its alignment, can be studied by measuring the angular distribution of the decay products of the excited TLN with respect to its recoil direction. Further, through the analysis of the $(b-c)$ angular correlation, it is possible to obtain a complete information on the polarization effects induced on the decaying nucleus B during the first sequence of the reaction.

Many experimental observations of sequential processes have revealed that the in-plane $(b-c)$ angular correlation is sharply forward-peaked, and not symmetric with respect either to the direction of the coincident projectile-like residue, or to the beam axis, with marked differences between distributions for positive and negative angles[2,4].

This clearly evidences the presence of a fast *non-equilibrium* emission of light particles, that, in spite of the sequentiality of the process, is an important decay mode. Then, the reaction time has to be small, compared to the rotational period of the intermediate system.

To describe this experimental behaviour, a theoretical approach has been developed [5-7], in which the solution of the Schrödinger equation has been calculated in such a way as to outline the evidence of this non-equilibrium component associated to the sequential reaction, together with an evaporative contribution (equilibrium component).

We have applied this approach to the angular distributions of protons and α-particles emitted in coincidence with PLFs in the deep inelastic reaction:

$$^{58}Ni(^{16}O,(C,N,O))(Zn,Cu,Ni)$$

performed at 132 MeV laboratory energy at IReS, Strasbourg (France).

2 Semiclassical approach to particle-particle angular correlation

Fig.1 shows the in-plane angular correlation data obtained for the coincidence between α-particles and projectile-like fragments (C, N, O) emitted during the sequential reaction:

$$^{16}O(132MeV) +^{58} Ni \rightarrow (C, N, O) + (Zn^*, Cu^*, Ni^*) + Q_2$$

$$\rightarrow (C, N, O) + (Ni, Co, Fe) + \alpha + Q_3$$

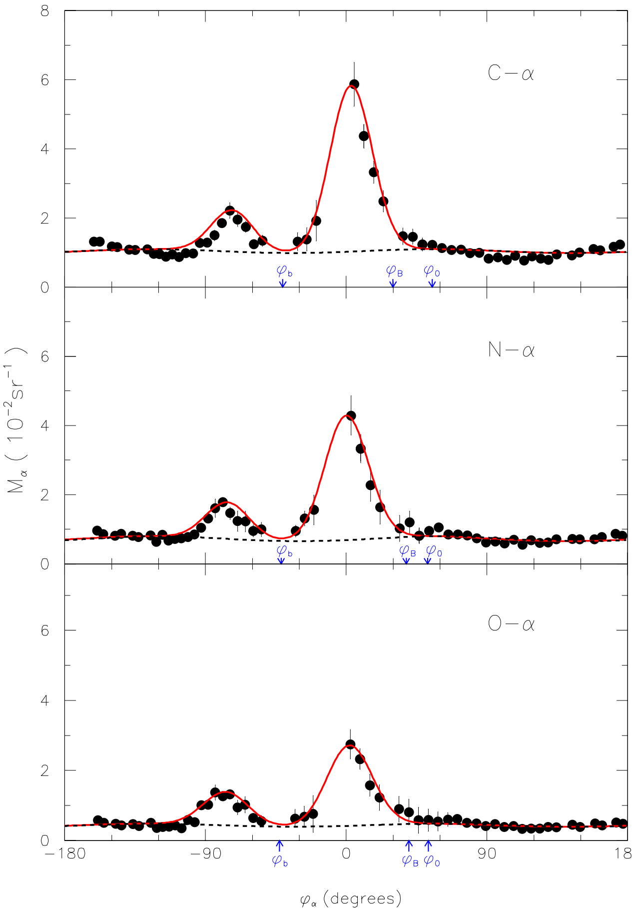

Figure 1: α differential multiplicity for the $^{16}O(132MeV) +^{58} Ni$ reaction. Solid curves represent the total multiplicity $(M(\varphi))$, while the dashed ones represent the equilibrium component $(M^E(\varphi))$.

In ordinate we have plotted the *differential multiplicity*, defined as the ratio between the double differential cross section for the particles in coincidence and the cross section for the inclusive reaction:

$$\mathcal{M}(\varphi) = \frac{d^2\sigma}{d\omega_b d\omega_c} \bigg/ \frac{d\sigma}{d\omega_b} \; ; \qquad (1)$$

while in abscissa there is the α-particles emission angle in the recoil centre of mass (RCM) reference system, that is the rest frame of the emitting TLN (with the Z axis normal to the first step reaction plane).

The theoretical curves have been calculated by using the already mentioned semi-classical approach, according to which the S-matrix associated to the decay of the excited TLN can be splitted into an equilibrium term and a non equilibrium one:

$$\begin{aligned} \mathcal{S}_{Bc} &= \mathcal{S}^{E} + \mathcal{S}^{NE} && (2) \\ \mathcal{S}^{E} &= \mathcal{S}_{Bc}(E^*_B) - \langle \mathcal{S}(E^*_B) \rangle_\Delta && (3) \\ \mathcal{S}^{NE} &= \langle \mathcal{S}_{Bc}(E^*_B) \rangle_\Delta && (4) \end{aligned}$$

where the average is taken over an energy interval Δ centered on the excitation energy of the emitting nucleus (E^*_B).

Supposing the phases of $\mathcal{S}^E$ and $\mathcal{S}^{NE}$ to be uncorrelated (so that their cross terms average out to zero) and the energies and widths of those levels in the energy interval Δ mainly contributing to the decay to be randomly distributed, interfe–rence terms generally will vanish, and therefore the differential multiplicity can be separated in two terms:

$$\mathcal{M}(\varphi) = \frac{1}{\int d\Lambda R(\Lambda)} \int \left(\mathcal{M}(\varphi,\Lambda)^E + \mathcal{M}(\varphi,\Lambda)^{NE} \right) R(\Lambda) d\Lambda \qquad (5)$$

The so-called *equilibrium term*:

$$\left(\mathcal{M}(\varphi,\Lambda)\right)^E = C_E \exp[-\gamma \cos^2 \Theta] \qquad (6)$$

describes the emission from a statistically equilibrated nucleus, which then has lost all memory of the first reaction step, except for the energy and spin received.

Consequently the angular distribution is axially symmetric about the spin axis direction and depends only on the Θ angle between this axis and the emission direction. γ is the *asymmetry parameter*; when it vanishes, the equilibrium term becomes constant, while, increasing γ, it will vary very rapidly with Θ.
The *non equilibrium term*:

$$\left(\mathcal{M}(\varphi,\Lambda)\right)^{NE} = C_{NE} \left\{ \exp\left[-\lambda^2 \left(\Phi + \chi_0\right)^2\right] + h_0 \exp\left[-\lambda^2 \left(\Phi - \chi_0\right)^2\right] \right\} \qquad (7)$$

which describes the fast pre-equilibrium emission, consists of two Gaussian terms, associated respectively to up and down polarization of the emitting TLN, corresponding to the two peaks in the differential multiplicity plot. The width of the peaks is related to the parameter λ, wich represents the width of that ℓ-window mainly contributing to the decay process.

Polar angles Θ and Φ are defined in that rest-frame of the emitting nucleus with Z' axis parallel to the spin direction, which is variable with respect to the RCM system. The two reference systems are related by a rotation of the axes defined by the Euler angles $(\xi, \Lambda, 0) = (\varphi_0 - \pi/2, \Lambda, 0)$, where φ_0 is the direction of the momentum transferred in the first reaction step, while Λ is the angle between Z and Z' axes.

Then, for the in-plane case ($\varphi = \pi/2$), Θ and Φ are related to the polar angles (ϑ, φ) of the RCM system by the following relations [7]:

$$\cos\Theta = -\sin\Lambda\cos(\varphi-\xi) \tag{8}$$

$$\tan\Phi = \frac{\sin(\varphi-\xi)}{\cos\Lambda\cos(\varphi-\xi)} \tag{9}$$

Many experimental observations have revealed that the spin of deep inelastic reaction products has a preferential direction which is nearly orthogonal to the first step reaction plane, then for the Λ angle we can assume a Gaussian distribution, centered on a small value Λ_0:

$$R(\Lambda) = \exp\left[-\frac{(\Lambda-\Lambda_0)^2}{2\Omega^2}\right]. \tag{10}$$

χ_0 is the quantal deflection function, which classically can be expressed as the product of the angular velocity of the emitting nucleus and the time interval τ_0 elapsing between the formation of the intermediate nucleus and the fast particle emission:

$$-\chi_0 = \omega_0\tau 0 = \frac{\hbar\ell_0}{\mathcal{I}}\tau_0 \tag{11}$$

where $\mathcal{I}$ is the rigid body moment of inertia of the pair (c,C).

3 α-emission in the $^{16}O +^{58} Ni$ reaction

Experimental data have been collected by means of the ICARE charged particle multidetector array, made of 48 multiple telescopes, particularly suitable for high resolution measurements of emission angle, kinetic energy and atomic number of the detected ions.

The strongly energy-damped projectile-like fragments (C, N, O) have been detected in 3 heavy-ion telescopes, each consisting of an ionization chamber (IC) followed by a silicon surface barrier diode of 500 μm effective thickness, placed at ±30° in the reaction plane.

The coincident light charged particles have been detected with 7 triple telescopes (40 μm Si, 300 μm Si, 2 cm CsI(Tl)) placed at forward angles, 16 double telescopes (40 μm Si, 2 cm CsI(Tl)) placed in the $40° \leq \vartheta_{lab} \leq 120°$ region, and 7 IC telescopes, located at the most backward angles of the reaction plane.

With this configuration, it has been possible to investigate 54 angles on the whole plane angle, and, in particular, triple telescopes have been able to accurately separate the different masses of isotopes of light charged particles.

Differential multiplicity data plotted in fig.1 have been fitted by the expression (1); as one can easily see, the forward region appears to be dominated by the pre-equilibrium component, which strongly depends on the mechanism of the first reaction step, while at backward angles only the equilibrium emission is present, and this component is almost isotropic for all the three coincidences.

Then, the polarization direction of the emitting nucleus is nearly orthogonal to the reaction plane, this fact being confirmed also by the value we have found for the average angle between the spin direction and the normal axis (Λ_0) that is 6° for all the three coincidences (see table 1).

Table 1: α coefficients obtained by the fit. C_E and C_{NE} are expressed in units of $10^{-2}sr^{-1}$

Coin.	C_E	γ	Λ_0	Ω	C_{NE}	λ	h_0	χ_0	ξ
C-α	1.1	2	6^o	13^o	4.4	2.5	0.25	-41^o	-33^o
N-α	0.8	4	6^o	13^o	3.5	2.3	0.30	-44^o	-33^o
O-α	0.48	4	6^o	13^o	2.5	2.4	0.36	-44^o	-33^o

The value of the parameter λ does not exceed 3 for all the three coincindences, thus confirming the peripheral nature of the NE decay process.

The parameter ξ is related to the direction φ_0 of the momentum transferred in the projectile-target interaction; if we had dealt with hard spheres, this direction would correspond to the recoil direction of the TLN. As listed in table 2, these angles are not equal, but their difference decreases for decreasing projectile-target mass transfer.

Table 2: α experimental values of φ_0 and φ_{TLN}

Coin.	φ_0	φ_{TLN}	$\varphi_0 - \varphi_{TLN}$
C-α	57^o	30^o	27^o
N-α	57^o	38^o	19^o
O-α	57^o	40^o	17^o

The parameter h_0 is related to the probability of positive polarization of the TLN on a quantization axis perpendicular to the reaction plane:

$$p_0 \equiv \frac{|f_{ba}(m_0)|^2}{|f_{ba}(m_0)|^2 + |f_{ba}(-m_0)|^2} = \frac{1}{1+h_0} = \begin{cases} 0.80 & (C\text{-}\alpha) \\ 0.77 & (N\text{-}\alpha) \\ 0.74 & (O\text{-}\alpha); \end{cases} \tag{12}$$

The polarization is therefore predominantly positive, and increases for increasing projectile-target mass transfer.

4 Proton emission in the $^{16}O +^{58} Ni$ reaction

In order to better highlight the behaviour of light charged particle sequential emission, we have extended our analysis to the study of angular correlation between protons and (C, N, O)-ions for the same reaction, shown in fig.2.

The parameters obtained by the fit are listed in table 3. By comparing these values with the ones obtained for the α-emission, one can easily see that the polarization direction of the emitting nucleus is nearly orthogonal to the reaction plane even for proton emission. As a matter of fact the value of the Λ_0 angle is still 6^o for all the three coincidences.

$$\begin{aligned} {}^{16}O(132MeV) + {}^{58}Ni &\rightarrow (C,N,O) + (Zn^*, Cu^*, Ni^*) + Q_2 \\ &\rightarrow (C,N,O) + (Cu,Ni,Co) + p + Q_3 \end{aligned}$$

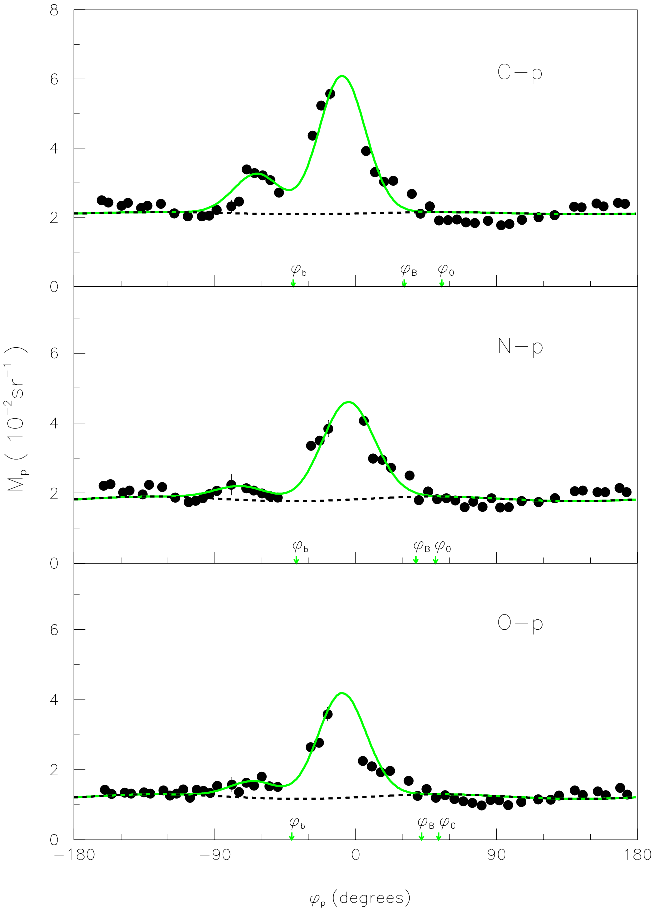

Figure 2: Proton differential multiplicity for the ${}^{16}O(132MeV) + {}^{58}Ni$ reaction

Table 3: Proton coefficents obtained by the fit.

Coin.	C_E	γ	Λ_0	Ω	C_{NE}	λ	h_0	χ_0	ξ
C-p	2.15	0.5	6^o	13^o	4.	2.7	0.29	-28^o	-35^o
N-p	1.9	1.3	6^o	13^o	2.8	2.4	0.14	-35^o	-39^o
O-p	1.3	2.	6^o	13^o	3.	2.6	0.16	-29^o	-37^o

As shown in table 4, the differences between the direction of the momentum transferred in the projectile-target interaction and the recoil direction of TLN are still decreasing for decreasing projectile-target mass transfer, but their values are lower than the ones calculated for α-emission.

The values of the polarization parameter:

$$p_0 \equiv \frac{|f_{ba}(m_0)|^2}{|f_{ba}(m_0)|^2 + |f_{ba}(-m_0)|^2} = \frac{1}{1+h_0} = \begin{cases} 0.78 & (C\text{-}p) \\ 0.88 & (N\text{-}p) \\ 0.86 & (O\text{-}p); \end{cases} \qquad (13)$$

Table 4: Proton experimental values of φ_0 and φ_{TLN}

Coin.	φ_0	φ_{TLN}	$\varphi_0 - \varphi_{TLN}$
C-p	55^o	31^o	24^o
N-p	51^o	38^o	13^o
O-p	53^o	43^o	10^o

are roughly greater than those ones obtained for the α-emission, then one can deduce that the information about the polarization induced on the TLN by the first step of the reaction grows by studying proton emission.

According to the Wilczynsky model of deep inelastic reactions, which ascribes the energy dissipation to frictional forces arising in the projectile-target contact region, up and down polarization can be related to positive and negative deflection function, respectively.

Then, the observed positive polarization can be explained by assuming that *only one type* of semi-classical trajectory predominantly contributes to the NE component of the sequential emission.

5 Conclusions

Differential multiplicities for the $^{16}O+^{58}Ni$ reaction at $8.25MeV/A$ have been measured for deep inelastic events.

A theoretical semiclassical approach, assuming the hypothesis of a two-step sequential process, is proposed to analyse more deeply and quantitatively the measured angular correlations between light particles (protons and α's) and (C,N,O) deep inelastic projectile-like fragments.

From this analysis, one immediately sees that the angular interval between the average momentum transferred during the first sequence and the recoil direction of the intermediate nucleus B increases with the transferred mass by ^{16}O to ^{58}Ni.

The positive alignment parameters which have been deduced suggest that the *far-side* trajectory is dominant.

Finally, we can obtain an estimate of the mean time elapsing between the formation of the TLN and its subsequent fast decay.
From eq.(11), using the value of ℓ_0 ($\approx 4\hbar$) calculated from our data , and approximating:

$$\mathcal{I} \approx \mathcal{I}_{rigid} \approx 0.0137 A^{5/3} \hbar^2$$

we obtain, for the τ_0 revolution time:

$$\tau_0 \approx 0.5 \cdot 10^{-22} s \qquad \alpha - emission$$

$$\tau_0 \approx 0.7 \cdot 10^{-22} s \qquad p - emission$$

These values, close to the first step reaction time ($\tau_r \approx 2 \cdot 10^{-22} s$), are at least two order of magnitude shorter than the compound nucleus lifetime.

As shown above, many features of proton and α-particle sequential emission are well reproduced by means of the simple semiclassical approach here used, that we plan to apply to other nuclear systems for a deeper investigation of the reaction mechanism of deep inelastic collisions.

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