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ANGULAR CORRELATIONS OF PROJECTILELIKE AND FISSION FRAGMENTS IN THE REACTION $^{16}O + ^{238}U$ AT 110 MeV

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Angular correlations of projectilelike and fission fragments in the reaction $^{16}O+^{238}U$ at 110 MeV

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Abstract

In-plane and out-of-plane angular correlations of fission fragments detected in coincidence with projectilelike residues produced in the nuclear collisions $^{16}O+^{238}U$ at 110 MeV have been investigated. The data present the essential features of a targetlike sequential fission process. A quantitative description of the experimental angular anisotropies requires the storage in the fissioning nucleus of a mean angular momentum in agreement with a dominant mass transfer mechanism.

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I. INTRODUCTION

In a recent paper we reported on the inclusive and the semi-exclusive elemental production cross section of projectilelike fragments (PLF) produced in the nuclear collisions $^{16}O+^{238}U$ at $E_{lab}(^{16}O)$ = 110.4 MeV [1]. It was shown that 21% of the reaction cross section corresponded to the production of PLF from oxygen to lithium. Energy spectra and angular distributions of the detected ejectiles were described supposing a massive transfer from the projectile nucleus to the target nucleus and they were found in agreement with the Diffractional DWBA transfer model of Ref. [2].

The in-plane coincidences between PLF's and fission fragments (FF) evidenced an asymmetric fission mode of the targetlike nucleus corresponding to about 14% of the total fission cross section. However this value was quoted supposing an isotropic emission of the FF in the frame of the fissioning targetlike nucleus.

In this paper, a detailed experimental investigation of both in-plane and out-of-plane angular correlations of the FF detected in coincidence with the PLF is presented for the same system and at the same bombarding energy as previously studied [1].

Experiments similar to the one presented in this work are crucial in order to: i) disentangle fission properties following different reaction channels; ii) evaluate fission probabilities and cross-sections; iii) determine the mean value $\overline{J}$ of the angular momentum carried by the fissioning nucleus.

II. EXPERIMENTAL APPARATUS AND RESULTS

The experiment was performed at the heavy ion facility LNS Laboratory at Catania. A 110 MeV oxygen 7^+ beam was used to bombard a $\approx$ 200 $\mu g/cm^2$ thick ^{238}U target obtained by evaporation of UF_4 onto a thin ($\approx 30\mu g/cm^2$) carbon foil. The detectors were placed inside the 200 cm diameter reaction chamber CT-2000 operating at vacuum of $\approx 10^{-6}$ torr.

In Fig. 1 a schematic view of the adopted experimental geometry is shown. The laboratory polar (θ) and azimuthal (ϕ) angles of the detectors have been measured in a frame of a coordinate system of reference with polar axis (Z axis) perpendicular to the reaction plane, defined by the direction of the PLF and the beam axis (X axis).

PLF were detected and charge identified in two ΔE-E telescopes placed at the polar angle $\theta = 90°$ and at azimuthal angles ϕ of -69.5° (GS1) and +79° (GS2), relative to the beam direction, covering solid angles of 1.2 and 3.4 msr respectively. Each telescope was made of an ionization chamber (operating with P10 at 60 torr) followed by a 500 μm thick silicon detector. The low pressure of the ΔE gas first element assured also the detection of fission fragments [1]. In addition, a micro-channel plate (MCP) fast timing device was placed at 7 cm from the target and acted as a start detector in connection with the GS1 telescope (stop) for velocity measurements (TOF) over a path of 18 cm.

FF were detected by means of five large area (600 mm^2 or 900 mm^2) 60μm depletion depth Si(SB) detectors. Three of these detectors (F1,F4,F5) were placed in the reaction plane ($\theta = 90°$) at the azimuthal angles ϕ of -40° (F5), +102° (F1), and +140° (F4) relative to the beam direction, covering solid angles of 74, 116 and 173 msr respectively. The two others detectors were placed in a plane perpendicular to the reaction plane, having the same azimuthal angle as F1 detector, with polar angles θ of 23° (F3) and 55° (F2) relative to the Z axis, each covering a solid angle of 100 msr.

In the following, the angular correlation between a PLF and the FF is described by means of the differential multiplicity:

$$\frac{dM}{d\Omega_2}(\theta_1, \phi_1, \theta_2, \phi_2) = \frac{N(\theta_1, \phi_1, \theta_2, \phi_2)_{coinc}}{N(\theta_1, \phi_1)_{single} d\Omega_2} \quad (1)$$

where 1 and 2 stand for PLF and FF respectively. An integration of this quantity over the solid angle of the FF gives the fission probability for a fixed detection angle of the PLF, i.e., $P_f = \frac{1}{2} \int \frac{dM}{d\Omega_2} d\Omega_2$ (the factor 1/2 takes the multiplicity of the fission fragments into account).

The geometry of the GS1 and GS2 telescopes allowed us to plot in Fig. 2a) the two different sets of the in-plane multiplicities GS1 $\cap$ (F1 $\cup$ F4 $\cup$ F5 $\cup$ GS2) and GS2 $\cap$ (F1

∪ F4 ∪ F5 ∪ GS1) by adopting the same physical representation. In fact, the beam axis defines two half-planes according to the location of the two PLF telescopes (see Fig. 1). A fission detector placed in the same half-plane of the corresponding coincident PLF telescope defines a positive azimuthal angle. Consequently, a fission detector placed in the opposite half-plane has been defined with a negative azimuthal angle. The two sets of the in-plane coincidences of Fig. 2a) show essentially the same physical picture. The multiplicity increases for the fission detectors placed in the opposite half plane of the corresponding coincident PLF telescopes and has a maximum around the value of ≈ -50°.

The out-of-plane laboratory multiplicity is shown in Fig. 2b). In this case, both the two sets of coincidences show a well defined out-of-plane anisotropy as expected under the assumption that the spin of the fissioning nucleus is predominantly aligned along the Z axis. However, the fission multiplicity relative to the GS1 telescope is systematically larger than the one relative to the GS2 telescope.

To gain insight into the properties of the angular laboratory correlations, the experimental data were compared with the results of a Monte Carlo simulation in a way similar to the one described in Ref. [1].

In brief, it was assumed that the fission of a target nucleus followed a two body transfer process according to the reaction: $^{16}O+^{238}U \rightarrow PLF^{*}+TLF^{*}$ where PLF* and TLF* stand for the projectilelike and the targetlike excited nuclei respectively.

The detection angle of the PLF was fixed to the mean value of 75° and its laboratory kinetic energy spectrum was taken according to the experimental one. The resulting mean excitation energy had a mean value of ≈ 20 MeV . The asymmetric fission of the TLF nucleus was described assuming the Viola systematic [3]. Then, supposing an isotropic emission of the FF in the frame of the fissioning nucleus, the effective detection efficiency ϵ , defined as the ratio between the number of collected FF over the total counts , as a function of the detection laboratory angle of the FF was evaluated.

The result of the computation procedure is shown in Fig. 2 (full histograms - right scales), as an example for carbon ejectile, where transfer of α particle from the projectile to the target nucleus was assumed. The ratio $\frac{\epsilon}{\epsilon_g}$ (the geometrical efficiency ϵ_g is equal to $\frac{\Delta\Omega}{4\pi}$) is compared with the experimental laboratory in-plane multiplicity (Fig. 2a) and the out-of-plane multiplicity (Fig. 2b).

The effect of the transformation between the two frames of reference, by increasing the detection efficiency of the FF in the direction of the target laboratory recoil angle (indicated by an arrow in Fig. 2a) represents, in this case, an important source of the in-plane laboratory anisotropy. In the case of the out-of-plane multiplicity, the computation does not explain the minimum observed around 0°. However, we note that the systematic excess of the experimental multiplicity with the GS1 telescope is fully explained, in the computation, as due to both linear momentum and energy conservation effects. Similar results have been found for all the detected PLF from oxygen to boron ejectiles. In Fig. 2 the simulation is also compared (dashed line) with a simple laboratory law distribution obtained supposing a two body fission process of a moving target source [4]:

$$G(\psi) = 2\frac{V}{V_0}\cos(\psi) + \frac{1 + \left(\frac{V}{V_0}\right)^2 \cos(2\psi)}{\sqrt{1 - \left(\frac{V}{V_0}\right)^2 \sin^2(\psi)}} \qquad (2)$$

V is the velocity of the source as given by the kinematics of the two body transfer process. V_0 is the velocity of the FF in the frame of the source calculated by assuming a value of 75 MeV for its mean kinetic energy [3] and ψ is the relative angle between the V vector and the laboratory direction of the FF.

In order to well characterize the fission process, the laboratory data were transformed in the frame of the targetlike fissioning nucleus. In this frame the Z' axis is parallel to the Z axis and the X' axis has the orientation of the laboratory recoil axis of the fissioning nucleus. Consequently, in this intrinsic frame of reference, the polar angle is unchanged, i.e. $\theta' = \theta$, while the azimuthal angles ϕ' is given by the expression: $\phi' = \phi - \phi_{recoil}$.

The jacobian of the transformation was taken equal to the ratio $\frac{\epsilon}{\epsilon_g}$ as given by the described Monte Carlo simulation. In doing the transformation, it was assumed that the experimental multiplicity represented FF taken in coincidence with ejectiles fragments detected at the mean PLF detection angle of 75°. In the present case, the slight difference between GS1 and GS2 laboratory angles did not introduce significant effects. In fact, two principal experimental conditions were fulfilled.

The first condition required that the variation of the recoil angle of the fissioning nucleus was negligible when the PLF was observed in GS1 or in GS2. In our case, as directly proven by the described two body reaction analysis of the sequential fission process, the variation of the absolute value of the recoil angle is limited around the value of $\approx 5°$ as the PLF angle varies from 69.5° to 79°. So, dynamical effects due to such a small variation of the recoil angle can not be visible within the angular accuracy of the experimental apparatus.

The second condition required that, by changing the detection angle of the PLF, the variation of both the excitation energy and the angular momentum of the targetlike fissioning nucleus were negligible. The DWBA analysis of the inclusive data discussed in Ref. [1] showed that at the grazing angle ($\approx 70°$) the PLF energy spectra were described by quite similar Q value and angular momentum distributions nearly independently of the PLF detection angle.

However, a remark concerns the quoted error on the jacobian. The full histograms of Fig. 2a) and Fig. 2b) have been obtained for a ^{12}C isotope ejectile and a ^{242}Pu fissioning target nucleus. As suggested in Ref. [1], others carbon isotopes are expected in the reaction, changing, consequently, the kinematic of the recoil target nucleus. Assuming that the carbon ejectile was equally populated by isotopes with mass between 11 and 14 uma, a dispersion on the value of the jacobian of $\approx 15\%$ was evaluated. Similar procedures were used for the others ejectile nuclei. So, in doing the transformation, the quoted uncertainty of the jacobian was quadratically added to the statistical errors.

Fig. 3) shows the obtained experimental fission multiplicity in coincidence with the various ejectiles from oxygen to boron. The out-of-plane multiplicities correspond to a fixed azimuthal angle given, for each element, by the relation $\phi' = 102° - \phi_{recoil}$. The data corroborate the results of Ref. [1] concerning the quoted peripheral fission probability. The fission probability is $\approx 70\%$ for those reactions involving a substantial removal of mass from the projectile, i.e., for carbon and boron ejectiles. In contrast, nitrogen and oxygen ejectiles show lower values of about 25% and 6% respectively (this latter value has to be regarded as a lower limit due to the possible persistence, after subtraction, of an elastic scattering contribution in the oxygen inclusive yield). In agreement with the observation of Refs. [7,8] the data also clearly indicate a basic trend: the in-plane anisotropy $W_{in} = \frac{\overline{dM_{\phi=0^\circ}}}{dM_{\phi=90^\circ}}$ shows a tendency to decrease with the increase of the mass transfer, while the out-of-plane anisotropy $W_{out} = \frac{\overline{(dM)_{\theta=90^\circ}}}{(dM)_{\theta=0^\circ}}$ shows an opposite behaviour. For very peripheral collisions, associated with the production of oxygen and nitrogen ejectiles, relatively large values of the in-plane anisotropy (up to ≈ 3) are observed.

The data of Fig. 3) have been described using the parameterized formalism of the sequential fission of Ref. [5], and used in Refs. [7,8], that represents a good approximation of the fully quantum mechanical description of Ref. [6].

The angular correlation is given by:

$$W(\phi,\theta) = \sum_J \rho(J)(2J+1) \times \sum_{K=-J}^{J} exp(-K^2/2{K_0}^2) \times \\ \times \int_{-\pi}^{\pi} exp(-\alpha^2/2{\alpha_0}^2) D(\phi,\theta,\alpha) d\alpha \tag{3}$$

with

$$D(\phi,\theta,\alpha) = \mid {d_{JK}}^J [\cos^{-1}(\cos\theta\cos\alpha - \sin\theta\sin\alpha\sin\phi)] \mid^2$$

The values of ${K_0}^2$, as listed in Table I, were quoted following the formalism of Ref. [6]. The effective moments of inertia of the final nuclei were assumed at zero angular momentum [7] and their temperatures were extracted from the most probable target excitation energies as predicted by the DWBA diffractional model already used in Ref. [1]. The adopted values of K_0 are in reasonable agreement with existing both experimental and theoretical evaluations in the region of the actinides nuclei [5–7,9]. However, due to a predominant asymmetric fission mode of the target-like nuclei a possible overestimation of K_0 values is not excluded. In eq. (3) the angular momentum vector is assumed to be in the plane perpendicular to the recoil axis. The parameter α is the angle between the angular momentum vector and the Z axis. Then, the width of the M distribution is proportional to α_0.

The parameter α_0 mainly determines the in-plane anisotropy. Under the experimental conditions of the present experiment its value has a lower limit of $\approx 10°$ corresponding approximatively to the angular opening of the fission detectors.

The $\rho(J)$ distribution mainly determines the out-of-plane anisotropy and, consequently, the mean angular momentum $\overline{J}$ of the fissioning nucleus.

As a crude estimation, the value of $\overline{J}$, for each PLF channel, has been obtained by fitting the corresponding out-of-plane angular correlation, under the assumption of a complete alignment, i.e., $J = M$ by means of eq. (3) with $\rho(J) = \delta(J - J_0)$ and $\alpha_0 = 10°$. The obtained results are listed in the last column of table 1. As expected, the mean value of J_0 decreases with the increase of the mass of the projectile residue.

While for boron and carbon ejectiles the assumption of the in-plane isotropy seems to be nearly fulfilled within the experimental errors, in contrast, for nitrogen and oxygen ejectiles the data require an increase of the value of α_0 indicating a substantial misalignment of the angular momentum. However, in this case, in order to fit well both the in-plane and the out-of-plane angular correlations it was necessary to increase both α_0 and J_0. As an example, for nitrogen ejectile an increase of α_0 from 10° to 40° required an increase of J_0 from $8\hbar$ to $13\ \hbar$.

The full lines of Fig. 3 have been obtained by adjusting, within ≈20% of accuracy, both α_0 and J_0. The results of the fits have been summarized in table 1. This latter analysis indicates a tendency to select larger values of the angular momentum than expected by fitting only the out-of-plane correlation data. The analysis presented in this paper strongly supports the physical picture of a sequential fission process as described by eq. (3) and developed in Ref. [5].

However, in order to reduce the number of parameters of eq. (3), an independent evaluation of the mean angular momentum $\overline{J}$ has been performed following the transfer DWBA analysis of Ref. [1].

In case of fission induced by heavy ion direct surface reaction, the $\rho(J)(2J+1)$ distribution of eq.(3) has to be replaced by the following formula:

$$F(J) = \frac{\rho(E^*)(2J+1)}{2\sigma^3\sqrt{2\pi}} exp(-J(J+1)/2\sigma^2)\sigma_{DWBA}(E_f, \phi, J) \quad (4)$$

where $\rho(E^*)$ is the total level density of the heavy excited TLF nucleus given by the Oblozinsky formula [2], σ^2 is the spin cut off term equal to the product of the temperature by the moment of inertia of the excited nucleus , σ_{DWBA} is the diffractional DWBA cross section already used in our previous paper [1] and in Ref. [2], E_f and ϕ are the centre of mass kinetic energy and detection angle of the PLF fragment taken in coincidence with the TLF. The DWBA cross section plays the role of a filter for the $\rho(J)$ spin distribution of formula 3).

The $F(J)$ function is a well shaped curve as shown in Fig. 4 for the various ejectiles. In Table I the predicted mean value of the transferred angular momentum $\overline{J}$ in the target nucleus is reported (eq. (4)).

The dashed lines of Fig. 3 have been computed by means of eq.(3) using the distribution $F(J)$ and α_0, for each channel, as obtained in the previous fits (see Table I).

In particular for carbon and boron ejectiles a reasonable agreement between calculations and experimental data is clearly seen. The result is very interesting. In fact, for the first time, a severe test of the $\rho(J)$ distributions, as predicted by the diffractional DWBA model has been performed by two independent ways: by fitting inclusive PLF energy spectra and angular distributions (see Ref. [1]) and by fitting the fission anisotropies of Fig. 3.

For nitrogen and oxygen data the calculations show a tendency to underestimate the experimental anisotropies. However, these two PLF residues have been observed with a very low fission probability. So, in doing the comparison, it is crucial to know how the distribution $F(J)$ is filtered by the fission channel. The present analysis seems to suggest the existence of a selection of large J values as observed in the tails of the distributions. Alternatively, the effect could be explained by assuming lower K_0 values than indicated in Table I. As an example, in the case of nitrogen data, a value of $K_0 \approx 5\hbar$ was able to reproduce the experimental data. Similar smaller values of K_0 are used in Ref. [8] for transfer-fission reactions in the system $^{16}O+^{232}Th$.

In conclusion, our analysis indicate that , using the formalism of sequential fission model of Ref. [5] it is possible to reproduce the basic trends of the experimental data. By fitting both the in-plane and the out-of-plane FF angular correlations the values of $\overline{J}$ of the fissioning nucleus are evaluated. These values are in agreement with a diffractional direct DWBA calculations.

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TABLES

TABLE I. Summary of the obtained results in the context of the present analysis.

TLF	K_0^2 ($\hbar^2$)	W_{in}	W_{out}	α_0	$J_0(\hbar)$	$\overline{J}(\hbar)$	$J_0(\hbar)(\alpha_0 = 10°)$
^{243}Am	100	1.0±0.5	2.8±0.4	10°	17	16.5	17±3
^{242}Pu	76	1.3±0.3	2.0±0.3	30°	15	14.7	12±2
^{239}Np	60	2.0±0.5	1.6±0.3	40°	13	9.2	8±2
^{238}U	39	3.0±0.5	1.2±0.5	50°	10	12.2	5±2

FIGURES

FIG. 1. Schematic view of the adopted experimental geometry.

FIG. 2. In-plane (a) and out-of-plane (b) differential laboratory fission multiplicity of fission fragments taken in coincidence with carbon ejectiles detected at the mean angle of 75°. Full and dashed lines represent detection efficiencies for fission fragments (see text). (The symbols • and ∘ represent FF taken in coincidence with GS1 and GS2 telescopes respectively.The symbol ■ represents the mean value of the FF multiplicity as obtained by the coincident yield GS1 $\cap$ GS2).

FIG. 3. In-plane (a) and out-of-plane (b) differential fission multiplicity in the frame of the targetlike fissioning nucleus. The full and dashed lines are explained in the text.

FIG. 4. $F(J)$ distributions of the transferred angular momentum as predicted by the spin cut-off law and the DWBA diffractional model already used in Ref. [1].

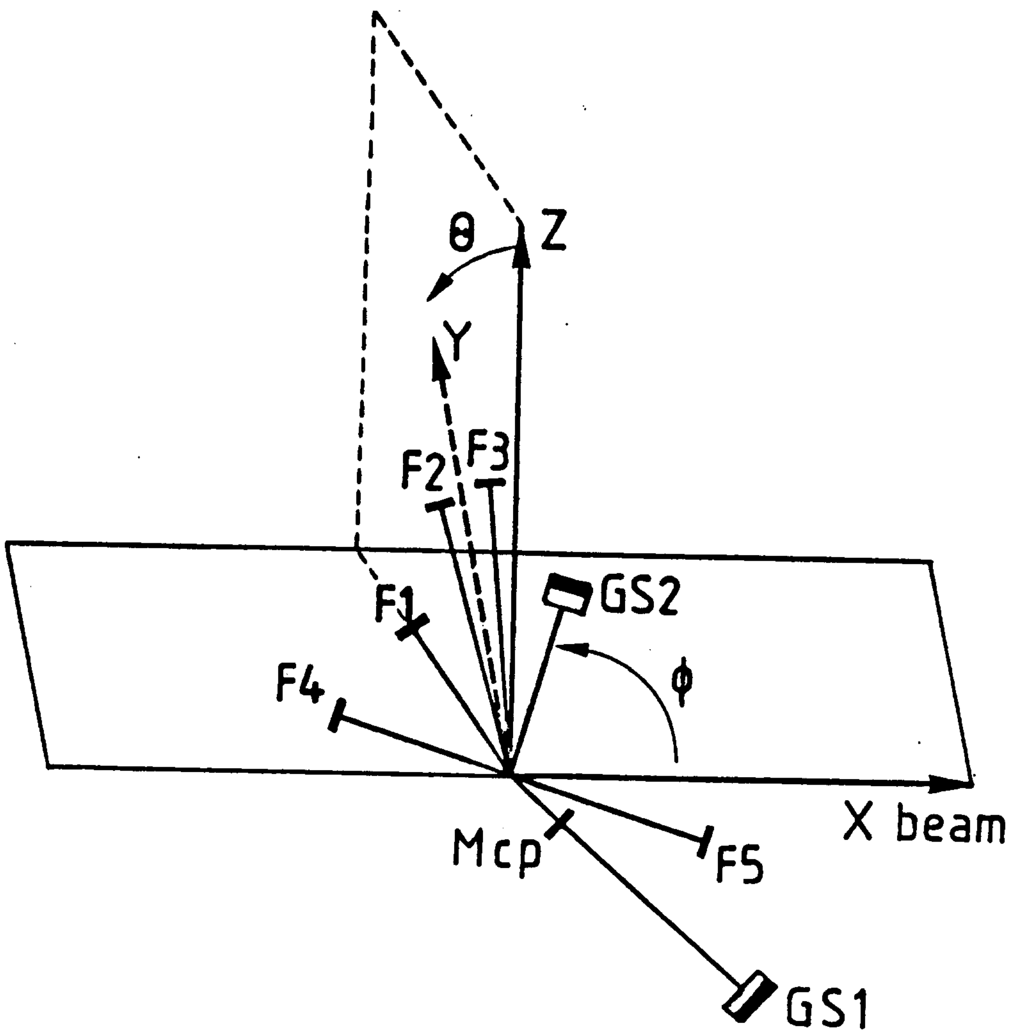
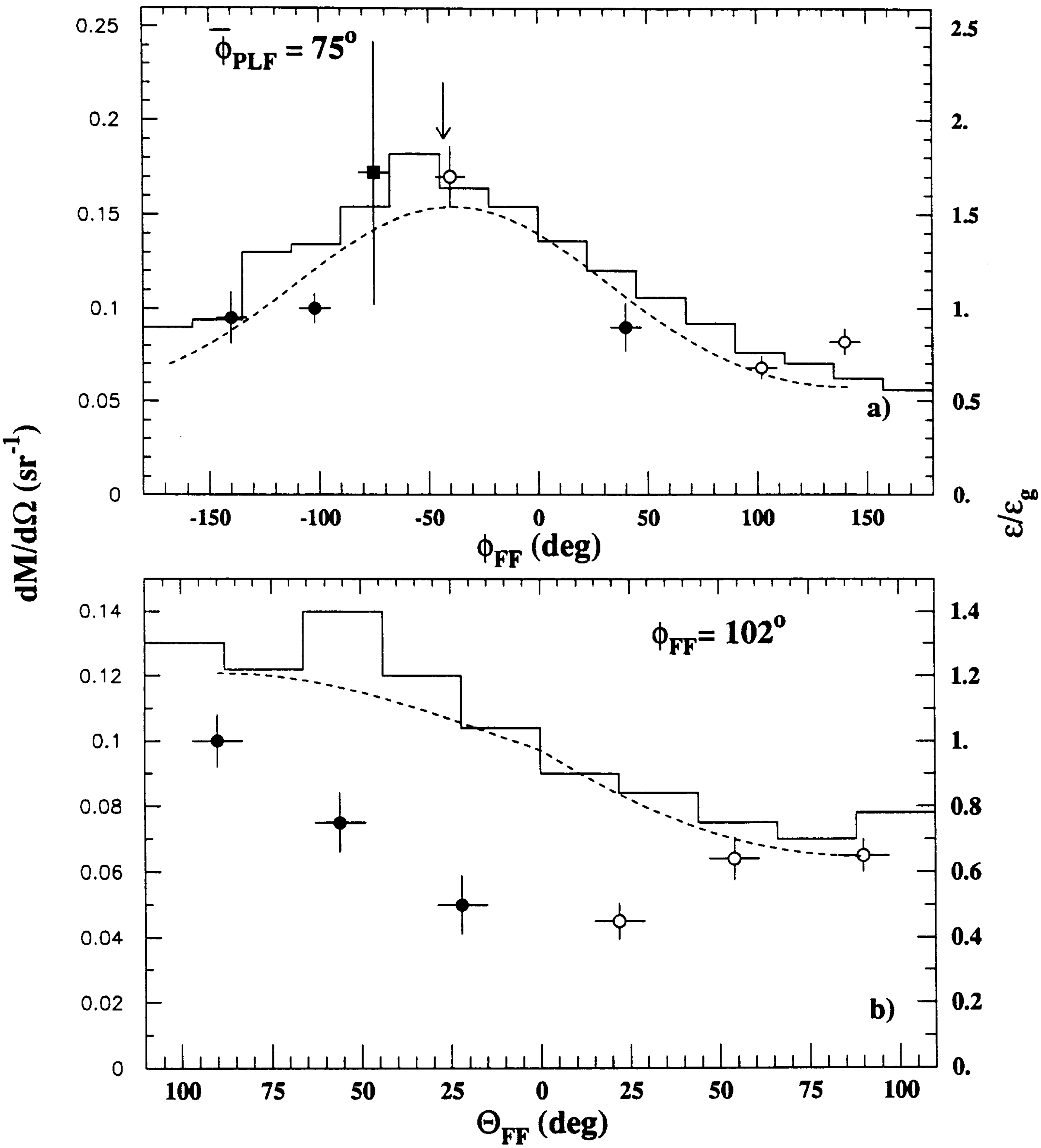


Fig. 1



$\overline{\phi}_{PLF}$ = 75°
a)
ϕ_{FF} (deg)
dM/dΩ (sr^{-1})
ε/ε$_g$
ϕ_{FF}= 102°
b)
Θ_{FF} (deg)

Fig. 2

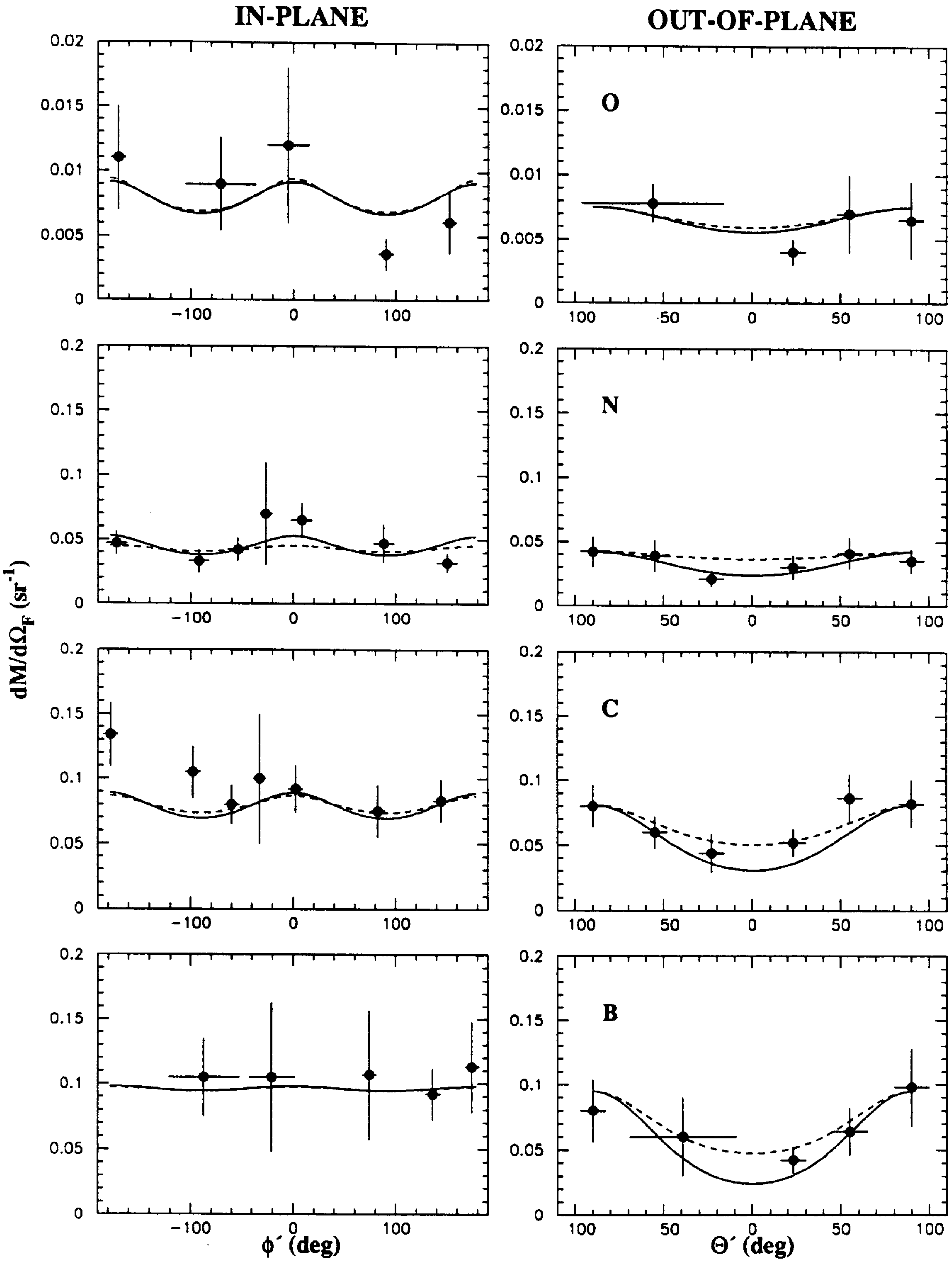


Fig. 3

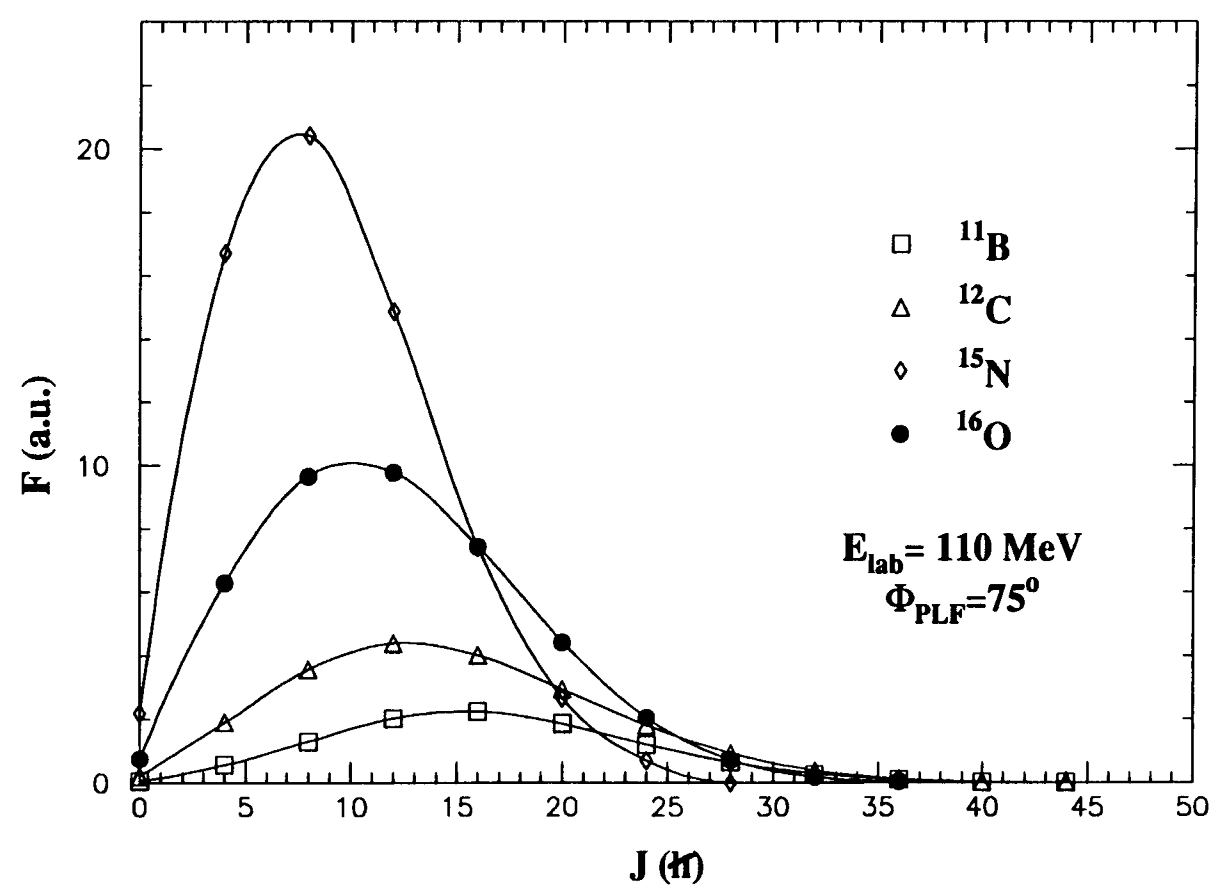

F (a.u.)
20
10
0
0
5
10
15
20
25
30
35
40
45
50
J (ħ)
11B
12C
15N
16O
Elab= 110 MeV
ΦPLF=75°

Fig. 4