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53, avenue des Martyrs – GRENOBLE

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B. CHAMBON*, D. DRAIN*, C. PASTOR*, A. DAUCHY, A. GIORNI, C. MORAND

*Institut de Physique Nucléaire, 43 Bd. du 11 Novembre 1918, 69621 Villeurbanne Cedex.

Laboratoire associé à l'Institut National de Physique Nucléaire et de Physique des Particules.

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B. Chambon, D. Drain, C. Pastor

Institut de Physique Nucléaire (UCBL-IN2P3)

43 Boulevard du 11 novembre 1918, F 69621 Villeurbanne

A. Dauchy, A. Giorni, C. Morand

Institut des Sciences Nucléaires (USMG-IN2P3)

53 Avenue des Martyrs, F 38026 Grenoble Cédex, FRANCE

Angular correlations between neutrons and projectile-like fragments detected near the grazing angle were analysed by assuming two incoherent neutrons sources. One source describes slower neutrons evaporated by target-like fragments in equilibrium. The faster, forward-peaked neutrons originate from a second source strongly correlated with the projectile-like fragments with regards to velocity and direction. In some cases neutron emission may even be attributed to known neutron emitter levels in excited ejectiles.

1 - INTRODUCTION

In the study of heavy ions collisions, fast particles emission provides an extensive means of investigation of the reaction mechanisms. When the incident energy is well above the Coulomb barrier, a fast forward-peaked component emerges on a slow component accounted for by evaporation from residues in equilibrium. In order to find the origin of these fast particles several models have been proposed (incomplete fusion, hot spot, projectile break-up,.....).

Beside these interpretations, the sequential break-up of the projectile-like fragments (PLF) has been recently suggested by Gavron et al. [1] to explain forward-peaked neutrons in a PLF-neutrons coincidences experiment via C + Gd reactions at 8-12 MeV/A. PLF is supposed to acquire enough excitation energy through deep inelastic collision to occupy neutron unbound states and then emit neutrons strongly correlated with the residual detected PLF. Such a sequential decay has been shown off lately in the ^{14}N + ^{159}Tb reaction by Van Driel et al. [2]. The α energy spectra in coincidence with a light fragment A clearly exhibit resonances of α unbound levels in the A + 4 rest frame.

In a previous γ-PLF coincidences experiment [3] using the ^{18}O + ^{48}Ti reaction at E = 6.4 MeV/A, we did identify γ lines from excited PLF. Most of the γ lines belonged however to residual target-like fragments (TLF) close to the fragment complement of the detected PLF in a two-body reaction.

This suggested that the complement was first formed during the collision (via deep inelastic, incomplete fusion, quasi-elastic processes....) and then decayed through γ and particles emission, especially neutrons. Accordingly, the present paper deals with neutron-PLF coincidences for that ^{18}O + ^{48}Ti system with the underlying idea that some neutrons would account for TLF sequential decay while others would originate from excited PLF.

While most of light particles emission experiments use charged particles for detection convenience, measurement of neutrons spectra was preferred because of the absence of Coulomb effects which complicate the interpretation of charged particles spectra in terms of uniform nuclear temperature. Another physical advantage of neutrons is the possibility to perform zero degree PLF-neutron angular correlations.

2 - EXPERIMENTAL SET-UP

The ^{18}O beam (E = 116 MeV) provided by the Grenoble Isochronous Cyclotron bombarded a self-supporting ^{48}Ti target 1.35 mg/cm^2 thick. At $\Theta = 20°$ with respect to the beam direction, PLF ($3 \lesssim Z \lesssim 8$) were detected and identified by a ΔE-E Si detectors telescope : one 43 µm thick and the other 1500 µm thick. Target and PLF telescope were placed inside a spherical 37 cm diameter aluminium chamber of 2 mm thickness.

Neutrons were detected outside by NE 213 liquid sintillators (2" x 4") positionned at 8 angles : Θ_n = 40°, 20°, 10°, -10°, -40°, -60°, -150° in the same plane as the beam axis and the Si detectors, the eighth one was out of the plane at $\phi = 90°$ (negative angles refer to the opposite side of the PLF side with respect to the beam axis). Forward neutrons detectors were 75 - 95 cm far from the target ($-40° \lesssim \Theta_n \lesssim +40°$), others were only 50 cm distant. To reduce the γ delayed background, each photomultiplier pulse was shape-discriminated by an electronic set-up [4]. Fast presort of data was performed by a programmed logic electronic design [5] before acquisition on magnetic tape via an on-line PDP 11 computer. An event was recorded on tape only if the Si detector telescope was in coincidence with at least one neutron counter. The kinetic energy of each detected neutron was obtained from the measured time-of-flight between Si-detector and any of the neutron detectors. This time was corrected, event by event, from the fragment time-of-flight from the target to the telescope as deduced from the measured fragment M and energy. The time calibration was derived from the prompt γ peak and the random γ peak from the neighbouring beam bursts. We used neutron events observed at other beam intervals to substract random events from the relevant velocity intervals. The neutron detection efficiency was calculated with a computer code developped by Kurz [6]. The detector threshold was set at 1 MeV neutron energy.

Fig. 1-2-3 display thus obtained differential cross-sections for eleven identified PLF ($^{6-7}$Li, ^{9}Be, ^{11}B, $^{12-13-14}$C, $^{14-15}$N, $^{16-17}$O).

3 - DATA ANALYSIS

Angular neutron cross-sections were analyzed by the means of two incoherent, isotropic neutron sources. The first one is assumed to be the heavy TLF complement of the detected PLF with the following spectrum in the laboratory :

$$\left(\frac{d^3\sigma}{d\Omega_p dE d\Omega}\right)^H = \frac{C_H}{2(\pi T_H)^{3/2}} \sqrt{E}\ \exp(-E_c/T_H) \quad (1)$$

The second one, supposed to be strongly correlated with the light PLF, has the pattern :

$$\left(\frac{d^3\sigma}{d\Omega_p dE d\Omega}\right)^L = \frac{C_L}{4\pi T_L^2} \sqrt{EE_c}\ \exp(-E_c/T_L) \quad (2)$$

Ω_p and Ω refer to the PLF and neutron directions.

Centre of mass E_c and laboratory E neutron energies are bound to the Θ_n neutron and Θ source angles through the relation :

$$E_c = E + \varepsilon - 2\sqrt{E\varepsilon}\cos(\Theta-\Theta_n) \quad (3)$$

where ε is proportional to the source velocity V_S square via

$$\varepsilon(\text{MeV}) = 2 \times 931\ (V_s/c)^2 \quad (4)$$

According to Gavron et al. [1] expression (1) describes better multi-neutrons emission than expression (2) which deals with a single neutron emission. Each source is then characterized by 4 parameters : C : intensity ; T : temperature ; Θ : direction ; ε : kinetic energy per nucleon. This two sources picture forms a rough model since there is no dispersion on the sources velocities and directions, the description of PLF excitation by a uniform temperature is questionable, etc.... So one has to put some constraints in the following fitting procedure to ensure a physical meaning to the parameters. We did not let the 8 parameters vary freely altogether but we determined them step by step in the following way by least square fit of the experimental data.

i) Assuming that fast neutrons proceed only from PLF, i.e. they contribute preferentially at forward angles close to the PLF detector at $\Theta = 20°$, source (1) alone was only fitted on backward angles ($\Theta_n = -40°$, $-60°$ and $-150°$). To check neutron emission from TLF in equilibrium, parameters ε_H and Θ_H were fixed at values (see Table I) deduced from kinematical considerations : from inclusive PLF spectra, the mean PLF energy fixed the average energy and direction of the complementary TLF in a two-body reaction. Despite of the poor statistics of the data, the quality of the fits and the temperatures values were satisfying enough to ensure the existence of the TLF source (see discussion).

ii) With above source (1) parameters fixed, source (2) was then added to describe forward angles spectra. To check the PLF source assumption we introduced the constraint on velocity $2.9 < \varepsilon_L < 6.4$ MeV/A. These limits were extracted from PLF inclusive spectra. In two cases (^{11}B and ^{13}C) where sharp structures appear at the forward angles $\Theta_n = 20°$ and $\Theta_n = 10°$, the PLF source was only fitted on 5 angles, excluding those angles. A second PLF source was then added to fit those two spectra with the supplementary constraint $\Theta'_L = 20°$ (see discussion). The parameters T_L, Θ_L, ε_L thus obtained are listed in Table I.

iii) To counter-balance too above the rigid determination of parameters, a last fit was performed over the 7 in plane spectra with only 3 free parameters : C_H, T_H, C_L. Final parameters are listed in Table I and whole fits are displayed on Fig. 1-2-3.

Table I also lists an anisotropy coefficient "a" for the TLF source :

$$a = (Y_{th}/Y_{exp})_{\phi = 90°} - 1 \qquad (5)$$

where Y_{th} is the theoretical yield calculated from equations (1) and (3) with $\Theta-\Theta_n = 90°$ and Y_{exp} denotes the experimental yield measured out-of-plane.

4 – DISCUSSION

4-1 EXISTENCE OF THE TLF SOURCE

Letting the four parameters in equation (1) vary freely led to unrealistic values. However, the ε_H value was always found to be very weak, suggesting a slow source. For neutrons detected in coincidence with a given PLF, the complementary fragment is obviously the needed slow source, which warrants the assumptions made in § 3, i). Moreover, deduced values for T_H quite agree with temperature values for evaporation of light particles from compound nuclei within similar excitation energy ranges (20-50 MeV).

Nevertheless T_H may be compared to calculated ones T from maximum excitation energy E_H^* acquired by the TLF in a two-body reaction via the relation $E_H^* = cT^2$ with $c = A/8\ \mathrm{MeV}^{-1}$, where A is the mass of the TLF in thermodynamical equilibrium. From inclusive spectra this TLF is assumed to recoil with energy ε_H in the direction Θ_H, and hence have the excitation energy E_H^* if the PLF is supposed not to be excited. These estimated values T are a little greater than the experimental ones T_H (Fig. 4).

This difference is easily accounted for by the above arbitrary sharing of excitation energy between PLF and TLF. Another reason also comes from the fact that, on average, more than one neutron are emitted from the excited TLF, so that the experimental T_H are effective temperatures which reflect successive lowerages of the initial temperature of the primary TLF at each neutron emission [7].

Another confirmation of the existence of the TLF source is that the results from neutron-PLF experiment well agrees with those from the γ-PLF coincidence experiment [3]. In the γ experiment the TLF neutron cross-section can be factorized as :

$$(d\sigma/d\Omega_p)^{xn\gamma} = (d\sigma/d\Omega_p)^i . \ Pr(TLF \to n) \qquad (6)$$

where $(d\sigma/d\Omega_p)^i$ is the inclusive PLF cross-section at $\Theta = 20°$, Pr (TLF → n) is the probability for the assumed complementary TLF to emit one or several neutrons. The neutron cross-section $(d\sigma/d\Omega_p)^{xn\gamma}$ was extracted, as in Ref. [8], after identification of γ-lines coincident with the detected PLF.

In the neutron experiment, the neutron production cross-section after integration over energy and space, may be written as follows :

$$(d\sigma/d\Omega_p)^{xn} = (d\sigma/d\Omega_p)^i . \ Pr(TLF \to n) . \bar{x}_n \qquad (7)$$

where $\bar{x}_n$ is the average number of neutrons emitted by the TLF. This cross-section is related to the parameter C_H by :

$$(d\sigma/d\Omega_p)^{xn} = \beta C_H \qquad (8)$$

β takes into account anisotropy effects (β = 1 for isotropy). Out of plane correlation was assumed to behave as :

$$W(\phi) \sim (1 + a \cos^2\phi) \qquad (9)$$

φ refers to the angle between emission direction and the plane perpendicular to the spin $\vec{I}$ of the polarized nucleus.

From (9) we deduce : $\beta = (1 + 2a/3)/(1+a)$

"a" was estimated via formula (5)

Combining equations (6), (7) and (8), we get :

$$\bar{x}_n = \beta C_H/(d\sigma/d\Omega_p)^{xn\gamma}$$

The $\bar{x}_n$ values, listed in Table II, are to be compared with those $\overline{x_{n\gamma}}$ extracted unambiguously from γ experiment for O and N ejectiles, since in those cases the γ lines identify only residual nuclei produced by neutron emission from the complementary TLF.

Another way to check the agreement between γ and neutrons results is the comparison between PLF cross-sections associated with neutron emission from the complementary TLF : $(d\sigma/d\Omega_p)^{xn_\gamma}$ and $\beta C_H/\bar{x}_{n\gamma}$.

The results listed in Table II verify that neutron cross-sections from TLF are quite similar wether they are extracted from γ experiment or from this neutron experiment. Moreover both are found significantly smaller than inclusive cross-section of PLF. The coherence of these 3 experimental results ensures the measurements.

The similitary of γ and neutron results (cross-sections or average neutron numbers) confirms the existence of the TLF source of neutrons.

We finally remark that the values of the anisotropy coefficient "a", listed in Table I, remain constant, around a = 1 for all PLF except ^{12}C, for which a = 6. We have no explanation why the polarisation of the complementary nucleus remains high before neutron emission.

4.2) - EXISTENCE OF THE PLF SOURCE

The necessity of a second faster neutron source is obvious at the first look at Fig. 1-2-3 : the neutron emission from equilibrated TLF cannot explain the whole angular distribution. With 4 free parameters the second source (formula 2) adjusted the 7 in-plane spectra with $5° < \theta_L < 15°$ and $2 < \varepsilon_L < 7$ MeV/A. When the constraint $2.9 < \varepsilon_L < 6.4$ MeV provided by the inclusive spectra was used, the θ_L values were still found greater than 5° (except for the non significant case of ^6Li for which the ratio C_L/C_H is only 10 %) thus excluding definitely a source moving along the beam axis. If the second source is assumed to be the detected PLF plus one neutron, the fact that $5° < \theta_L < 20°$ is easily explained by the strongly forward peaked angular distributions of the inclusive PLF spectra. Moreover, values of ε_L are generally near of the mean ones of the detected PLF.

Another proof of the existence of the PLF source may be found out from the parameter T_L values. This parameter, which could be hardly considered as a temperature with regards to the mass levity of the PLF, appears to be strongly correlated with the ability of neutron emission from an excited light fragment. Fig. 5 displays, versus T_L extracted from the fitting procedure ii), the quantity $E^* - S_n$ where E^* refers to the excitation energy of a neutron emitting level, and S_n is the neutron binding energy of the light fragment assumed to have emitted one neutron before detection. For instance ^{12}C - neutron coincidence spectra provide T_L = 2.3 MeV which is to be compared to $E^* - S_n$ = 1.92 MeV knowing that the neutron threshold is S_n = 4.94 MeV in ^{13}C and the first neutron emitter level is situated at E^* = 6.86 MeV. In this interpretation formula (2) does not account for neutron evaporation from PLF in equilibrium, but describes neutron levels above the threshold since T_L locates the maximum of spectrum (2) in the source moving frame.

In Fig. 5 the points are clearly non uniformly distributed in the plane : most of them lie near the bissectrix line (except for ^{17}O, ^{7}Li, ^{6}Li PLF and the first levels in ^{15}N and ^{17}O). In the cases of ^{6}Li and ^{7}Li the weakness of the ratio $R = C_L/C_H$ = 10 % may explain difficult extraction of reliable PLF source parameters. A more global explanation of the discrepancies may be found if the idealistic picture of one PLF emitting one neutron is resigned : other more complex processes have to be considered, for instance : $A \rightarrow A'+n \rightarrow (A''+\alpha)+n$ would give an A''-neutron coincidence.

The agreement between E^*-S_n and T_L must not be considered as poor with regards to the roughness of the model (unique direction and unique velocity of source, use of a temperature to describe discrete levels effects). So we tried to fit structures emerging in the ^{11}B and ^{13}C spectra at Θ_n = 20° and 10° with a second PLF source. The strong bumps lie at rather low energies around 5 MeV and do not appear at other angles, which indicates slow neutron emission from fast moving sources. To avoid too much arbitrary parameters, the direction Θ'_L of this second source was fixed at 20° (which is right is one assumes the emission of a single neutron because of the target -PLF detector-neutron detector alignment at 20°). The parameters (T'_L = 50 keV for ^{11}B and T'_L = 110 keV for ^{13}C) thus obtained were found surprisingly close to the $E^* - S_n = 119$ keV level at 3.388 MeV in $^{12}B^* \rightarrow {}^{11}B+n$ and the $E^* - S_n = 141$ keV level at 8.318 MeV in $^{14}C^* \rightarrow {}^{13}C+n$. These levels are the first neutron emitter states above the neutron binding energy. Concerning the source velocities, the values $\varepsilon'_L = 4.5$ and 5.3 MeV/A for $^{12}B^*$ and $^{14}C^*$ respectively, well agree with PLF speeds.

All the involved neutron emitter levels have widths $\Gamma < 45$ keV for those PLF sources which spreads all over the forward angles (from 40° to −40°). For ^{11}B and ^{13}C widths of the lowest levels are 3.1 keV and 3.4 keV respectively. These values confirm Gavron's suggestion that only long lived states may contribute to neutron emission from PLF. So Fig. 5 also indicates the centroid of the neutron emitter levels weighted by their lifetime.

5 – CONCLUSION

The present paper clearly establishes that PLF and TLF are the neutrons emitters. These two sources have been incoherently added to fit the spectra. From PLF spectra, the available excitation energy estimated in a two-body reaction, is always found higher than

the energy which is required by the TLF to produce the observed number of neutron. Moreover this available energy is also sufficient to ensure neutron emission from both PLF and TLF. The possibility of coherence of both sources can be checked by the total linear momentum conservation. With masses attributed to both presumed, coherent sources, and velocities and directions from Table I, the momentum is actually conserved within 10 %.

Most of the coincident neutrons cross-section is accounted for by the TLF source. The fast forward-peaked neutrons that we found to originate from the PLF are a contribution of the so-called direct light particles emission. Because of the sharp angular distribution of fast neutrons around the PLF direction, a little part of the total cross-section, devoted to the excitation of the PLF is sufficient to make fast neutrons emerge. Such a process however much depends on the energy sharing between fragments. So the values of C_H and C_L cross-sections, as well as the related neutron multiplicities, were not interpreted since they depend on the first stage of the collision, analysis of which would need more refined models.

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FIGURE CAPTIONS

Fig. 1

Angular distribution of neutrons in coincidence with PLF (^{17}O, ^{16}O, ^{15}N, ^{14}N) detected at $\Theta = 20°$ in the $^{18}O + ^{48}Ti$ reaction at E = 116 MeV. 7 spectra (from $\Theta_n = 40°$ to $\Theta_n = -150°$) were taken in the same plane as the PLF detector and beam axis. Negative angles are on apposite side to the PLF detector with respect to the beam axis. The 90° spectrum was recorded at a perpendicular direction with respect to this plane.

The solid curve shows the fit resulting from two sources with parameters listed in Table I. The dashed curve is the contribution of the TLF source alone.

Fig. 2

Same caption as Fig. 1 for the PLF : ^{14}C, ^{13}C, ^{12}C. For ^{13}C at $\Theta_n = 20°$ and 10°, the contribution of a second PLF source is indicated by a dotted line.

Fig. 3

Same caption as Fig. 1 for the PLF : ^{11}B, ^{9}Be, ^{7}Li, ^{6}Li. For ^{11}B at $\Theta_n = 20°$ and 10°, the contribution of a second PLF source is indicated by a dotted line.

Fig. 4

Versus PLF mass are displayed temperatures T_H of the TLF sources. Circles indicate theoretical values calculated from PLF inclusive spectra via two-body kinematics (see the text).

Fig. 5

For each PLF of mass A in coincidence with neutrons, are displayed

- along the X-axis the parameters T_L (first PLF source) extracted from angular correlation analysis (Table I)
- along the Y-axis the $E^* - S_n$ values concerning neutron emitter levels in the A + 1 nucleus.

Circles indicate ^{11}B and ^{13}C cases where a second PLF source was needed to explain sharp structures at forward angles $\Theta_n = 20°$ and 10°. For ^{9}Be, ^{12}C, ^{14}N, ^{15}N and ^{16}O, horizontal strokes figure the centroids of the neutron emitter levels (see the text).

Table I

Analysis of neutron angular correlations

F	C_H	T_H	Θ_H	ε_H	C_L	T_L	Θ_L	ε_L	C'_L	$T'L$	Θ'_L	ε'_L	R	a
Li	6.5 0.4	2.1 .1	-10	0.27	0.8 0.13	1.1 0.17	2.6 3.5	4.6 0.7	0				0.12	0.7 0.6
Li	9.2 0.45	2.3 0.08	-10	0.28	1.1 0.15	1.04 0.15	11.4 3.4	2.9 1.	0				0.12	0.3 0.5
Be	6.8 0.4	2.3 0.11	-15	0.23	0.9 0.15	0.9 0.13	7.5 2.9	3.3 0.8	0				0.13	0.4 0.5
B	12.2 0.5	1.81 0.07	-20	0.20	1.9 0.21	1.4 0.17	11. 2.	3.9 0.7	0.17 0.02	0.05 0.03	20	4.5 0.06	0.16	1.2 0.7
C	31.2 0.9	2.5 0.06	-25	0.17	9.9 0.4	2.3 0.1	6.1 1.4	3.3 0.3	0				0.32	6.0 1.8
C	18.7 0.6	2.3 0.7	-30	0.15	2.2 0.18	1.1 0.09	4.6 1.7	5.6 0.5	0.2 0.03	0.11 0.014	20	5.3 0.1	0.13	1.6 1.
C	6.6 0.3	2.0 0.1	-40	0.12	0.6 0. 7	1.4 0.18	5. 2.2	6.8 0.8	0				0.07	0.8 0.3
N	8.0 0.4	1.75 0.09	-35	0.13	2.8 0.2	1.2 0.07	15. 1.4	3.6 0.5	0				0.35	2.4 1.1
N	18.4 0.6	2.0 0.06	-35	0.14	4.3 0.2	1.5 0.07	7.9 1.	5.2 0.2	0				0.23	1.3 0.4
O	28.8 0.7	2.0 0.06	-50	0.12	13.1 1.3	1.6 0.05	11.5 0.7	6.0 0.1	0				0.45	1.6 1.3

0	7.6	1.7	-55	0.11	2.0	1.0	10.4	4.7	0		0.26	0.6
	0.4	0.1			0.14	0.1	1.2	0.4				0.4

* Parameters C_H, T_H, Θ_H, ε_H refer to the neutron source (1) from TLF (heavier fragment).
Parameters C_L, T_L, Θ_L, ε_L refer to the neutron source (2) from PLF (lighter fragment).
In the ^{11}B and ^{13}C cases a second similar PLF source has been used (C'_L, T'_L, Θ'_L, ε'_L)
C, T, Θ and ε are in mb/sr, MeV, degree, MeV/A respectively.
R denotes the ratio $(C_L + C'_L)/C_H$. a is the anisotropy coefficient calculated from formula (5)

** (For ^{12}C, the weak contribution from the PLF source was neglected)

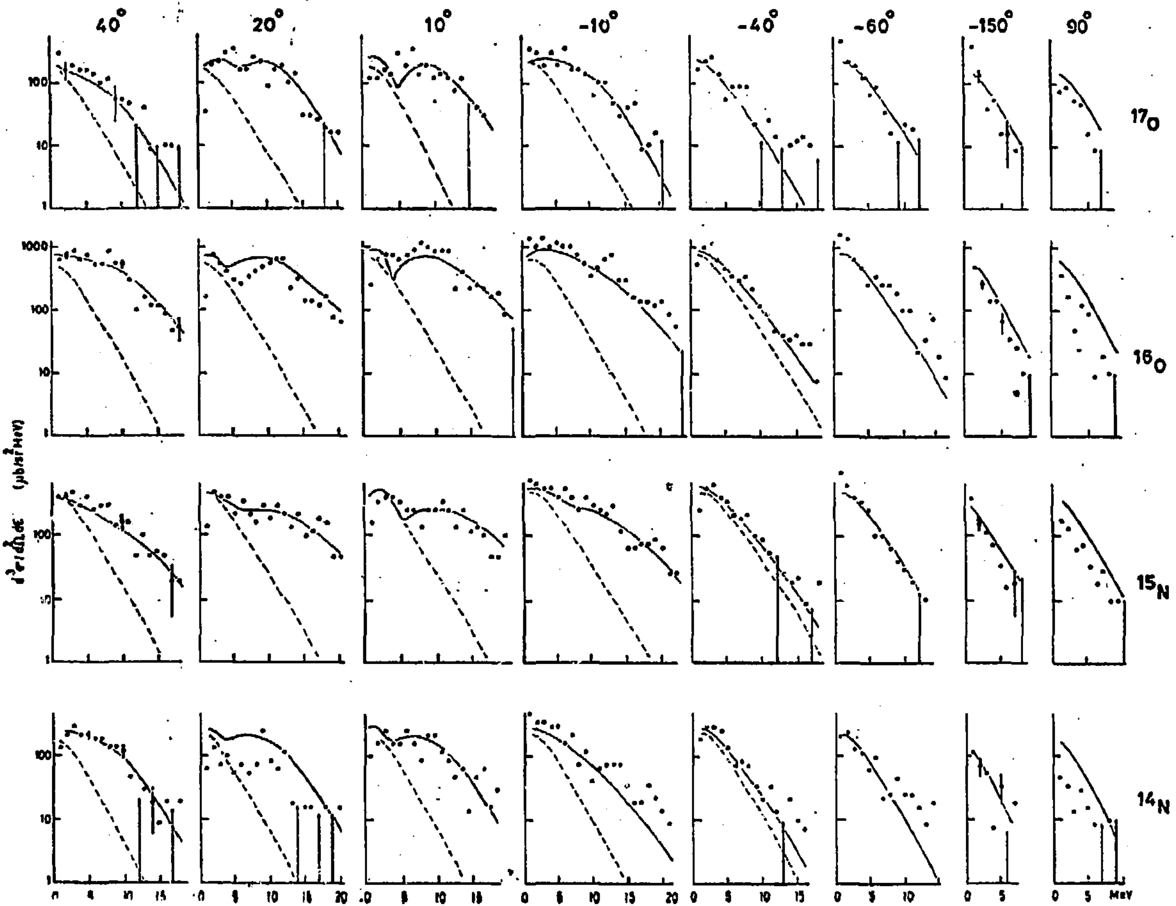
Underlying values are the parameters incertitudes (Θ_H, ε_H and Θ'_L were set fixed)

Table II

Comparison between results from γ and neutron coincidences experiments

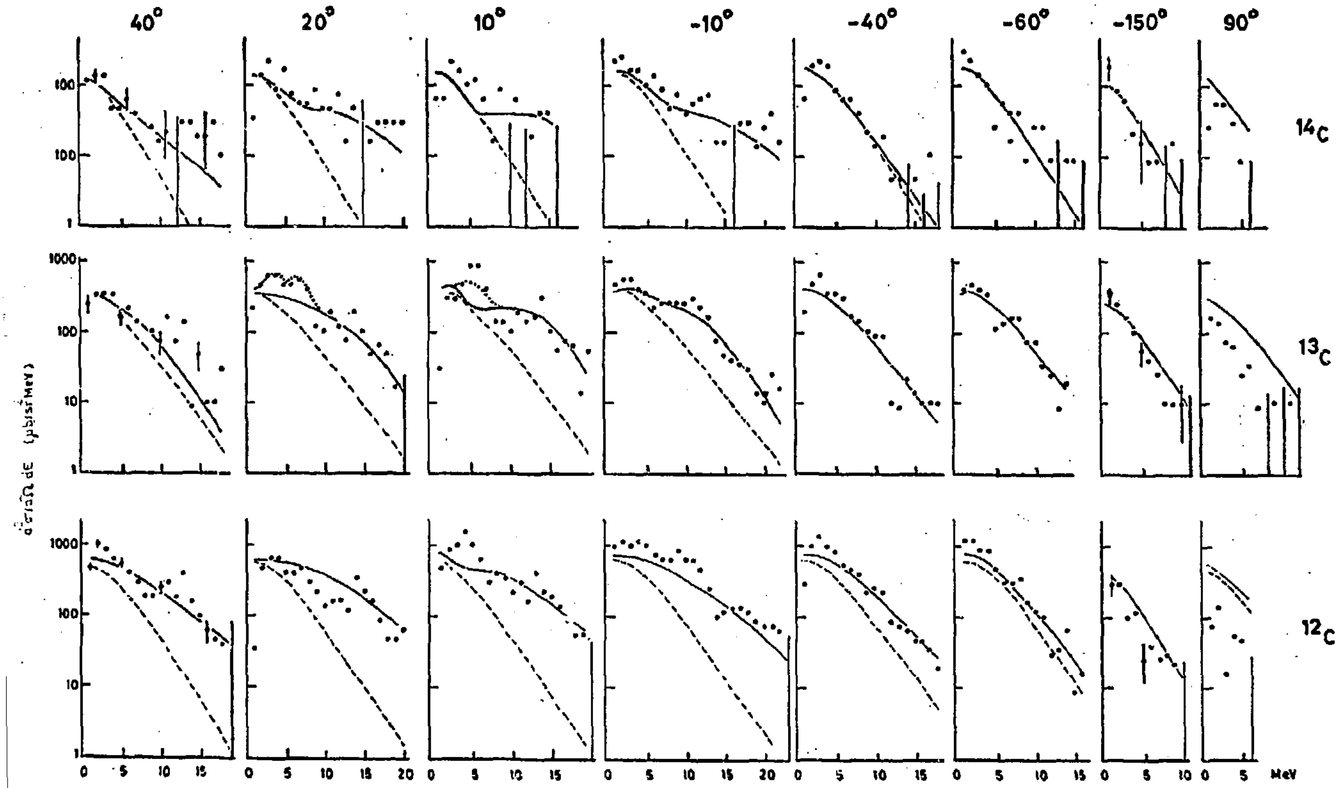
PLF	$(d\sigma/d\Omega_p)^i$	$(d\sigma/d\Omega_p)^{xn\gamma}$	$\beta C_H/\bar{x}_{n\gamma}$	$\bar{x}_n$	$\bar{x}_{n\gamma}$
^{17}O	19.7	7	6.3	0.9	1
^{16}O	15.6	9.3	13.3	2.6	1.8
^{15}N	15.4	10	7.3	1.5	2.1
^{14}N	4.5	3.9	3	1.8	2.2

PLF cross-sections are in mb/sr. See the definition of the listed quantities in the text. Incertitudes on inclusive cross-sections are about 5 %, and for other data entirely or partly extracted from γ-experiment may reach 30 %.

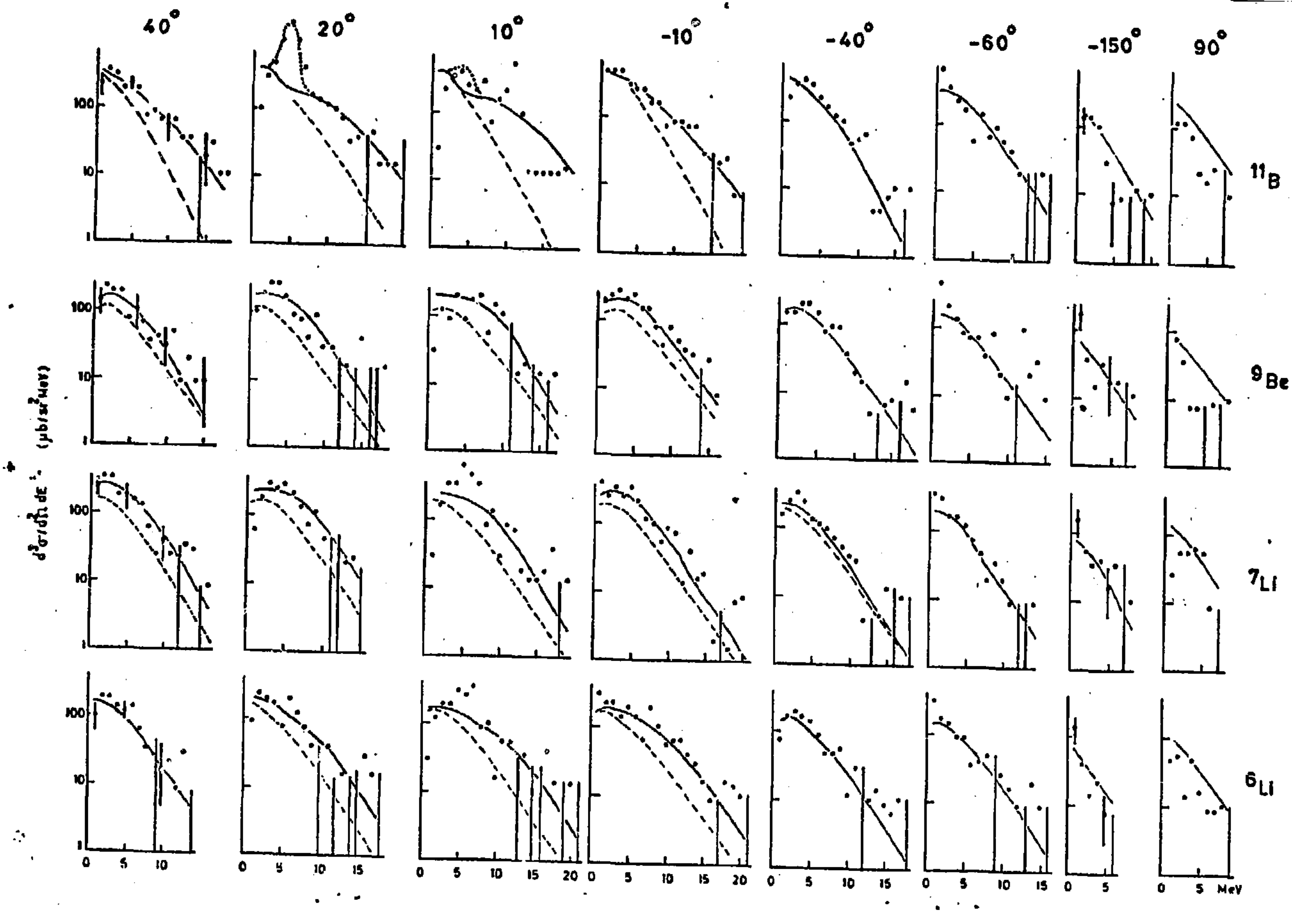


40°
20°
10°
-10°
-40°
-60°
-150°
90°
^{17}O
^{16}O
^{15}N
^{14}N
$d^3\sigma/d\Omega_1 d\Omega_2 d\epsilon$ ($\mu b/sr^2$ MeV)
MeV

4.



40°
20°
10°
-10°
-40°
-60°
-150°
90°
^{14}C
^{13}C
^{12}C
MeV


40°
20°
10°
-10°
-40°
-60°
-150°
90°
11B
9Be
7Li
6Li
d²σ/dΩ dE (μb/sr MeV)
100
10
1
0
5
10
15
20
MeV

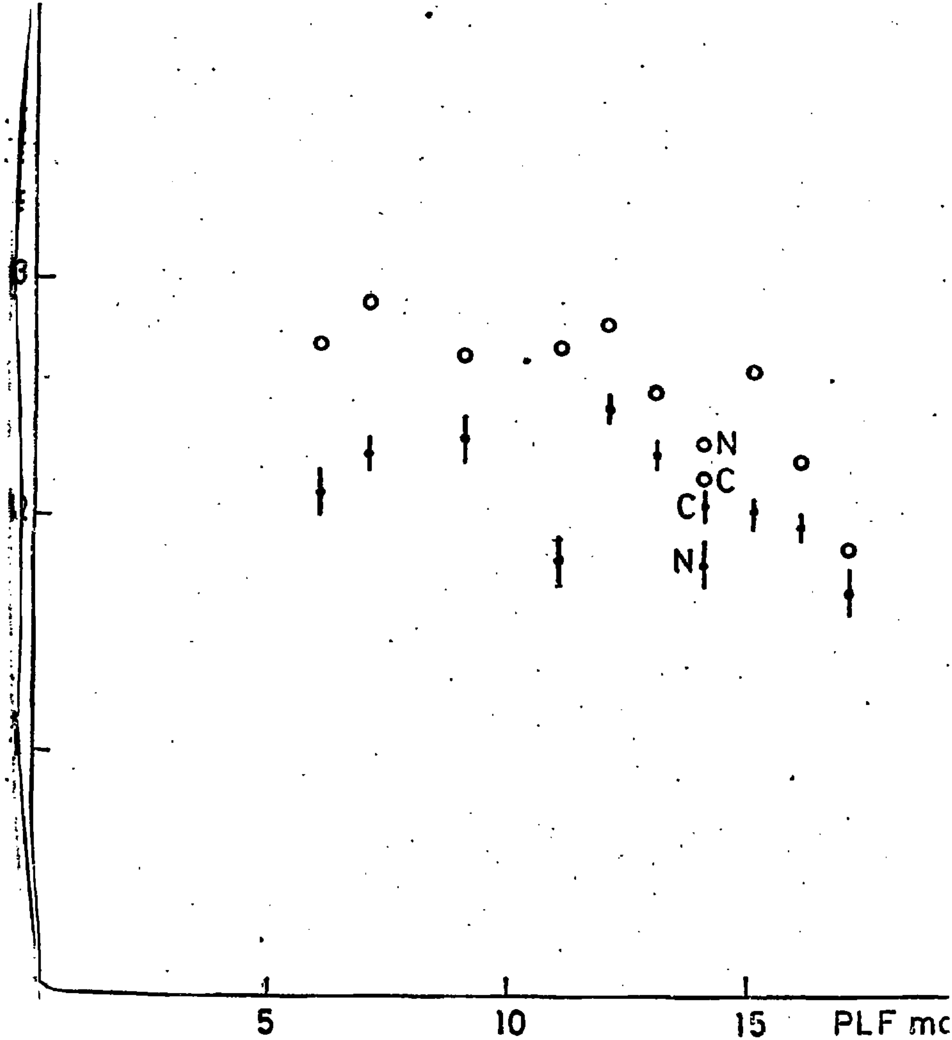
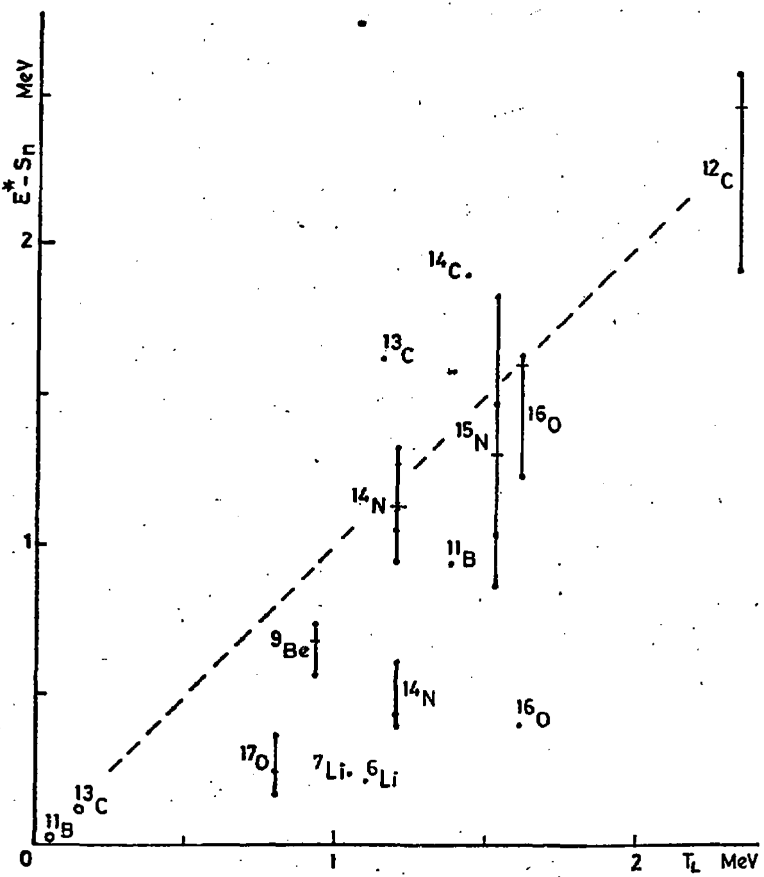


Fig 4


E* - Sn MeV
2
1
0
1
2
T_L MeV
12C
14C
13C
15N
16O
14N
11B
9Be
14N
16O
17O
7Li
6Li
13C
11B