MULTIPLICITY OF GAMMA-RAY TRANSITIONS OBSERVED IN LITHIUM-INDUCED REACTIONS

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The multiplicities of the γ-rays observed in ^{6}Li bombardment of ^{56}Fe, ^{165}Ho and ^{169}Tm targets have been measured using the detector system described elsewhere.[1,2] These studies were undertaken to augment our understanding of the mechanism of the lithium induced reactions which had earlier[3] been studied at IUCF through (a) energy dependence of the production cross sections of various final nuclei determined by inclusive γ-ray technique and (b) the systematics of the recoil ranges, both integral and differential, of the final nuclei.

Fig. 1 shows typical zero-, one-, two- and three-fold Ge(Li) detector spectra for the case of the ^{165}Ho target bombarded with 66 MeV ^{6}Li projectiles. γ-ray transitions which have the highest multiplicity stand out more distinctly above the background in the higher-fold spectrum relative to those of lower multiplicity. From these data the average multiplicities as well as the higher moments of its distributions have been extracted using two techniques. The energies and the multiplicities of the relatively intense gamma rays and the transitions that they correspond to are given for a representative set of final nuclei produced with the ^{56}Fe target in Table 1 and with the ^{165}Ho target in Table 2. For comparison it is worth noting here that the average angular momentum transferred to the compound nucleus by the incident ^{6}Li-projectile is 22 ħ and 16 ħ for the ^{165}Ho and ^{56}Fe target nuclei, respectively.

The γ-rays transitions which belong to the highest-Z nuclei produced in the ^{6}Li bombardment are, for example ^{58}Ni with the ^{56}Fe target and ^{166}Yb with the ^{165}Ho target, found to have the highest multiplicity, the values for which are consistent with (assuming the γ-transitions are quadrupole in nature) the average angular momentum transferred to the compound nucleus (see Table 1 and 2). On the other hand it is interesting to note, especially for transitions in ^{165}Tm and ^{164}Er nuclei produced with the ^{165}Ho target, that the multiplicity of the transitions among the lower lying and lower J states is noticeably smaller (on an average 4-5 vs. 8-10) than those originating from higher lying (and higher J) states. This pattern can only be understood if the lower energy states besides being populated from the higher lying states through γ-cascade are <u>also</u> being populated independently by another process. If σ_1 and σ_2 are the cross sections with which the two processes contribute to the population of the lower lying states and M_1 and M_2 are the average multiplicities due to each of the two processes, respectively, then the observed multiplicity of the transitions from the lower lying states will be

$$\langle M_{\text{observed}} \rangle = \frac{\sigma_1 M_1 + \sigma_2 M_2}{\sigma_1 + \sigma_2}$$

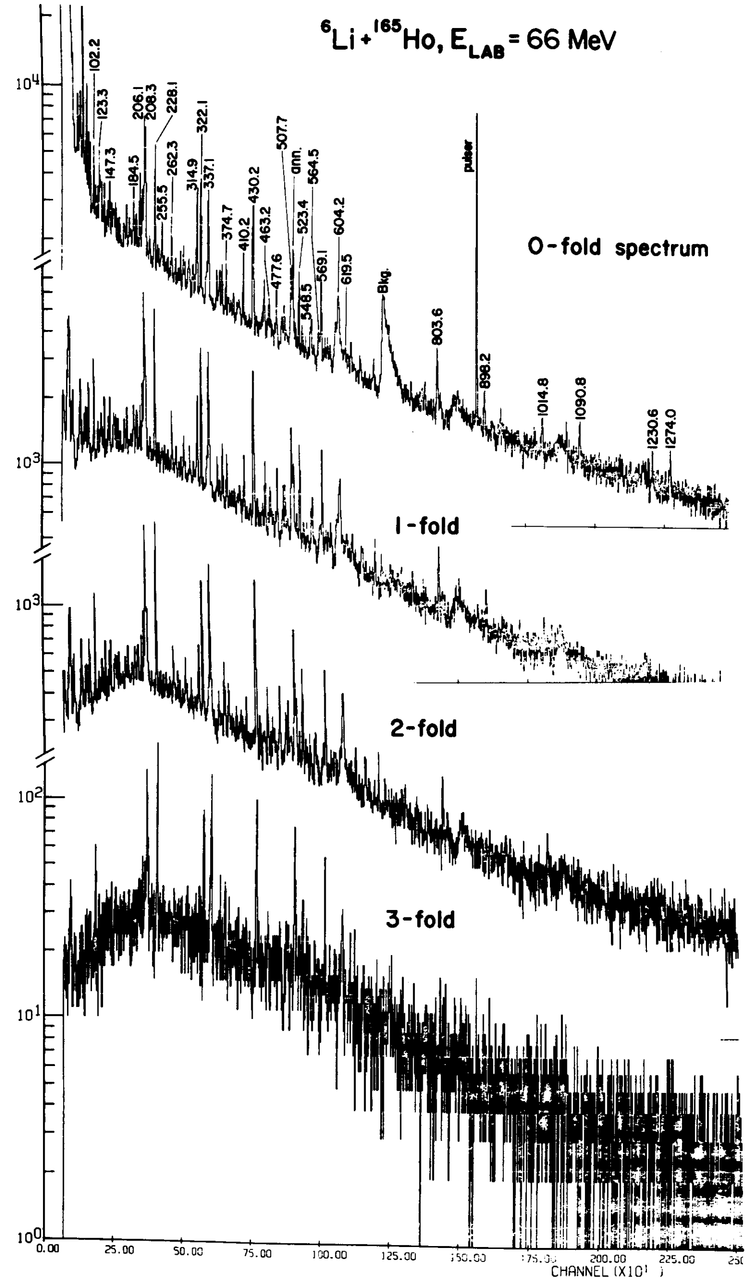
^{6}Li + ^{165}Ho, E$_{LAB}$ = 66 MeV
102.2
123.3
147.3
184.5
206.1
208.3
228.1
255.5
262.3
314.9
322.1
337.1
374.7
410.2
430.2
463.2
477.6
507.7
ann.
523.4
548.5
564.5
569.1
604.2
619.5
Bkg.
803.6
pulser
898.2
1014.8
1090.8
1230.6
1274.0
0-fold spectrum
1-fold
2-fold
3-fold
10^4
10^3
10^3
10^2
10^1
10^0
0.00
25.00
50.00
75.00
100.00
125.00
150.00
175.00
200.00
225.00
250
CHANNEL (X10^1)

Figure 1

Table 1. γ-Ray Multiplicities Observed in ^{6}Li + ^{56}Fe Reaction at 66 MeV Bombarding Energy

Nucleus	Eγ	Transition	<M>
^{58}Ni	1454.6	$2^+ \rightarrow 0^+$	10.6
	1005.1	$4^+ \rightarrow 2^+$	8.9
	762.6	$8^+ \rightarrow 6^+$	9.1
	537	$10^+ \rightarrow 8^+$	9.4
^{58}Co	365.9	$3^+ \rightarrow 2^+$	5.7
	1050.7	$(2^+, 3^+) \rightarrow 2^+$ gs	6.8
	321.1	$5_1^+ \rightarrow 4^+$	7.7
	432.9	$4_1^+ \rightarrow 5^+$	8.1
^{57}Co	1377.5	$3/2^- \rightarrow 7/2^-$ gs	5.5
	1223.7	$3/2^- \rightarrow 7/2^-$ gs	6.5
	465.7	$11/2^- \rightarrow 3/2^-$	6.9
^{56}Co	576.5	$5^+ \rightarrow 4^+$ gs	7.0
	1706.1	$7^+ \rightarrow 5^+$	6.0
^{56}Fe	846.8	$2^+ \rightarrow 0^+$	4.2
	1238.3	$4^+ \rightarrow 2^+$	5.5
	1303.4	$6^+ \rightarrow 4^+$	6.3
^{55}Fe	411.4	$1/2^- \rightarrow 3/2^-$ gs	5.4
	931.4	$5/2^- \rightarrow 3/2^-$ gs	5.9
	1316.8	$7/2^- \rightarrow 3/2^-$ gs	6.7
	385.3	$7/2^- \rightarrow 5/2^-$	8.4
	1369.8	$9/2^- \rightarrow 5/2^-$	8.2
	605.6	$15/2^- \rightarrow 13/2^-$	8.3
	1680.6	$15/2^- \rightarrow 15/2^-$	8.6
^{54}Fe	1408.6	$2^+ \rightarrow 0^+$	4.9
	1130.3	$4^+ \rightarrow 2^+$	5.9
	146.2	$10^+ \rightarrow 8^+$	5.6
^{54}Mn	156.4	$4^+ \rightarrow 3^+$ gs	5.5
	212.0	$5^+ \rightarrow 4^+$	5.9
	704.8	$6^+ \rightarrow 5^+$	6.5
	852.0	$\rightarrow 6^+$	6.0
^{52}Cr	1434.3	$2^+ \rightarrow 0^+$	5.8
	935.5	$4^+ \rightarrow 2^+$	6.4
	1334.0	$4_1^+ \rightarrow 2^+$	6.7

Experimental errors in the values of <M> quoted in Tables 1 and 2 are about 20%.

Table 2. γ-Ray Multiplicities Observed in ^{6}Li + ^{165}Ho Reaction at 66 MeV Bombarding Energy

Nucleus	Eγ	Transition	<M>
^{166}Yb	102.2	$2^+ \rightarrow 0^+$	11.9
	228.1	$4^+ \rightarrow 2^+$	14.5
	337.1	$6^+ \rightarrow 4^+$	13.9
	430.2	$8^+ \rightarrow 6^+$	14.3
	507.7	$10^+ \rightarrow 8^+$	16.1
	569.7	$12^+ \rightarrow 10^+$	14.3
	604	$14^+ \rightarrow 12^+$	9.9
	495	$16^+ \rightarrow 14^+$	16.4
^{164}Yb	123.3	$2^+ \rightarrow 0^+$	9.4
	262.3	$4^+ \rightarrow 2^+$	10.8
	374.7	$6^+ \rightarrow 4^+$	12.2
	463.2	$8^+ \rightarrow 6^+$	9.9
^{165}Tm	92.0	$9/2^- \rightarrow 7/2^-$	6.9
	116.7	$11/2^- \rightarrow 9/2^-$	5.6
	134.6	$9/2^- \rightarrow 7/2^-$	3.9
	142.5	$13/2^- \rightarrow 11/2^-$	8.3
	147.3	$7/2^+ \rightarrow 3/2^+$	8.5
	255.0	$11/2^+ \rightarrow 7/2^+$	10.5
	298.5	$17/2^- \rightarrow 13/2^-$	8.9
	334.4	$13/2^+ \rightarrow 9/2^+$	9.8
	355.2	$15/2^+ \rightarrow 11/2^+$	11.6
	380.3	$15/2^+ \rightarrow 11/2^+$	11.1
	389.7	$21/2^- \rightarrow 17/2^-$	12.3
	397.6	$19/2^- \rightarrow 15/2^-$	12.6
^{164}Er	97.5	$2^+ \rightarrow 0^+$	6.9
	208.0	$4^+ \rightarrow 2^+$	6.0
	314.9	$6^+ \rightarrow 4^+$	8.9
	410.2	$8^+ \rightarrow 6^+$	9.2
	564.5	$12^+ \rightarrow 10^+$	9.2
	619.5	$14^+ \rightarrow 12^+$	9.1

The fact that the observed multiplicity of the transitions among the lower lying states is significantly less than that of transitions among the higher states implies that lower lying states are also being populated by a mechanism which transfers relatively lower angular momentum to the final system. Using the observed intensities of the γ-rays it is estimated that, both for ^{165}Tm and ^{164}Er, whereas the multiplicity of the higher transition is of the order of 8-10 that of the process feeding the lower states only is about 4.

Recently in another experiment in progress at IUCF,[4)] it has been observed that (a) the particle spectra following ^{6}Li bombardment of ^{197}Au and ^{56}Fe are characterized by broad α and d peaks with energy corresponding to the beam velocity and (b) that the γ-rays in coincidence with the beam velocity α[or d] have the feature as if those γ-rays were produced by (d,xn)[or (α,xn)] type reactions. These results are being interpreted as if the incident ^{6}Li projectile dissociates in the field of a nucleus into an α fragment and a deuteron fragment which in turn interact with the same nucleus producing, among other things, (d,xnγ) and (α,xnγ) reactions. If this picture were true then it must show up as higher multiplicity for those γ-rays which are produced following the fusion of ^{6}Li projectile with the target nucleus and lower multiplicity for those which are produced following the fusion of α-particle with the target nucleus. It is interesting to compare the two types of observed multiplicities with the average amount of angular momentum that the fusion of beam velocity ^{6}Li, α and d can transfer to the compound nucleus. These values are about 22, 12 and 7 $\hbar$ units, respectively. Note that, for example, $<M>$ of 8-10 and 4 for the two mechanisms correspond to average J in ^{165}Tm and ^{164}Er, before γ decay started, of 16-20 and 8 $\hbar$ units (assuming that the average multipolarity of the γ-rays in quadrupole). The proximity of the average J deduced from the two values of the multiplicity to those transferred by ^{6}Li and the beam velocity alpha (or d) give credence to the above picture. In other words, the higher spin states in ^{165}Tm and ^{164}Er are produced following the nuclear evaporation from the ^{171}Yb compound nucleus formed by fusion of ^{6}Li with ^{165}Ho while the low lying states are also produced following the nucleon evaporation from ^{169}Tm formed by the process of the beam velocity α with the ^{165}Ho. The former is a higher multiplicity while the latter is a lower multiplicity process. From the observed cross sections it can also be concluded, if this were the case, that ^{165}Tm is produced about twice as strongly by the latter process than by the former one.

Though further analysis of data is needed to be sure that the above results and conclusions are valid, it is obvious, however, that the multiplicity information can be useful in identifying and determining the extent to which different processes may be contributing in the production of a nucleus in a given nuclear reaction.

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1) D.G. Sarantites et al., Phys. Rev. C14, 2138 (1976).

2) IUCF Annual Report, 1977, page 77.

3) IUCF Annual Report, 1977, p. 73 and this report p. 128.

4) this report p.134.