Gamma Radiation from Lithium-Lithium Nuclear Reactions*

E. BERKOWITZ, S. BASHKIN, R. R. CARLSON, S. A. COON, AND E. NORBECK
Department of Physics and Astronomy, State University of Iowa, Iowa City, Iowa

(Received May 31, 1962)

A three crystal pair spectrometer was used to determine the relative intensities of gamma radiation produced in the bombardment of separated Li^6 and Li^7 targets by Li^6 and Li^7 ions at energies of 2.6 and 3.6 MeV. The observed gamma radiation arises from excited states of residual nuclei. These include Be^{10}, B^{10}, B^{11}, B^{12}, B^{13}, C^{11}, and C^{12} in the present experiment. Relative populations deduced from the data indicate that a difference of one unit of charge for the matter transferred in the reaction does not strongly influence the relative cross sections. In particular, the production of B^{12} (ground state) and the equivalent state in C^{12} (15.11 MeV) in the bombardment of Li^7 by Li^6 were in the ratio 2:1. A value of 2.3:1 is predicted for this ratio on the basis of simple stripping theory and cluster breakup in this reaction. The relative populations of the excited states of B^{11} produced in the three reactions show systematic variations as a function of excitation.

I. INTRODUCTION

PREVIOUS studies of gamma rays produced by lithium beam reactions have been carried out with single NaI(Tl) crystals.[1,2] The characteristic triple-peak response of NaI to a single gamma-ray energy and the background of high-energy beta particles makes the analysis of these complicated spectra somewhat uncertain. In the energy range where pair production is significant these difficulties have been avoided by using spectra obtained with a three-crystal pair spectrometer.

II. EXPERIMENTAL APPARATUS AND PROCEDURE

Thick targets of Li^6F and Li^7F were bombarded with Li^6 and Li^7 beams from the State University of Iowa 4-MeV Van de Graaff accelerator.

The three-crystal pair spectrometer has been described in detail by Carlson[3] an Valerio.[4] Two identical 5-in.-diam by 3-in.-thick NaI(Tl) crystals, each with a groove in one flat face and a phototube viewing the crystal on the other flat face, were placed with their grooves together. A 2-in.-diam by 2-in.-long NaI(Tl) crystal was placed in the $2\frac{1}{2}$-in.-diam cylindrical hole formed by the two grooves. The 2-in. center crystal viewed the target chamber through a thin Lucite window at 90° to the beam direction. It was connected to a 256-channel pulse-height analyzer.

The analyzer was gated by time-coincident (50-nsec) annihilation photons in the side crystals. In addition to the suppression of the photopeak and one escape peak, the triple coincidence removes the large backgrounds of 13-MeV beta particles from B^{12} and B^{13} which are produced in some of the reactions being studied. Energy calibration of the gamma-ray data was obtained from the self-consistency of the numerous gamma ray assignments made on the basis of the known gamma-ray decay modes of the residual nuclei[5] and by use of a ThC″ (2.62 MeV) gamma ray source. The efficiency as a function of energy was taken from data presented in reference 4. The counts in the Gaussian peaks of the data were obtained by numerical integration and corrected for efficiency. These numbers, after normalization, appear under Relative Intensity in Tables I through III.

These relative intensities were analyzed into relative populations of states in the residual nuclei by use of their known gamma-ray branching ratios, and the known relative particle cross sections for states in B^{11}. These have been measured for the first four states in B^{11} from the reactions $Li^6(Li^6,p)B^{11}$, $Li^6(Li^7,d)B^{11}$, and $Li^7(Li^7,t)B^{11}$ at 2.1 MeV.[6,7] It has been assumed that these relative cross sections are not very sensitive to bombarding energy, at least for energies well below the Coulomb barrier. This assumption is consistent with all available information. Furthermore, gamma-ray spectra obtained at one angle can be compared to integrated cross sections since observations have shown no appreciable anisotropy of the gamma radiation.

The error in determination of relative intensities of gamma rays from spectra obtained with the three crystal pair spectrometer does not exceed 20%. Relative intensities of gamma rays below 2.5 MeV from Li^6+Li^6 and Li^7+Li^7 bombardments have been obtained by subtraction of a smooth continuum attributed to edge effects. An error of ±30% is suggested for most of the relative populations which have been deduced from gamma-ray spectra of the present paper. Populations obtained directly from the particle cross-section measurements are much better known. "Population" is to be interpreted as direct population throughout this paper.

A. Li^6+Li^6

The spectrum appears in Fig. 1 and the data are summarized in Table I. A careful study of the high-

* Supported, in part, by the U. S. Atomic Energy Commission.
[1] E. Berkowitz, Phys. Rev. **126**, 2168 (1962).
[2] C. Lemielle, L. Marquez, and N. Saunier, J. phys. rad. **22**, 349 (1961).
[3] R. R. Carlson, Nuclear Phys. **28**, 443 (1961).
[4] J. I. Valerio, Ph. D. dissertation, State University of Iowa, 1960 (unpublished).
[5] F. Ajzenberg-Selove and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).
[6] G. C. Morrison and M. N. Huberman, Proceedings of the Second Conference on Reactions between Complex Nuclei, 1960 (unpublished), p. 246.
[7] G. C. Morrison, Phys. Rev. **121**, 182 (1961).

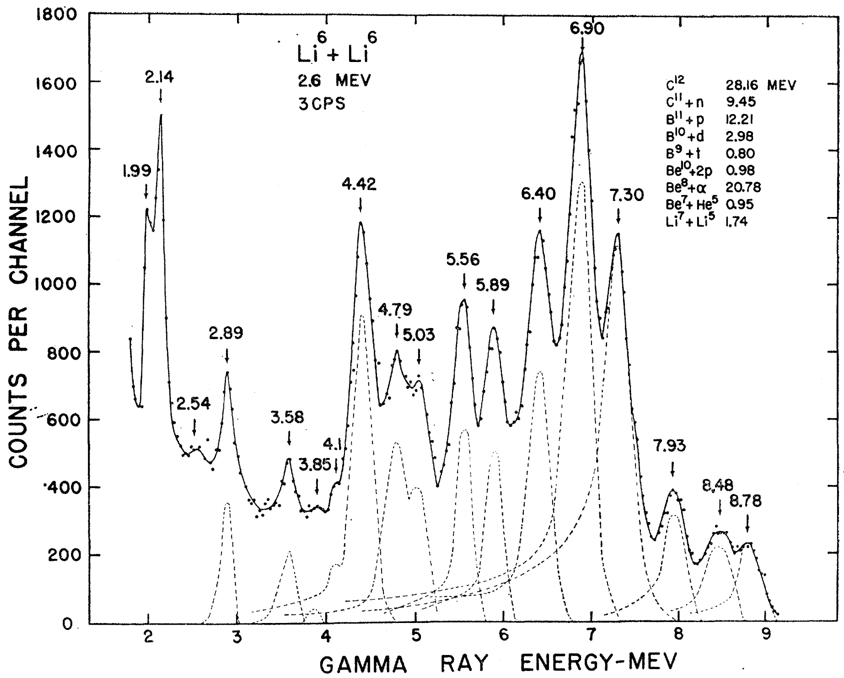

FIG. 1. Gamma-ray spectrum from Li^6 bombardment of Li^6. The dashed lines show the subtracted peak shapes, uncorrected for efficiency.

energy region of this spectrum (10 to 20 MeV) with a 5-in.-diam×6-in.-long crystal revealed no evidence for any gamma radiation of energy greater than 9 MeV with an intensity as much as 1% of the 7.3-MeV radiation. In particular, no evidence was found for the production of gamma-emitting states in Be^8 or C^{12}.

It is evident from Table I that an analysis of intensities from this spectrum is difficult in the absence of detailed knowledge of gamma-ray branching ratios in C^{11}. If it is assumed that B^{11} states at 7.99, 8.57, and 8.93 MeV and C^{11} states at 7.5, 8.11, and 8.43 MeV are, respectively, mirror states with similar branching ratios, the intensity analysis becomes consistent. This mirror pairing finds further justification in the Coulomb energy differences between B^{11} and C^{11} states, which are found to be approximately proportional to the excitation up to and including these proposed mirror pairs. The assumption of similar branching ratios of mirror states has been justified by Morpurgo.[8] He has shown that for $E1$ transitions the branching ratios are equal, while for $M1$ transitions the difference does not exceed 50%. Moreover, the known[9] branching ratios in C^{11} are very nearly equal to their equivalents in B^{11}. These assumptions, in conjunction with the data, lead to the conclusion that the observed mirror levels are equally populated in the Li^6+Li^6 bombardment. This conclusion has been confirmed for Li^{7*} and Be^{7*} produced in the same bombardment.[10] The population of corresponding states in B^{11} and C^{11} is shown in Table II which has the results of Table I listed by state. At first glance this conclusion does not appear surprising, but it is pointed out that on the basis of a cluster model, Li^7 and Be^7 states are populated by a neutron transfer and proton transfer, respectively, and similarly, C^{11} and B^{11} are populated by Li^5 and He^5 transfers. Therefore, a difference of one unit of charge for the transferred cluster seems to have little effect here.

Moreover, if one sums the relative populations for the bound excited states in the residual nuclei Li^7, Be^7, B^{10}, B^{11}, and C^{11}, the ratio of the sums is approximately 24:22:11:3:3. The less massive clusters transfer more readily. This conclusion is in agreement with a similar conclusion by Norbeck[11] based on a study of various lithium-induced reactions. In the ratio quoted above, the ground state populations do not contribute since this experiment does not detect reactions leading to the ground state. It is known from reference 7 that the ground state of B^{11} does not appreciably change the number quoted above.

On the basis of our intensity analysis and reference 8 we suggest the following additions to the gamma ray transitions observed for C^{11} states; $8.66 \rightarrow 4.81$, $8.43 \rightarrow 0$, $7.5 \rightarrow 0$, $6.9 \rightarrow 0$, and $6.9 \rightarrow 4.32$.

B. Li^7+Li^7

The data are displayed in Fig. 2 and summarized in Table III.

[8] G. Morpurgo, Phys. Rev. **114**, 1075 (1959).
[9] P. F. Donovan, J. V. Kane, R. E. Pixley, and D. H. Wilkinson, Phys. Rev. **123**, 589 (1961).
[10] R. L. McGrath, M. S. thesis, State University of Iowa, 1962 (unpublished).
[11] E. Norbeck, Phys. Rev. **121**, 824 (1961).

TABLE I. Li^6+Li^6.

E_γ [a]	Relative intensity[b]	Source[c]	Branching ratio (%)[d]	Relative direct population of initial state[e]
8.78	0.15	C^{11} 8.66 → 0		*cf.* 3.85γ
		B^{11} 8.93 → 0	86	0.2
8.48	0.27	C^{11} 8.43 → 0	(86)	*cf.* 4.11γ
		B^{11} 8.57 → 0	62	<0.1
7.93	0.31	C^{11} 8.11 → 0	(62)	<0.1
		B^{11} 7.99 → 0	55	*cf.* 5.89γ
7.30	1.00	C^{11} 7.5 → 0	(55)	*cf.* 5.56γ
		B^{11} 7.3 → 0	93	0.6
6.90	1.07	C^{11} 6.9 → 0	(93)	*cf.* 2.54γ
		B^{11} 6.81 → 0	79 }	∼0.7
		B^{11} 6.76 → 0	83 }	
6.40	0.58	C^{11} 6.48 → 0	(79) }	0.7
		C^{11} 6.34 → 0	(83) }	
		B^{11} 8.57 → 2.13	28	*cf.* 8.48γ
5.89	0.33	B^{11} 7.99 → 2.13	45	0.7
5.56	0.35	C^{11} 7.5 → 1.99	(45)	0.8
5.03	0.28	B^{11} 5.03 → 0	86	0.31[f]
4.79	0.31	C^{11} 4.81 → 0	85	0.4
4.42	0.62	C^{11} 6.34 → 1.99	(21)	*cf.* 6.40γ
		C^{11} 4.32 → 0	100	0.4
		B^{11} 4.46 → 0	100	0.31[f]
4.11	0.01	C^{11} 8.43 → 4.32	(5)	∼0.2
3.85	0.02	C^{11} 8.66 → 4.81	(85)	0.02
3.58	0.14	B^{11} 8.57 → 5.03	10	*cf.* 8.48γ
		B^{10} 3.58 → 0	20	0.6
2.89	0.41	C^{11} 4.81 → 1.99	15	*cf.* 4.79γ
		B^{11} 7.30 → 4.46	7	*cf.* 7.3γ
		B^{11} 5.03 → 2.13	14	*cf.* 5.03γ
		B^{10} 3.58 → 0.72	60	*cf.* 3.58γ
2.54	0.04	C^{11} 6.9 → 4.32	(7)	∼0.6
2.14	2.6	C^{11} 6.48 → 4.32	(17)	*cf.* 6.40γ
		B^{11} 2.13 → 0	100	0.17[f]
		B^{10} 2.15 → 0	30	6.0
1.99	0.66	C^{11} 1.99 → 0	100	∼0.1
1.40	2.5[g]	B^{10} 2.15 → 0.72	40	*cf.* 2.14γ
		B^{10} 3.58 → 2.15	20	*cf.* 3.58γ
1.02	1.5[h]	B^{10} 1.74 → 0.72	100	<0.1
0.72	9.0[h]	B^{10} 0.72 → 0	100	4.4
0.48	24[h]	Li^7 0.48 → 0	100	24
0.44	24[h]	Be^7 0.44 → 0	100	22
		B^{11} gnd. state		0.37[f]

[a] Experimental value in MeV. For complete list of low-energy gamma rays see reference 1.
[b] Experimental value corrected for detector efficiency.
[c] Sources of the observed gamma ray which analysis indicates may contribute significantly to the observed intensity.
[d] Branching ratio from references 5 and 9. Bracketed values for C^{11} transitions are assumed values taken from corresponding B^{11} transitions.
[e] Population values are listed with gamma-ray energy from which the value was obtained. Reference to this energy is made in other cases where the same initial state occurs.
[f] Relative population from Morrison, references 6 and 7.
[g] Relative gamma-ray intensity from reference 1.
[h] Relative gamma-ray intensities from reference 10.

No gamma rays from B^{13} have been reported previously. The B^{13}, 4.16 → 0, radiation listed in Table III is seen as a small peak only poorly resolved from the very large 4.44 MeV peak. The peak at 3.68 MeV could be B^{13}, 3.70 → 0 or C^{13}, 3.68 → 0 or both. If it is mostly C^{13}, then the $3/2^-$ level at 3.68 MeV is populated very much more than the $5/2^+$ level at 3.85 and the $1/2^+$ level at 3.09 MeV, thereby indicating the action of strong selection rules.

One prominent feature of this spectrum is the large relative yield of 4.4-MeV radiation. Although this radiation might have four sources, we estimate that at least two thirds of the intensity is to be ascribed to C^{12}, 4.43 MeV → 0. This estimate is obtained by comparing the relative intensities of 4.4- and 5.0-MeV radiation with the relative cross-sections obtained by Morrison[6] for the 4.46- and 5.03-MeV states in B^{11} from Li^7+Li^7. Suitable allowance has been made for cascade contributions.

TABLE II. Relative population of B^{11} and C^{11} states in Li^6+Li^6 reactions.

B^{11} state (in MeV)	Relative population	C^{11} state (in MeV)	Relative population
2.13	0.17	1.99	∼0.1
4.46	0.31	4.32	0.4
5.03	0.31	4.81	0.4
6.76 }	∼0.7	6.34 }	0.7
6.81 }		6.48 }	
7.30	0.6	6.90	∼0.6
7.99	0.7	7.50	0.8
8.57	<0.1	8.11	<0.1
8.93[a]	0.2	8.43	∼0.2
9.19[a]		8.66	0.02

[a] Unbound states.

C. Li^6+Li^7

The data are displayed in Figs. 3 and 4 and summarized in Table IV.

The high-energy region (up to 20 MeV) of this spectrum was investigated with a 5-in. × 6-in. NaI(Tl) crystal (Fig. 4). The 15.1-MeV gamma ray was identified with C^{12}, 15.11 MeV → 0. The identification was confirmed by extending the gamma-ray calibration to 17 MeV by means of the reaction, $Li^7+p \rightarrow Be^8+\gamma$,

TABLE III. Li^7+Li^7.

E_γ [a]	Relative intensity[b]	Source[c]	Branching ratio (%)[d]	Relative direct population of initial state[e]
7.30	1.00	B^{11} 7.3 → 0	93	1.1
6.80	2.77	B^{11} 6.81 → 0	79	3.4
		B^{11} 6.76 → 0	83	
5.9–6.2		Be^{10} 6.23 → 0		
		Be^{10} 6.18 → 0		
		Be^{10} 5.96 → 0	22	*cf.* 2.59γ
5.03	4.10	B^{11} 5.03 → 0	86	4.76[f]
4.44	14.20	B^{11} 6.81 → 2.13	21	*cf.* 6.8γ
		B^{11} 4.46 → 0	100	4.15[f]
		C^{12} 4.43 → 0	100	9.9
4.16		B^{13} 4.16 → 0		
3.68	3.4	B^{13} 3.7 → 0	100	
		C^{13} 3.68 → 0	100	
3.36	4.6	Be^{10} 3.36 → 0	100	≤1.4
2.91	0.8	B^{11} 7.30 → 4.46	7	*cf.* 7.3γ
		Be^{10} 6.23 → 3.37		
		B^{11} 5.03 → 2.13	14	*cf.* 5.03γ
2.59	3.2	Be^{10} 5.96 → 3.37	78	4.1
2.14	4.1	B^{11} 2.13 → 0	100	1.62[f]
1.58		B^{12} 1.67 → 0	100	
		B^{11} gnd. state		7.30[f]

[a–f] See Table I for explanation.

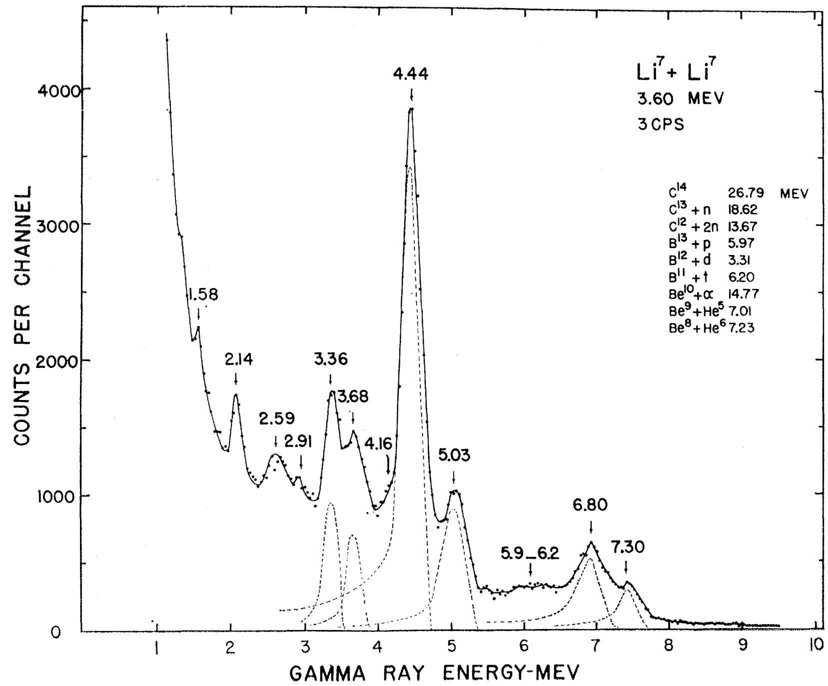

FIG. 2. Gamma-ray spectrum from Li^7 bombardment of Li^7. The dashed lines show the subtracted peak shapes uncorrected for efficiency.

generated by bombardment of organic material with the Li^7 beam.

An interesting comparison can be made between states of C^{12} and B^{12} produced in this reaction. Consider the 15.11-MeV state ($T=1$) of C^{12} and the yield of ground state B^{12} which is obtained by normalization of the data of reference 7 to the data of the present paper. The states in question belong to an isotopic spin multiplet. The B^{12} ($T=1$) state is favored over the equivalent C^{12} state by roughly $0.042:0.02=2:1$.

The production of these $T=1$ states by cluster transfer requires the transfer of Li^6 ($T=1$), or Li^5 in the C^{12} case. It requires the transfer of He^6 ($T=1$), or He^5 in the B^{12} case. If the reactions proceed by a direct-interaction mechanism, the ratio of the cross sections for production of B^{12} to that for production of C^{12}

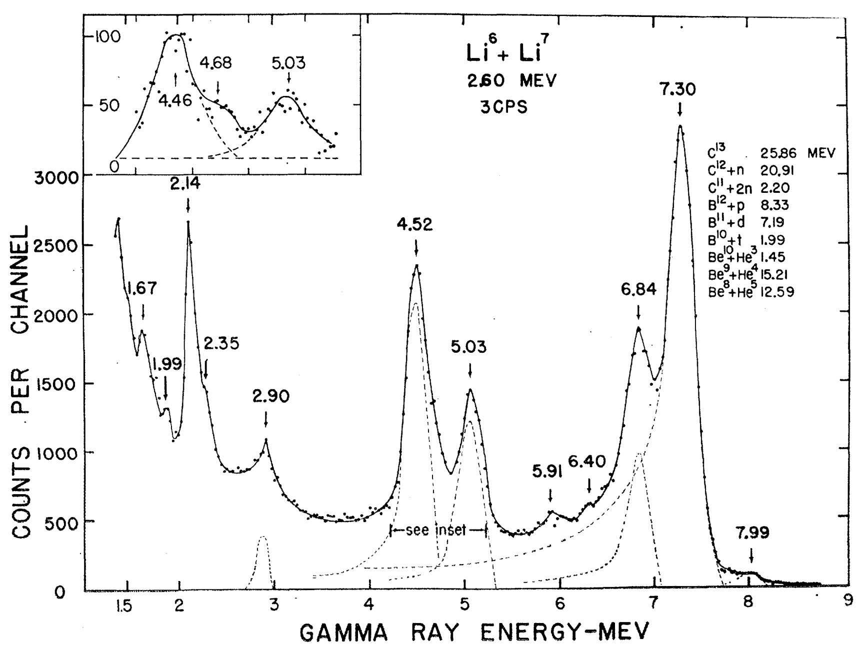

FIG. 3. Gamma-ray spectrum from Li^6 bombardment of Li^7. The dashed lines show the subtracted peak shapes, uncorrected for efficiency.

TABLE IV. Li^6+Li^7.

E_γ [a]	Relative intensity[b]	Source[c]	Branching ratio (%)[d]	Relative direct population of initial state[e]
15.1[i]	0.018[i]	C^{12} 15.11 → 0	77	0.02
8.6[i]		B^{11} 8.57 → 0	62	*cf.* 6.40γ
7.99	0.02	B^{11} 7.99 → 0	55	*cf.* 5.91γ
7.30	1.00	B^{11} 7.30 → 0	93	1.1
6.84	0.26	B^{11} 6.81 → 0	79	*cf.* 4.68γ
		B^{11} 6.76 → 0	83	0.15
6.40	0.01	B^{11} 8.57 → 2.13	28	0.03
5.91	0.02	B^{11} 7.99 → 2.13	45	0.05
5.03	0.33	B^{11} 5.03 → 0	86	0.38[f]
4.68	0.03	B^{11} 6.81 → 2.13	21	0.15
4.46	0.65	B^{11} 4.46 → 0	100	0.33[f]
		C^{12} 4.43 → 0	100	0.2
2.90	0.13	B^{11} 7.3 → 4.46	7	*cf.* 7.3γ
		B^{11} 5.03 → 2.13	14	*cf.* 5.03γ
2.35		B^{11} 6.76 → 4.46	17	*cf.* 6.84γ
2.14	0.68	B^{10} 2.15 → 0	30	1.2
		B^{11} 2.13 → 0	100	0.24[f]
1.99	0.08	C^{11} 1.99 → 0	100	0.08
1.67	0.10	B^{12} 1.67 → 0	100	0.05[f]
1.02	0.35[g]	B^{10} 1.74 → 0.72	100	≤0.01
0.72	1.27[g]	B^{10} 0.72 → 0	100	0.5
		B^{11} gnd. state		0.38[f]
		B^{12} gnd. state		0.042

[a–g] See Table I for explanation.
[i] Two high-energy gamma rays were observed with a single large NaI(Tl) crystal.

should simply be

$$\frac{\sigma_p}{\sigma_n}=\left(\frac{k_p}{k_n}\right)\left(\frac{|H_{if}(p)|^2}{|H_{if}(n)|^2}\right),$$

where k is the wave number in the center-of-mass system and H_{if} is the matrix element for the direct interaction. At 2.6-MeV bombarding energy the first ratio on the right is 1.15. Assuming pure isotopic spin states are involved and neglecting Coulomb effects, the second ratio is simply the ratio of the squares of isotopic-spin vector-coupling coefficients and equals 2. The experimental result of 2:1 is in good agreement with the predicted value of 2.3:1 implying that the reaction proceeds by a direct-interaction, or stripping, mechanism in this case.

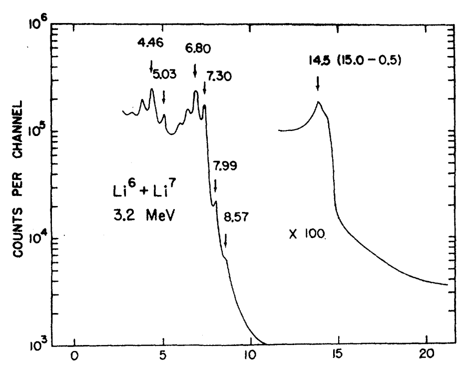

FIG. 4. Single-crystal gamma-ray spectrum from Li^6+Li^7 bombardment.

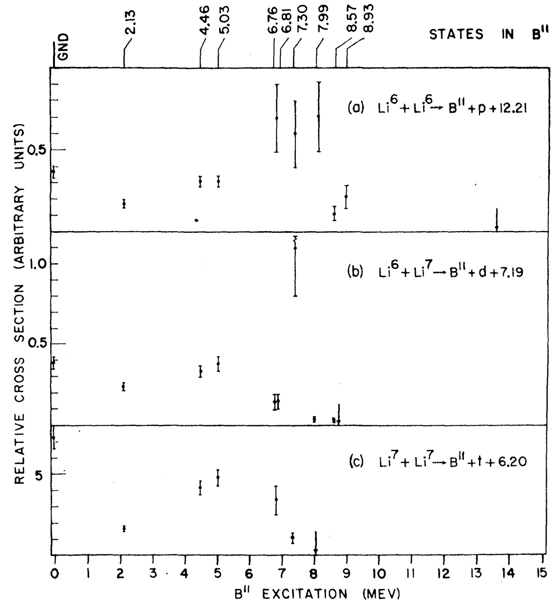

FIG. 5. The distribution of relative populations between the states of B^{11} from the indicated reactions: (a) and (b) Li energy =2.6 MeV, (c) Li^7 energy=3.6 MeV. Arrows indicate the maximum excitation energy available to the B^{11} nucleus in each reaction. Relative cross sections are in arbitrary units which are different in each of the three reactions.

In this reaction it would appear that all possible levels of B^{11} are populated. The inset in Fig. 3 shows the experimental evidence for the cascade decay of the 6.81-MeV level to the 2.31-MeV level. It is also believed that the other member of this doublet at 6.76 MeV is populated since there is evidence for the cascade decay of this level to the 4.46-MeV level in the observation of the 2.35-MeV gamma ray.

The distribution of relative population among the states of B^{11}, produced in all three bombardments, is pictured in Fig. 5. There is a similarity in shape for all three distributions.