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Dr. Balraj Singh,

The attached documents contain results from our experiments at TOFI (1987-1995). Much more detail is contained in the PhD thesis of Yi- Kyung Kim, Utah State University, 1994.

Let me know if you need additional information.

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Beta Decay Half-Lives and Delayed Particle Emission from TOFI Measurements

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We have used the Time-of-Flight Isochronous (TOFI) spectrometer at the LAMPF accelerator to systematically measure the half-life ($t_{1/2}$), delayed neutron emission probability (P_n), beta-delayed multi-neutron emission, average energy of delayed neutron spectra, and beta-delayed alpha emission for a large number of neutron-rich isotopes for all Z values between Li and Cl. The TOFI spectrometer identifies the Z, A, and Q of each recoiling ion produced by fragmentation reactions from proton bombardment of a ^{232}Th target. These ions are stopped in a thin Si detector surrounded by a 2-mm-thick plastic scintillator plus a thick Si detector which together are used to measure beta particles. The vacuum pipe containing these detectors is surrounded by a polyethylene-moderated neutron counter. Ions are detected during the LAMPF beam pulse. Beta-decay products are detected during the 7-ms period between beam pulses. Half-lives are determined by a delayed coincidence technique based on time-interval histograms using the arrival time of a specific ion as the start time and the arrival time of subsequent betas or neutrons as the stop time. The neutron yield relative to the number of ions of a specific type provides a measurement of the P_n. Beta-neutron coincidence counting gives an alternative measurement of P_n. Average energies of delayed-neutron spectra are determined from ratios of counts in the outer ring of neutron counter tubes to counts in the inner ring. Besides remeasurements on about 50 nuclides, half-lives have been measured for the first time on ^{26}F, ^{35}Mg, ^{33}Al, ^{36}Al, ^{37}Si, ^{41}S, and ^{44}Cl. New P_n values have been obtained for ^{35}Mg, ^{33}Al, and ^{36}Al. Average neutron energies are reported for 11 nuclides ranging from ^{11}Li to ^{21}N.

Results from our first experiment done in 1987 on the Li to Al nuclides have been published.[4] We reported half-lives for 18 nuclides and neutron-emission probabilities for 19 nuclides. The half-lives of ^{25}F and ^{28}Ne were measured for the first time. Delayed neutron emission was observed for the first time from ^{12}Be, ^{14}B, ^{17}C, ^{18}N, ^{25}F, and ^{28}Ne.

In 1992, we repeated our measurements in the Li to F region with an emphasis on the extremely neutron-rich nuclides. The new data (1992) gave decay results for ^{11}Li, ^{14}Be, ^{17}B, ^{20}C, and ^{22}N and improved data for the other neutron-rich nuclides.[5] A partial listing of the 1992 results is given in Table 1. For ^{17}C, ^{18}C, and ^{18}N, our P_n values are significantly higher and our average energies are significantly lower than the values recently measured at Michigan State University.[6] These discrepancies are probably explained by the fact that our neutron counter was sensitive to all neutron energies, including thermal energies, whereas the MSU/Notre Dame time-of-flight detector was not sensitive below about 0.8 MeV.

The beta-delayed charged-particle data were dominated by alphas from implanted ^{8}Li and ^{9}Li. However, well known alpha peaks from ^{18}N were clearly seen, and preliminary evidence for beta-delayed alpha emission from ^{14}B was observed. In 1993, we took extensive data in the F to Cl mass region. Analysis has begun on this data set, but only preliminary results are available.

ACKNOWLEDGMENTS

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TABLE I. Half-lives, delayed-neutron emission probabilities, and average neutron energies from 1992 TOFI experiment.

Nuclide	Half-life (ms)	P_n (%)	Average Neutron Energy (MeV)
^{8}Li	858. ± 16.	(a)	(a)
^{9}Li	178.1 ± 0.6	50.1 ± 0.5	0.64 ± 0.004[d]
^{11}Li	8.4 ± 0.2	81.6 ± 2.5	0.83 ± 0.05
^{12}Be	21.32 ± 0.06	0.52 ± 0.09[b]	
^{14}Be	4.8 ± 0.2	96.1 ± 4.7	0.61 ± 0.06
^{12}B	19.80 ± 0.75	(a)	(a)
^{13}B	16.7 ± 0.6	0.24 ± 0.15[b]	
^{14}B	12.4 ± 0.3	6.1 ± 0.3	1.3 ± 0.3
^{15}B	9.83 ± 0.08	93.5 ± 1.3	2.34 ± 0.07[d]
^{17}B	5.20 ± 0.45	104. ± 26.	3.3 ± 1.3
^{16}C	816. ± 18.	98.8[c]	0.96 ± 0.02[d]
^{17}C	191. ± 12.	26.0 ± 1.8	0.93 ± 0.09
^{18}C	92.9 ± 5.3	30.2 ± 1.7	0.88 ± 0.11
^{19}C	44.1 ± 4.2	67. ± 9.	1.3 ± 0.7
^{20}C	16.7 ± 3.5	58. ± 17.[b]	
^{18}N	658. ± 44.	12.0 ± 1.3	0.54 ± 0.12
^{19}N	255. ± 10.	48.7 ± 2.1	0.92 ± 0.06
^{20}N	129. ± 8.	52.0 ± 3.3	1.3 ± 0.3
^{21}N	86. ± 7.	77. ± 7.	1.0 ± 0.2
^{22}N	14. ± 6.	34. ± 14.	
^{23}O	600. ±340.		
^{24}F	440. ±130.		
^{25}F	94 ± 24.	28.6 ± 7.5	

[a] Not a delayed neutron precursor.

[b] The neutron counter efficiency was assumed to be the same as for ^{16}C. The uncertainty on the neutron counting efficiency was increased to ±2.6%.

[c] The literature P_n value for ^{16}C was used to determine the effective neutron counting efficiency (= 54.8 ± 0.3%).

[d] Used to determine calibration curve of Ring Ratio vs Average Energy.

BETA DECAY HALF-LIVES AND DELAYED PARTICLE EMISSION FROM TOFI MEASUREMENTS

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Half-lives, delayed-neutron emission probabilities, and average neutron energies have been measured for very neutron-rich nuclides from ^{8}Li to ^{45}Cl.

We have used the Time-of-Flight Isochronous (TOFI) spectrometer at the LAMPF accelerator to systematically measure the half-life ($t_{1/2}$), delayed neutron emission probability (P_n), and average energy of delayed neutron spectra for a large number of neutron-rich isotopes for all Z values between Li and Cl. The TOFI spectrometer identifies the Z, A, and Q of each recoiling ion produced by fragmentation reactions from 800-MeV proton bombardment of a ^{232}Th target. These ions are stopped in a thin Si detector surrounded by a 2-mm-thick plastic scintillator plus a thick Si detector, which together are used to measure beta particles. The vacuum pipe containing these detectors is surrounded by a polyethylene-moderated neutron counter. Ions are detected during the LAMPF beam pulse. Beta-decay products are detected during the 7-ms period between beam pulses (87.6% duty factor).

Half-lives are determined by a delayed coincidence technique based on time-interval histograms using the arrival time of a specific ion as the start time and the arrival time of subsequent betas or neutrons as the stop time. The neutron yield relative to the number of ions of a specific type provides a measurement of the P_n.

Beta-neutron coincidence counting gives an alternative measurement of P_n. An energy dependent neutron counting efficiency is used based on a calibration curve of efficiency vs. the ratio of counts in the outer ring of neutron counter tubes to counts in the inner ring (ring ratio). Nuclides with well-known P_n values are used to construct the calibration curve. Similarly, average energies of delayed-neutron spectra are determined using a calibration curve of energy vs. ring ratio for nuclides with well-known energy spectra.

Preliminary results with this technique for about 30 nuclides were published previously.[1] Measurements are now available for about 60 nuclides based on data collected over several years. Half-lives have been measured for 55 nuclides and include the first half-life measurements for ^{25}F, ^{26}F, ^{28}Ne, ^{35}Mg, ^{33}Al, ^{36}Al, ^{37}Si, ^{41}S, and ^{44}Cl. We report P_n values for 40 nuclides including previously unmeasured P_n values for ^{14}B, ^{17}C, ^{18}N, ^{35}Mg, ^{32}Al, ^{33}Al, ^{36}Si, ^{37}Si, ^{38}P and ^{45}Cl. Average neutron energies are reported for 14 nuclides ranging from ^{11}Li to ^{30}Na.

The average neutron energies for ^{17}N and ^{29}Na measured here are in excellent agreement with average energies derived from spectra measured with ^{3}He spectrometers. However, the average energies measured here for ^{14}Be, ^{17}C, ^{18}C, and ^{18}N are much lower than average energies deduced from neutron spectra measured by a time-of-flight technique at Michigan State University.[2] This can readily be explained as being due to the high threshold at about 700 keV for the time-of-flight spectrometer. In particular, our average neutron energy of 0.60±0.06 MeV for ^{14}Be is below the threshold of the MSU detector and suggests that most of the delayed neutrons are emitted from a state at about 1.6 MeV in ^{14}B.

The P_n values measured here are generally in agreement with previously measured values except for the nuclides listed in Table 1.

Table 1. Nuclides with discrepant P_n values.

Nuclide	P_n from TOFI (%)	P_n from Lit. (%)
^{31}Mg	6.2 ± 2.0	1.7 ± 0.3 [3]
^{34}Al	12.5 ± 2.5	54. ±12. [4]
^{35}Al	26. ± 4.	87. +37 -25 [4]
^{36}Si	12.4 ± 4.6	<10. [4]
^{38}P	12. ± 5.	<10. [4]

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(a)Pacific Northwest Laboratory is operated for the U. S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

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Table 1. Comparison of TOFI result (bold) with literature values. Values from model calculations are labeled with T.

Nuclei	T1/2 (ms)	±	s	Pn (%)	±	s	Ave. N Energy (MeV)	±	s
6He	**858.**	**±**	**16.**						
	806.7	±	1.5						
8He	**116.**	**±**	**43.**	--	±	--			
	119.	±	1.5	16.	±	1.			
8Li	**870.**	**±**	**23.**						
	838.	±	6.						
9Li	**178.**	**±**	**0.6**	**50.8**	**±**	**0.2**	**0.64**		
	178.3	±	0.4	50.	±	4.	0.64		
	176.	±	1.						
	175.	±	1.						
11Li	**8.4**	**±**	**0.2**	**81.6**	**±**	**2.6**	**0.83**	**±**	**0.05**
	8.7	±	0.1	95.		8.			
12Be	**21.3**	**±**	**0.1**	**0.52**	**±**	**0.09**			
	24.4	±	3.	<1.0					
	21.3	±	2.2						
	24.	±	1.						
14Be	**4.78**	**±**	**0.19**	**96.1**	**±**	**4.7**	**0.6**	**±**	**0.06**
	4.35	±	0.17	86.	±	3.			
12B	**20.1**	**±**	**0.4**						
	20.2	±	0.02						
13B	**16.7**	**±**	**0.3**	**0.28**	**±**	**0.08**			
	17.6	±	1.2	0.28	±	0.04			
	17.33	±	0.17						
14B	**12.3**	**±**	**0.29**	**6.04**	**±**	**0.23**	**1.26**	**±**	**0.26**
	16.1	±	1.2						
	12.8	±	0.8						
15B	**9.87**	**±**	**0.07**	**93.6**	**±**	**1.2**	**2.34**		
	10.8	±	0.5	99.	±	1.	2.34		
	10.4	±	0.3						
	11.	±	1.						
	10.3	±	0.4						

17B	**5.2 ± 0.4**	**91. ± 21.**	
	5.3 ± 0.6	70. ± 30	
	5.08 ± 0.05	63. ± 1.	
		79. ± 2.	
16C	**770. ± 12.5**	**98.8**	**0.96**
	747. ± 8.	98.8	0.96
17C	**188. ± 10.3**	**28.4 ± 1.3**	**0.96 +0.27-0.09**
	180. ± 31.	<11	2.19
	202. ± 17.	>10.8	
	220. ± 80.		
	191. ± 8.		
18C	**92. ± 5.**	**31.5 ± 1.5**	**0.81 ± 0.09**
	66. +25-15	29.2 ± 4.1	1.46
	78. +20-15	50. ± 10.	
	92. ± 5.	>21.4 ± 4.3	
		25. ± 4.5	
19C	**44. ± 4.**	**66. ± 9.**	**1.22 +0.73-0.41**
	49. ± 4.	54. ± 3.	
		47. ± 3.	
20C	**16.7 ± 3.5**	**58. ± 18.**	
	16. +14-7	50. ± 30.	
	14. +6-5	72. ± 14.	
17N	-- ± --	**102.4 ± 6.**	**0.85 ± 0.03**
	4173.00 ± 4.	95. ± 1.	0.9
		95.1 ± 0.7	
18N	**660. ± 35.**	**10.9 ± 0.9**	**0.57 ± 0.10**
	624. ± 12.	>2.2 ± 0.4	
	630. ± 20.		
19N	**271. ± 7.8**	**54.6 ± 1.4**	**1.13 ± 0.13**
	210. +200-100	33. +34.-11.	
	235. ± 32.		
	320. ±100.		
20N	**130. ± 6.6**	**57.0 ± 2.5**	**1.33 ± 0.27**
	100. +30-20	53. +11.-7.	
	70. ± 40.		
21N	**83.6 ± 6.7**	**78.3 ± 6.5**	**1.28 +0.41-0.35**

	95.	+15-11	84.	± 9.		
22N	**14.**	**± 5.6**	**34.**	**± 14.**		
	24.	+7-6	35.	± 5.		
22O	--	± --	**<22.**			
	2250.	±150.				
23O	**89.4**	**± 75.5**	**28.**	**± 30.**		
	82.	+45-28	31.	± 7.		
24O	--	± --	--	--		
	61.	± 26.	58.	± 12.		
22F	--	± --	**<11.**			
	4230.	± 40.				
23F	--	± --	**<14.**			
	2230.	±140.				
24F	**435.**	**± 65.**	**<5.9**			
	340.	± 80.				
25F	**86.8**	**± 16.3**	**24.1**	**± 4.6**	**0.79**	**+0.37-0.24**
	T(118.)		28.6	± 7.5		
26F	**185.**	**±105.**	**<32.**			
	T(55.)					
25Ne	**606.**	**± 42.**				
	620.	± 30.				
26Ne	**180.**	**± 15.**	**<8.**			
	197.	± 1.	0.13	± 0.03		
	250.	± 20.				
27Ne	**23.3**	**± 10.1**	**<12.**			
	32.	± 2.	2.	± 0.5		
28Ne	**8.2**	**± 2.51**	**16.**	**± 9.**		
	17.	± 4.	22.	± 3.		
27Na	**292.**	**± 14.**	**1.0**	**± 0.6**		
	289.	± 2.	0.11	± 0.04		
28Na	**30.4**	**± 1.**	**0.4**	**± 0.4**		
	32.	± 0.3	0.8	± 0.2		

29Na	**38.5 ± 2.9**	**27.1 ± 1.6**	**0.95 +0.27-0.09**
	44.4 ± 0.6	22. ± 3.	0.97
		21.5 ± 3.	
30Na	**38.5 ± 6.6**	**47.9 ± 6.5**	**0.69 +0.46-0.33**
	51. ± 1.2	47. ± 5.	
		33. ± 5.	
31Na	**11.5 ± 7.3**	**40. ± 14.**	
	17.2 ± 0.3	43. ± 11.	
		38. ± 6.	
32Na	**18.1 ± 14.8**		
	13.5 ± 0.3	39. ± 6.	
33Na	**6.3 ± 4.6**		
	8.1 ± 0.3	77. ± 15.	
34Na	-- ± --		
	5.5 ± 1	115. ± 20.	
30Mg	**333. ± 28.**		
	342. ± 18.		
	325. ± 30.		
31Mg	**235. ± 25.**	**6.2 ± 1.9**	
	230. ± 20.	1.7 ± 0.3	
	250. ± 30.		
32Mg	**85. ± 13.**	**4.3 ± 2.1**	
	120. ± 20.	2.4 ± 0.5	
33Mg	**63. ± 25.**	**25. ± 13.**	
	90. ± 20	17. ± 5.	
35Mg	**72. ± 43.**	**52. ± 46.**	
	T(81.)		
31Al	**646 ± 45.**	**<1.6**	
	644 ± 25		
32Al	**31.7 ± 0.8**	**0.7 ± 0.5**	
	31. ± 6.		
33Al	**40.5 ± 2.8**	**8.5 ± 0.7**	**0.69 ± 0.1**
	T(200)		

34Al	**41.6**	**± 6.1**	**12.5**	**± 2.5**	**0.85**	**+0.39-0.20**
	50.	± 25.	27.	± 5.		
	70.	+30.-20.	54.	± 12.		
35Al	**30.**	**± 4.**	**26.**	**± 4.**	**1.37**	**+1.30-0.69**
	30.	± 10.	40.	± 10.		
	130.	+100.-50.	87.	+37.-25.		
	170.	+90.-50.				
36Al	**94.**	**± 37.**	**<31.**			
	T(115.)					
35Si	**1016.**	**±125.**	**<5.26**			
	870.	±170.				
36Si	**541.**	**±205.**	**12.4**	**± 4.6**		
	540.	±150.	<10.			
37Si	**94.**	**± 62.**	**17.**	**± 13.**		
	T(285.)		<15.			
38P	**681.**	**±200.**	**12.0**	**± 5.3**		
	640.	±140.	<10.			
39P	**189.**	**± 45.**	**26.**	**± 8.**	**0.67**	**+0.38-0.32**
	160.	+300.-100.	41.	± 24.		
40P	--	--	**34.**	**± 26.**		
	260.	± 80.	30.	± 10.		
41S	**2580.**	**±1400.**	--	--		
	T(2410)					
43S	**176.**	**± 73.**	--	--		
	220.	+80.-50.	40.	± 10.		
44Cl	**4600.**	**±3400.**				
	T(1390)					
45Cl	**192.**	**±105.**	129.	**± 98.**		
	400.	± 43.				