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Old Text   Paper ENAM   Summary
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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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5. Y.-K. Kim, "Measurement of the Half-Life, Delayed-Neutron Emission Probability, Delayed-Neutron Average Energy, and Delayed Charged-Particle Energy Spectrum for Very Neutron-Rich Helium Through Sodium Nuclides," Ph.D. Thesis, Utah State University, June, 1994.

6. K. W. Scheller,"The β^- Delayed Neutron Decay of the Exotic Nuclei ^{18}N, ^{17}C, and ^{18}C", Ph.D. Thesis, Notre Dame University, Nov., 1993.

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]

References:

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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 ± s (ms)			Pn ± s (%)			Ave. N Energy ± s (MeV)		
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**
	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

For 25F row: 0.79   +0.37-0.24

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.				