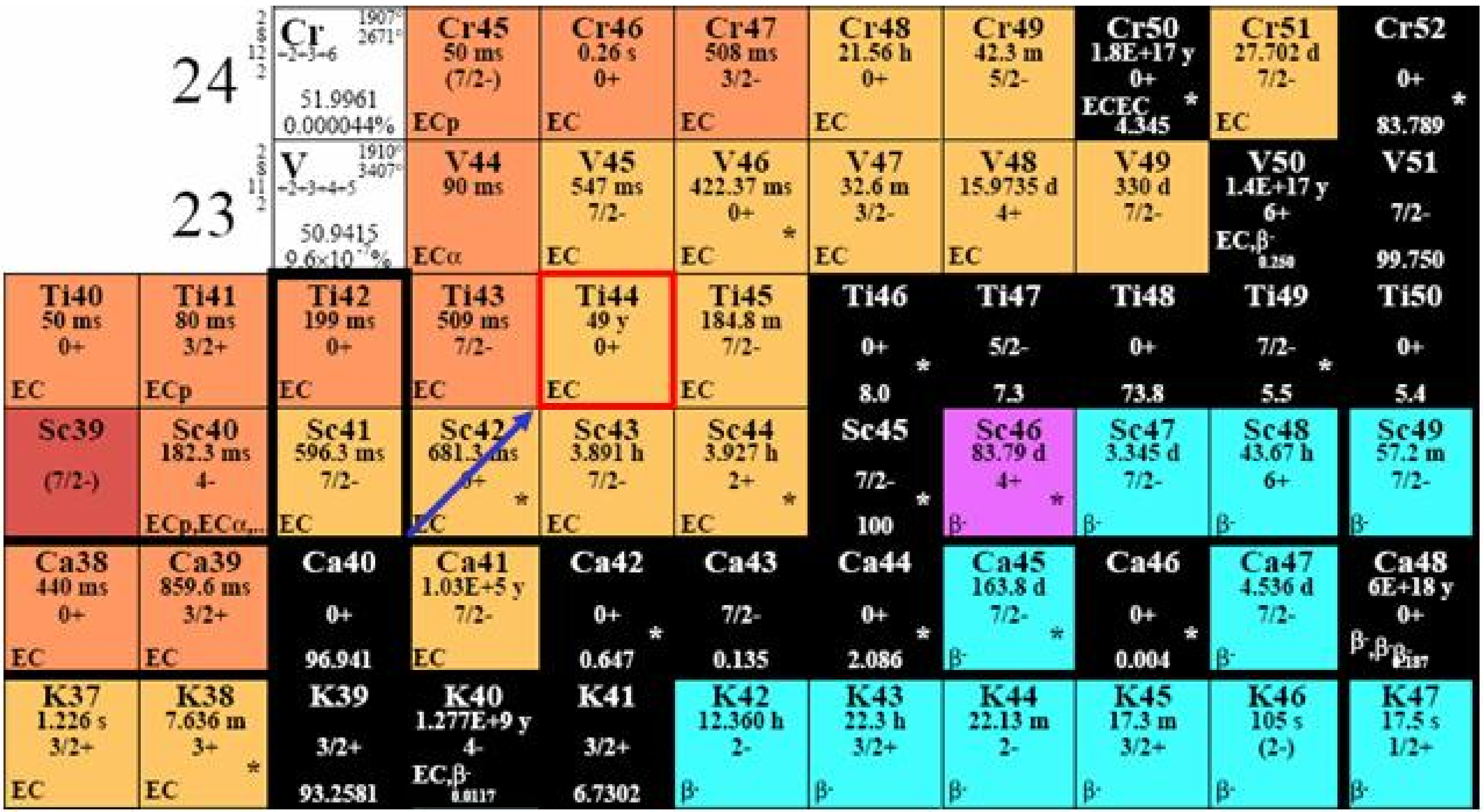
$^{40}Ca(\alpha,\gamma)^{44}Ti$ at DRAGON

Nuclear Chart



Motivation

- ^{44}Ti is one of the few radionuclides where direct observation has been found
- live by γ-ray astronomy (Cas A)
- extinct by ^{44}Ca excess in SiC grains

- AMS measurement indicates that $^{40}Ca(\alpha,\gamma)^{44}Ti$ is about factor 10 higher (M. Paul, NIC8)

- Half-life is important to measure SN yield ($t_{1/2} = 59.2 \pm 0.2$ y)

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ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

COMPTEL observations of ^{44}Ti gamma-ray line emission from Cas A

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Abstract. The COMPTEL telescope aboard the Compton Gamma-Ray Observatory (CGRO) is capable of imaging gamma-ray line sources in the MeV region with a sensitivity of the order 10^{-5} photons/(cm^{2}s). During two observation periods in July 1992 and February 1993 the Galactic plane in the region of the young supernova remnant Cas A was observed, showing evidence for line emission at 1.16 MeV from the decay of ^{44}Ti at a significance level of $\sim 4\,\sigma$.

This is the first time a supernova remnant has been detected in the gamma-ray line from ^{44}Ti decay. Adopting a distance of 2.8 kpc to the Cas A remnant, the measured line flux $(7.0\pm1.7)\cdot10^{-5}$ photons/(cm^2 s), can be translated into a ^{44}Ti mass ejected during the Cas A supernova explosion, between $(1.4\pm0.4)\cdot10^{-4}$ $M_\odot$ and $(3.2\pm0.8)\cdot10^{-4}$ $M_\odot$, depending on the precise value of the ^{44}Ti mean life time and on the precise date of the event. Implications of this result for supernova nucleosynthesis models are discussed.

Key words: Gamma-rays: observations – Line: identification – Supernovae: individual: Cas A

THE ASTROPHYSICAL JOURNAL, 462: L31–L34, 1996 May 1

EXTINCT ^{44}Ti IN PRESOLAR GRAPHITE AND SiC: PROOF OF A SUPERNOVA ORIGIN

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ABSTRACT

Large excesses in ^{44}Ca, from the radioactive decay of short-lived ^{44}Ti, have been observed in four low-density graphite grains and five SiC grains of type X extracted from the Murchison meteorite. Titanium-46, ^{49}Ti, and ^{50}Ti excesses were also observed in several of these grains. Because ^{44}Ti is only produced in supernovae, these grains must have a supernova origin. Moreover, Si-, C-, N-, Al-, O-, and Ti-isotopic compositions of the grains require a Type II supernova source, and indicate extensive and heterogeneous mixing of different supernova regions, including the nickel core.

Subject headings: dust, extinction — nuclear reactions, nucleosynthesis, abundances — supernovae: general

THE ASTROPHYSICAL JOURNAL, 504:500–515, 1998 September 1

NUCLEAR REACTIONS GOVERNING THE NUCLEOSYNTHESIS OF ^{44}Ti

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ABSTRACT

Large excesses of ^{44}Ca in certain presolar graphite and silicon carbide grains give strong evidence for ^{44}Ti production in supernovae. Furthermore, recent detection of the ^{44}Ti γ line from the Cas A supernova remnant by the *Compton Gamma Ray Observatory* Compton Telescope shows that radioactive ^{44}Ti is produced in supernovae. These make the ^{44}Ti abundance an observable diagnostic of supernovae. Through use of a nuclear reaction network, we have systematically varied reaction rates and groups of reaction rates to experimentally identify those that govern ^{44}Ti abundance in core-collapse supernova nucleosynthesis. We survey the nuclear-rate dependence by repeated calculations of the identical adiabatic expansion, with peak temperature and density chosen to be 5.5×10^9 K and 10^7 g cm^{-3}, respectively, to approximate the conditions in detailed supernova models. We find that, for equal total numbers of neutrons and protons ($\eta = 0$), ^{44}Ti production is most sensitive to the following reaction rates: ^{44}Ti(α, p)^{47}V, α(2α, γ)^{12}C, ^{44}Ti(α, γ)^{48}Cr, and ^{45}V(p, γ)^{46}Cr. We tabulate the most sensitive reactions in order of their importance to the ^{44}Ti production near the standard values of currently accepted reaction rates, at both a reduced reaction rate (times 0.01) and an increased reaction rate (times 100) relative to their standard values. Although most reactions retain their importance for $\eta > 0$, that of ^{45}V(p, γ)^{46}Cr drops rapidly for $\eta \geq 0.0004$. Other reactions assume greater significance at greater neutron excess: ^{12}C(α, γ)^{16}O, ^{40}Ca(α, γ)^{44}Ti, ^{27}Al(α, n)^{30}P, ^{30}Si(α, n)^{33}S. Because many of these rates are unknown experimentally, our results suggest the most important targets for future cross section measurements governing the value of this observable abundance.

Subject headings: nuclear reactions, nucleosynthesis, abundances — supernovae: general

TABLE 4

ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$

RANK	REACTION RATE MULTIPLIED BY 1/100		REACTION RATE MULTIPLIED BY 100	
	Reaction	^{44}Ti Change (percent)	Reaction	^{44}Ti Change (percent)
1	$^{44}Ti(\alpha, p)^{47}V$	+173	$^{45}V(p, \gamma)^{46}Cr$	−98
2	$\alpha(2\alpha, \gamma)^{12}C$	−100	$\alpha(2\alpha, \gamma)^{12}C$	+67
3	$^{40}Ca(\alpha, \gamma)^{44}Ti$	−72	$^{44}Ti(\alpha, p)^{47}V$	−89
4	$^{45}V(p, \gamma)^{46}Cr$	+57	$^{44}Ti(\alpha, \gamma)^{48}Cr$	−61
5	$^{57}Ni(p, \gamma)^{58}Cu$	−47	$^{57}Co(p, n)^{57}Ni$	+25
6	$^{57}Co(p, n)^{57}Ni$	−33	$^{40}Ca(\alpha, \gamma)^{44}Ti$	+22
7	$^{13}N(p, \gamma)^{14}O$	−16	$^{57}Ni(n, \gamma)^{58}Ni$	+10
8	$^{58}Cu(p, \gamma)^{59}Zn$	−14	$^{54}Fe(\alpha, n)^{57}Ni$	+9.4
9	$^{36}Ar(\alpha, p)^{39}K$	−11	$^{36}Ar(\alpha, p)^{39}K$	+5.5
10	$^{12}C(\alpha, \gamma)^{16}O$	+3.5	$^{36}Ar(\alpha, \gamma)^{40}Ca$	+5.3

TABLE 7

ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0.002$

RANK	Reaction Rate Multiplied by 1/100: Reaction	Reaction Rate Multiplied by 1/100: ^{44}Ti Change (percent)	Reaction Rate Multiplied by 100: Reaction	Reaction Rate Multiplied by 100: ^{44}Ti Change (percent)
1	$^{44}Ti(\alpha, p)^{47}V$	+208	$^{44}Ti(\alpha, p)^{47}V$	−93
2	$^{12}C(\alpha, \gamma)^{16}O$	−72	$^{44}Ti(\alpha, \gamma)^{48}Cr$	−66
3	$^{40}Ca(\alpha, \gamma)^{44}Ti$	−66	$^{27}Al(\alpha, n)^{30}P$	−60
4	$^{20}Ne(\alpha, \gamma)^{24}Mg$	−16	$^{30}Si(\alpha, n)^{33}S$	−33
5	$^{30}Si(p, \gamma)^{31}P$	−9.2	$^{12}C(\alpha, \gamma)^{16}O$	+18
6	$^{36}Ar(\alpha, p)^{39}K$	−7.9	$^{40}Ca(\alpha, \gamma)^{44}Ti$	+15
7	$^{59}Ni(p, n)^{59}Cu$	−4.7	$^{23}Na(\alpha, p)^{26}Mg$	−4.7
8	$^{59}Ni(p, \gamma)^{60}Cu$	−4.7	$^{39}K(\alpha, p)^{42}Ca$	+4.7
9	$^{44}Ti(\alpha, \gamma)^{48}Cr$	+2.8	$^{27}Al(p, \gamma)^{28}Si$	+4.3
10	$^{27}Al(\alpha, n)^{30}P$	+2.7	$^{24}Mg(\alpha, \gamma)^{28}Si$	+4.2

TABLE 8

ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0.006$

RANK	Reaction Rate Multiplied by 1/100: Reaction	Reaction Rate Multiplied by 1/100: ^{44}Ti Change (percent)	Reaction Rate Multiplied by 100: Reaction	Reaction Rate Multiplied by 100: ^{44}Ti Change (percent)
1	$^{44}Ti(\alpha, p)^{47}V$	+211	$^{44}Ti(\alpha, p)^{47}V$	−93
2	$^{12}C(\alpha, \gamma)^{16}O$	−79	$^{44}Ti(\alpha, \gamma)^{48}Cr$	−65
3	$^{40}Ca(\alpha, \gamma)^{44}Ti$	−65	$^{27}Al(\alpha, n)^{30}P$	−56
4	$^{20}Ne(\alpha, \gamma)^{24}Mg$	−11	$^{30}Si(\alpha, n)^{33}S$	−39
5	$^{30}Si(p, \gamma)^{31}P$	−9.6	$^{12}C(\alpha, \gamma)^{16}O$	+19
6	$^{36}Ar(\alpha, p)^{39}K$	−7.5	$^{40}Ca(\alpha, \gamma)^{44}Ti$	+15
7	$^{27}Al(\alpha, p)^{30}Si$	−4.0	$^{58}Ni(\alpha, \gamma)^{62}Zn$	−8.7
8	$^{33}S(p, \gamma)^{34}Cl$	+3.8	$^{27}Al(p, \gamma)^{28}Si$	+6.0
9	$^{16}O(\alpha, \gamma)^{20}Ne$	−3.8	$^{24}Mg(\alpha, \gamma)^{28}Si$	+6.0
10	$^{30}Si(\alpha, n)^{33}S$	+3.5	$^{39}K(\alpha, p)^{42}Ca$	+5.3

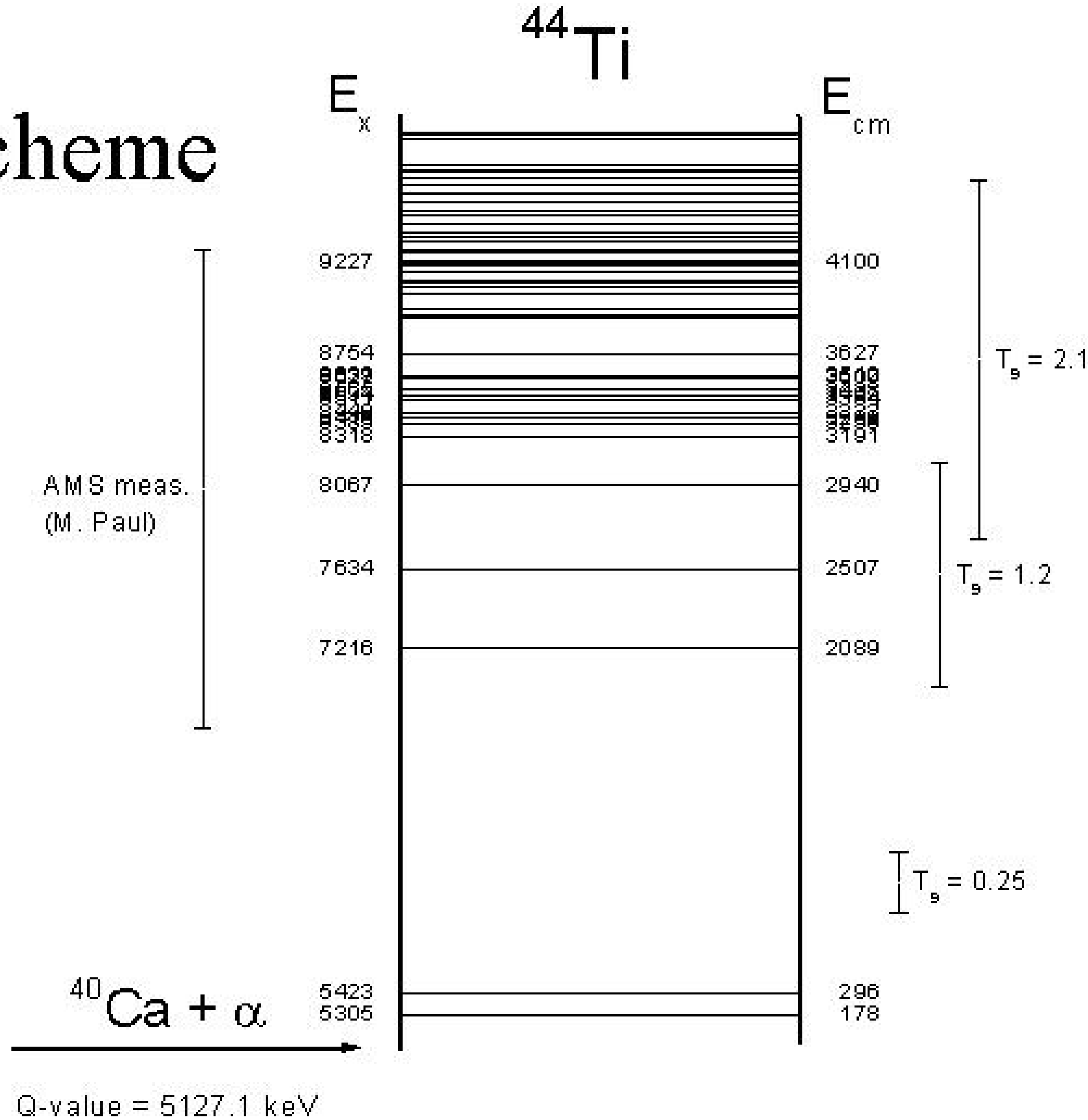
TABLE 5

ORDER OF IMPORTANCE OF REACTIONS PRODUCING ^{44}Ti AT $\eta = 0$[a]

Reaction	Slope
^{44}Ti(α, p)^{47}V	−0.394
α(2α, γ)^{12}C	+0.386
^{45}V(p, γ)^{46}Cr	−0.361
^{40}Ca(α, γ)^{44}Ti	+0.137
^{57}Co(p, n)^{57}Ni	+0.102
^{36}Ar(α, p)^{39}K	+0.037
^{44}Ti(α, γ)^{48}Cr	−0.024
^{12}C(α, γ)^{16}O	−0.017
^{57}Ni(p, γ)^{58}Cu	+0.013
^{58}Cu(p, γ)^{59}Zn......	+0.011
^{36}Ar(α, γ)^{40}Ca	+0.008
^{44}Ti(p, γ)^{45}V	−0.005
^{57}Co(p, γ)^{58}Ni	+0.002
^{57}Ni(n, γ)^{58}Cu	+0.002
^{54}Fe(α, n)^{57}Ni	+0.002
^{40}Ca(α, p)^{43}Sc	−0.002

[a] Order of importance of reactions producing ^{44}Ti at $\eta = 0$ according to the slope of $X(^{44}\mathrm{Ti})$ near the standard reaction rates.

Level Scheme



E_x	E_{lab}/m_p	q_{min_MD1}	q_{min_ED1}	q_{min_MD2}	q_{min_ED2}	q_{gas}	B_{MD1}	E_{ED1}	B_{MD2}	E_{ED2}	q_{carbon}
[keV]	[keV/amu]	[e]	[e]	[e]	[e]	Sayer	[T]	[kV]	[T]	[kV]	Sayer
5305	49	2	0	2	0	2	0.64	44.5	0.78	35.6	5
5423	81	3	1	2	1	3	0.55	49.3	0.67	39.5	6
7216	574	7	5	7	5	8	0.55	130.6	0.67	104.4	11
7634	689	8	6	7	6	9	0.53	139.3	0.65	111.4	12
8067	808	9	7	8	7	10	0.52	147.0	0.64	117.6	13
8318	877	9	8	8	8	10	0.54	159.5	0.66	127.6	13
8385	896	9	8	8	8	10	0.55	162.9	0.67	130.3	13
8416	904	9	8	8	8	10	0.55	164.4	0.67	131.6	13
8449	914	9	8	8	8	10	0.55	166.1	0.68	132.9	13
8511	931	9	8	8	8	10	0.56	169.2	0.68	135.4	13
8534	937	9	9	8	9	10	0.56	170.3	0.69	136.3	13
8565	945	10	9	8	9	10	0.56	171.9	0.69	137.5	13
8627	962	10	9	8	9	10	0.57	175.0	0.70	140.0	13
8639	966	10	9	9	9	10	0.57	175.6	0.70	140.5	13
8754	997	10	9	9	9	10	0.58	181.3	0.71	145.1	13
8946	1050	10	10	9	10	11	0.54	173.6	0.66	138.9	13
8954	1052	10	10	9	10	11	0.54	174.0	0.66	139.2	13
8960	1054	10	10	9	10	11	0.54	174.2	0.66	139.4	14
8987	1061	10	10	9	10	11	0.54	175.5	0.66	140.4	14
8992	1063	10	10	9	10	11	0.54	175.7	0.67	140.5	14
9073	1085	10	10	9	10	11	0.55	179.4	0.67	143.5	14
9100	1093	10	10	9	10	11	0.55	180.6	0.67	144.5	14
9120	1098	10	10	9	10	11	0.55	181.5	0.68	145.2	14
9140	1104	10	10	9	10	11	0.55	182.4	0.68	145.9	14
9180	1115	10	10	9	10	11	0.55	184.2	0.68	147.4	14
9215	1124	10	10	9	10	11	0.56	185.8	0.68	148.7	14
9227	1127	10	10	9	10	11	0.56	186.4	0.68	149.1	14
9239	1131	10	10	9	10	11	0.56	186.9	0.69	149.5	14

Separation

q	$\Delta(E/q)/(E/q)$	$E_{beam}/(q+1)$	$m_{beam}/(q+1)$	$E*m_{beam}/(q+1)$	$E_{beam}/(q-1)$	$m_{beam}/(q-1)$	$E*m_{beam}/(q-1)$
	[%]	[%]	[%]	[%]	[%]	[%]	[%]
2	10%	-26.7%	-39.4%	-33.3%	120.0%	81.8%	100.0%
3	10%	-17.5%	-31.8%	-25.0%	65.0%	36.4%	50.0%
8	10%	-2.2%	-19.2%	-11.1%	25.7%	3.9%	14.3%
9	10%	-1.0%	-18.2%	-10.0%	23.8%	2.3%	12.5%
10	10%	0.0%	-17.4%	-9.1%	22.2%	1.0%	11.1%
11	10%	0.8%	-16.7%	-8.3%	21.0%	0.0%	10.0%
12	10%	1.5%	-16.1%	-7.7%	20.0%	-0.8%	9.1%
13	10%	2.1%	-15.6%	-7.1%	19.2%	-1.5%	8.3%
14	10%	2.7%	-15.2%	-6.7%	18.5%	-2.1%	7.7%
15	10%	3.1%	-14.8%	-6.2%	17.9%	-2.6%	7.1%
16	10%	3.5%	-14.4%	-5.9%	17%	-3.0%	6.7%

local TOF (50 cm): ΔT ~3.5 ns

E_x	E_{lab}/m_p	$\omega\gamma$	err	Yield	$rate_{recoil}$	$time_{1count}$	$\Phi_{1/2}$
[keV]	[keV/amu]	[eV]	[ev]		[1/h]	[h]	[mrad]
5305	49						
5423	81						
7216	574						
7634	689	0.013	0.003	2.6E-13	0.064	15.7	5.3
8067	808	0.022	0.004	3.8E-13	0.093	10.8	5.2
8318	877	0.12	0.02	1.9E-12	0.470	2.1	5.1
8385	896	0.52	0.1	8.2E-12	1.997	0.5	5.1
8416	904	0.33	0.07	5.2E-12	1.256	0.8	5.1
8449	914	0.28	0.06	4.3E-12	1.057	0.9	5.1
8511	931	0.22	0.04	3.4E-12	0.816	1.2	5.1
8534	937	0.33	0.07	5.0E-12	1.217	0.8	5.1
8565	945	0.11	0.02	1.7E-12	0.402	2.5	5.1
8627	962	0.08	0.02	1.2E-12	0.288	3.5	5.1
8639	966	0.23	0.05	3.4E-12	0.825	1.2	5.1
8754	997	0.33	0.07	4.7E-12	1.151	0.9	5.1
8946	1050	0.11	0.02	1.5E-12	0.366	2.7	5.1
8954	1052	0.22	0.04	3.0E-12	0.731	1.4	5.1
8960	1054	0.4	0.08	5.5E-12	1.328	0.8	5.1
8987	1061	0.3	0.06	4.1E-12	0.989	1.0	5.1
8992	1063	0.6	0.1	8.1E-12	1.977	0.5	5.1
9073	1085						
9100	1093						
9120	1098						
9140	1104						
9180	1115						
9215	1124	0.5	0.1	6.5E-12	1.568	0.6	5.0
9227	1127	5.8	0.12	7.5E-11	18.136	0.1	5.0
9239	1131	2	0.4	2.6E-11	6.238	0.2	5.0
9280	1142						

TABLE 1

Decay properties of $^{40}Ca(\alpha, \gamma)^{44}Ti$ resonances observed in this work

Resonance energy (keV)	Resonance J^π	Transition energy (keV)	Final-state energy (keV)	J^π	Mixing ratio E2/M1	Branching ratio (%)
7634±20	?	5730	1904	0^+		38±20
		7634	0	0^+		62±20
8067±20	?	8067	0	0^+		100
8318± 5	?	5432	2886	2^+		46±10
		7235	1083	2^+		54±10
8385± 5	2^+	5449	2886	2^+	?	50±10
		7302	1083	2^+	?	20±10
		8385	0	0^+		30±10
8416± 5	$(0^+, 1^-)$	7333	1083	2^+		100
8449± 5	2^+	5995	2454	4^+		21±10
		7366	1083	2^+	0 → +4.0	79±10
8511± 5	2^+	7428	1083	2^+	−0.1 → +1.0	100
8534± 5	$(2^+, 3^-)$	7451	1083	2^+	−1.0 → −0.5	100
8565± 5	2^+	5200	3365	4^+		20±10
		6034	2531	2^+	−1.0 → −0.5	18±10
		7482	1083	2^+	−0.1 → +1.0	62±10
8627± 6	2^+	7544	1083	2^+		100
8639± 6	2^+	7556	1083	2^+	−0.1 → +1.0	75±10
		8639	0	0^+		25±10
8756± 5	2^+	5330	3415	(2, 3)		
		or				5
		4803	3942	3^-		
		7662	1083	2^+	≈ −0.6	70± 5
		8745	0	0^+		25± 5

E.L. Copperman et al., Nucl. Phys. A284 (1977) 163