TRIUMF — RESEARCH PROPOSAL

Experiment no.

Title of proposed experiment:

^{40}Ca$(\alpha,\gamma)^{44}$Ti for Astrophysics

Name of group: DRAGON

Spokesperson for group: Christof Vockenhuber

E-Mail address: christof.vockenhuber@triumf.ca

Fax number: 604 222 1074

Members of the group (name, institution, status, per cent of time devoted to experiment)

Name	Institution	Status	Time
C. Vockenhuber	TRIUMF	Research Associate	80%
L. Buchmann	TRIUMF	Research Scientist	10%
J. Caggiano	TRIUMF	Research Scientist	15%
A. Chen	McMaster University	Assistant Professor	10%
J. M. D'Auria	Simon Fraser University	Professor	20%
B. Davids	TRIUMF	Research Scientist	10%
D. G. Gigliotti	University of Northern British Columbia	Graduate Student	15%
U. Greife	Colorado School of Mines	Associate Professor	10%
M. Hass	Weizmann Institute	Professor	5%
A. Hussein	University of Northern British Columbia	Professor	5%
D. A. Hutcheon	TRIUMF	Research Scientist	25%
J. Jose	UPC/IEEC Barcelona	Associate Professor	10%
A. M. Laird	University of York	Lecturer	10%
H. Nassar	Hebrew University	Graduate Student	10%
A. Olin	TRIUMF	Research Scientist	10%
P. Parker	Yale University	Professor	5%
M. Paul	Hebrew University	Professor	25%
J. Pearson	TRIUMF	Research Associate	15%
C. Ruiz	TRIUMF	Research Associate	15%
G. Ruprecht	TRIUMF	Research Associate	15%
M. Trinczek	TRIUMF	Research Associate	15%

Start of preparations: Now

Date ready: January 2005

Completion date: End of 2005

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
60	ISAC-HE	No

^{44}Ti ($t_{1/2} = 60.0 \pm 1.1$ yr) is an interesting nuclide for astrophysics. The detection of ^{44}Ti through the 1.157 MeV line by COMPTEL in supernova remnant Cas A has generated a great interest in ^{44}Ti. The light curves of relatively recent and nearby supernovae from the ^{44}Ti decay provide an observational test for nucleosynthesis models. Today, the measurement of ^{44}Ti from known and yet unknown supernovae as well has high priority in the current γ-ray astronomy mission of INTEGRAL. In addition to the observation in space, excess of ^{44}Ca found in presolar grains indicates ^{44}Ti production in supernovae.

The major production of ^{44}Ti takes place through α capture on ^{40}Ca in α-rich freeze-out phase in the last stage of a supernova event. Thus a deep understanding of this production rate of the reaction ^{40}Ca$(\alpha,\gamma)^{44}$Ti is essential for an accurate comparison of measured supernova yield and theoretical calculations.

This reaction has been studied in the past by prompt γ-ray spectrometry in the energy range of $E_\alpha = 2.75 - 4.00$ MeV, which corresponds to stellar temperatures of $T_9 = 1.2 - 2.1$ ($T_9 = 10^9$ K). Resonance strengths were measured for 12 isolated narrow resonances. However, a recent off-line measurement using Accelerator Mass Spectrometry (AMS) for counting of ^{44}Ti atoms from a preceding ^{40}Ca irradiation of a He gas target, which covered a larger temperature region $T_9 \sim 0.8 - 3$, showed a significantly larger production rate.

Here we propose a detailed study of the reaction ^{40}Ca$(\alpha,\gamma)^{44}$Ti at astrophysically relevant energies with the recoil mass spectrometer DRAGON.

Experimental area

DRAGON facility in the ISAC experimental hall

Primary beam and target (energy, energy spread, intensity, pulse characteristics, emittance)

^{40}Ca, 0.5 - 1.2 MeV/u, 1 pnA or more

Secondary channel None

Secondary beam (particle type, momentum range, momentum bite, solid angle, spot size, emmittance, intensity, beam purity, target, special characteristics)

None

TRIUMF SUPPORT:

Continued infrastructure support from TRIUMF for DRAGON at ISAC, including assigned personnel.

Special support for the production of ^{40}Ca beam with charge state 2+ from OLIS.

NON-TRIUMF SUPPORT

NSERC DRAGON Project Grant (J.M. D'Auria), approved by NSERC in 2004 for 3-year support.

SAFETY

Standard DRAGON procedures for stable beam experiments will be observed.

1 Scientific Justification

The detection of live ^{44}Ti in supernova remnants provides a direct observational evidence for ongoing nucleosynthesis. Moreover the ^{44}Ti gamma afterglow is used to determine the amount of ^{44}Ti produced in supernovae and allows a direct comparison with theoretical nucleosynthesis models. First observation of the decay of ^{44}Ti through the 1.157 MeV line by COMPTEL was found in supernova remnant Cas A [IDB$^+$94]. Other young supernova remnants are expected to be found by the enhanced sensitivity of SPI onboard INTEGRAL [GDI$^+$01], see Figure 1.

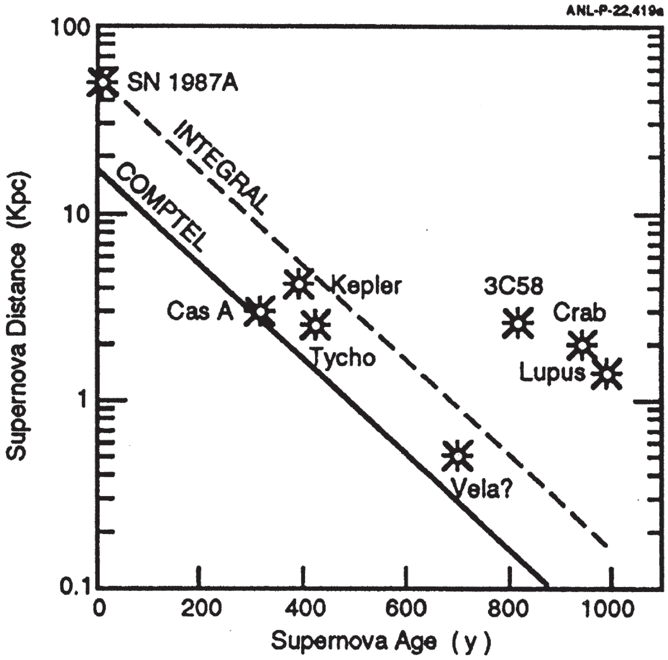

Fig. 1 Sensitivity of COMPTEL and INTEGRAL spectrometers. The instruments will be able to detect supernova explosions with distance and age below the line. Figure taken from [AGKP00].

^{44}Ti decays by electron capture to stable ^{44}Ca via ^{44}Sc. Subsequent to the COMPTEL result the then very uncertain half-life was remeasured by a couple of groups, which resulted in an value of 60.0 ± 1.1 yr, [CS99]. At this point it should be noted that the effective half-life of ^{44}Ti depends on its ionization, i.e. the half-life of H-like ^{44}Ti^{21+} is less than half of the laboratory half-life, even more fully ionized ^{44}Ti^{22+} becomes stable, since the decay Q-value from ground state ^{44}Ti to a second excited state of ^{44}Sc is less than the required two times 511 keV for positron emission [MK04]. This is important for accurate interpretation of the measured SN light curves from the ^{44}Ti decay.

Another observational evidence comes from the excess of ^{44}Ca relative to the other stable Ca isotopes in certain presolar grains of primitive meteorites [NAZ$^+$96]. Tiny grains (with diameters smaller than several μm) are specially selected and isotopic ratios are measured using secondary ion mass spectrometry (SIMS). Isotopic anomalies of other elements (e.g. C, N, Al, Si) give a clear indication of presolar origin, which means they still contain material from the time before the solar system was formed. Based on comparison with isotopic ratios predicted from supernova models, these grains are believed to be supernova condensates. The large excess of ^{44}Ca (up to $> 100\times$ solar) indicates a significant production from the in-situ decay of ^{44}Ti.

^{44}Ti is produced primarily in the α-rich freeze-out from nuclear statistical equilibrium, which takes place in the last stage of a supernova when at low densities α-particles are available for capture reactions on heavier nuclei. The calculation of the ejected amount of ^{44}Ti in a core-collapse supernova depends on the mass cut, the pre-supernova composition and the maximum temperature and density reached in the ejecta, all of them are still very uncertain. Also the nuclear reaction rates related to ^{44}Ti are still uncertain. However, a clear picture of ^{44}Ti nucleosynthesis will improve our understanding of supernovae.

The nuclear reactions governing the nucleosynthesis of ^{44}Ti were studied in detail by [TCJM98]. The dependence of the final ^{44}Ti yield on various nuclear reactions in order of significance for equal total number of neutrons and protons ($\eta = 0$) is shown in Table 1. Since the reaction $^{40}\mathrm{Ca}(\alpha,\gamma)^{44}\mathrm{Ti}$ is the main process for the nucleosynthesis of ^{44}Ti this reaction has a high influence on the final ^{44}Ti yield and is not very critically dependent on η. Table 2 shows the order of significance for reactions at $\eta = 0.006$.

Table 1 Order of importance of reactions producing ^{44}Ti at $\eta = 0$. Table taken from [TCJM98].

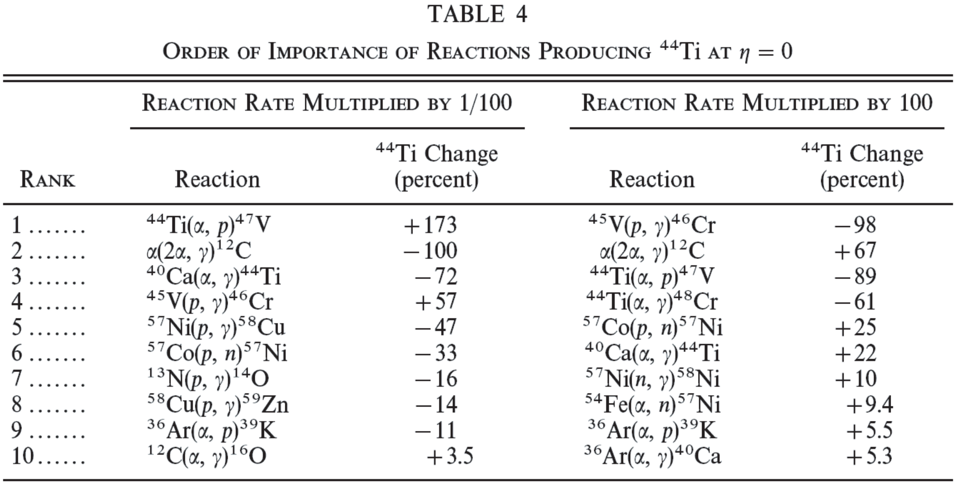

TABLE 4

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

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

The capture of α particles by isospin-symmetric nuclei has interest in nuclear physics as indicated by [RTGW00]. Isospin selection rules do not allow E1 γ transitions with $T = 0 \rightarrow T = 0$ and M1 transitions are strongly suppressed. Because of isospin conservation, α capture on self-conjugate nuclei ($N = Z$, $T = 0$) is only possible on states with isospin $T = 0$. Thus the rate of (α, γ) reactions of self-conjugate nuclei should be reduced.

The reaction $^{40}\mathrm{Ca}(\alpha,\gamma)^{44}\mathrm{Ti}$ was first investigated in the astrophysically relevant energy range by bombarding a ^{40}Ca target with α particles with energies of $E_\alpha = 2.75 - 4.00$ MeV, which corresponds to stellar temperatures of $T_9 = 1.2 - 2.1$ ($T_9 = 10^9$ K) [CSW77]. By analyzing the prompt γ rays from the reaction, resonance strengths were measured for 12 isolated narrow resonances (see Table 3). The measured γ-branching ratios are shown

Table 2 Order of importance of reactions producing ^{44}Ti at $\eta = 0.006$. Table taken from [TCJM98].

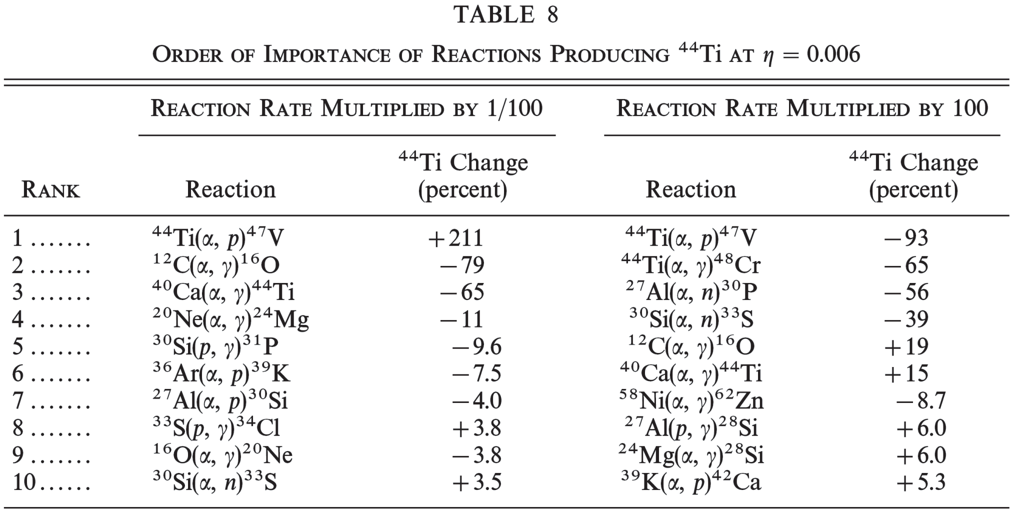

TABLE 8

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

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

in Figure 2. At higher energies ($E_\alpha = 3.79 - 5.94$ MeV) the resonance strength of other states were measured by [DSS77], including the rather strong resonance at $E_\alpha = 4.52$ MeV, which was later identified as an isospin-mixed triplet at energy levels $E_x = 9.215$, 9.227 and 9.239 MeV [DSS80].

This reaction has also been recently investigated at the 14UD Pelletron Tandem accelerator at the Weizmann Institute in Rehovot/Israel. This method consists of an activation of a ^{4}He gas target by a ^{40}Ca beam and implantation of the ^{44}Ti recoils in a catcher foil [HPB$^+$]. After chemical extraction with Ti carrier by etching the isotopic ratio ^{44}Ti/Ti ($< 10^{-12}$) is measured by Accelerator Mass Spectrometry (AMS). The measurement of the total resonance strength of two close-lying, rather strong resonances at $E_x = 9.227$ and 9.239 MeV resulted in 7.4 ± 2.5 eV [PFA$^+$00] and is in agreement with the established values of 5.8 eV and 2 eV respectively [CS99]. A second experiment which covers a range of $E_x = 6.8 - 9.3$ MeV showed a significant (about factor 10) higher total resonance strength [NPG$^+$04] than previously known from [CSW77,DSS77] at $E_x = 7.634 - 8.992$ MeV and $E_x = 9.227 - 9.239$ MeV (see Figure 3).

This indicates that there is a significant production of ^{44}Ti at other E_x levels of ^{44}Ti besides the already measured levels, provided these measurements are accurate. The possibility of a direct measurement of this reaction with DRAGON allows a detailed study of certain resonances of ^{44}Ti which are important for ^{44}Ti production.

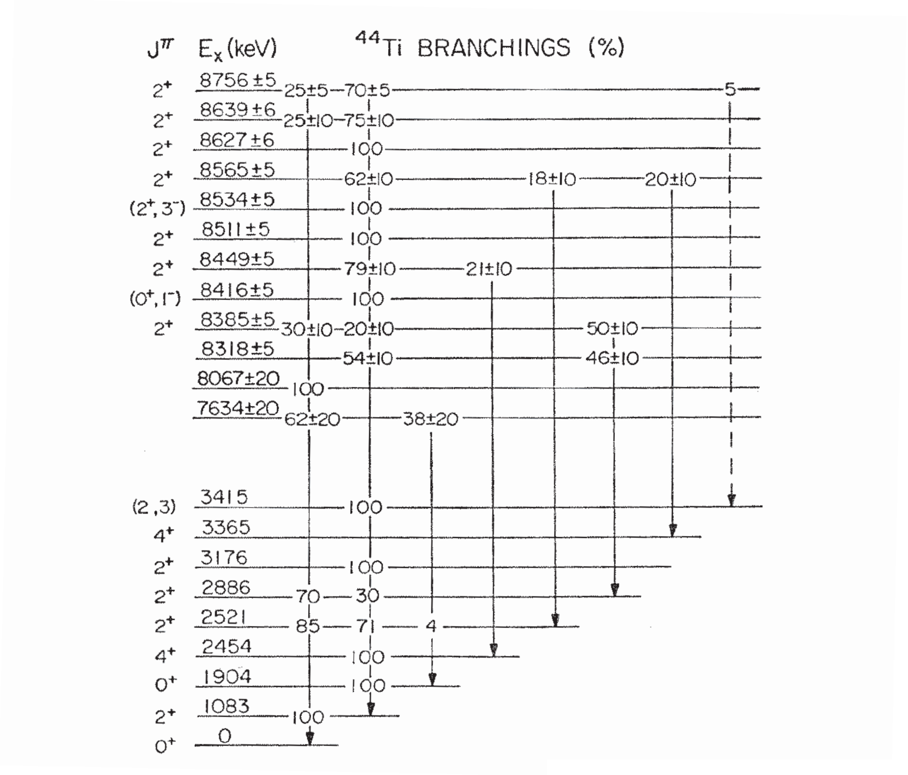

Fig. 2 γ-branching ratios for resonances between $E_x = 7624$ and $E_x = 8756$ keV. Figure taken from [CSW77].

Table 3 Measured resonance strengths $\omega\gamma$ of excitation energies (E_x) in ^{44}Ti and the centre-of-mass resonance energy (E_{cm}) of ^{40}Ca + α, assigned spin-parities and reference.

E_x [keV]	E_{cm} [keV]	J^π	$\omega\gamma$ [eV]	reference
7634	2507		0.013 ± 0.003	[CSW77]
8067	2940		0.022 ± 0.004	[CSW77]
8318	3191		0.12 ± 0.02	[CSW77]
8385	3258	2+	0.52 ± 0.1	[CSW77]
8416	3289	(0+,1–)	0.33 ± 0.07	[CSW77]
8449	3322	(2+,3–)	0.28 ± 0.06	[CSW77]
8511	3384	2+	0.22 ± 0.04	[CSW77]
8534	3407	(2+,3–)	0.33 ± 0.07	[CSW77]
8565	3438	2+	0.11 ± 0.02	[CSW77]
8627	3500	2+	0.08 ± 0.02	[CSW77]
8639	3512	2+	0.23 ± 0.05	[CSW77]
8756	3629	(2+)	0.33 ± 0.07	[CSW77]
8947	3820		0.11 ± 0.02	[DSS77]
8954	3827	1–	0.22 ± 0.04	[DSS77]
8960	3833	(2+,3–)	0.4 ± 0.08	[DSS77]
8987	3860	2+	0.3 ± 0.06	[DSS77]
8992	3865	4+	0.6 ± 0.1	[DSS77]
9215	4088	2+	0.5 ± 0.1	[DSS80]
9227	4100	2+	5.8 ± 0.12	[DSS80]
9239	4112	2+	2 ± 0.4	[DSS80]

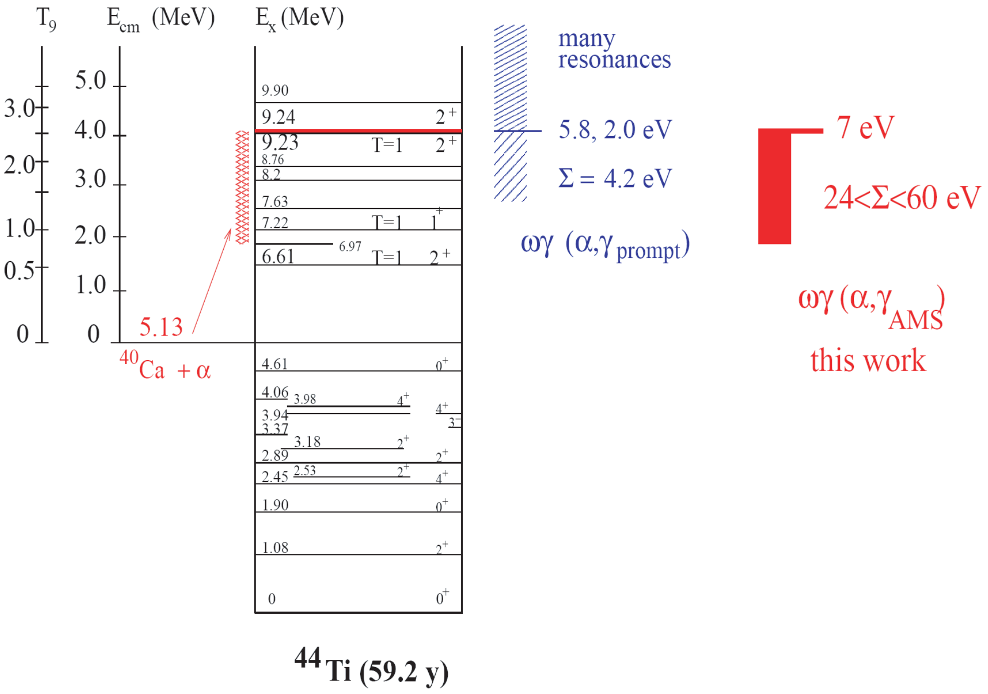

Fig. 3 Level scheme of ^{40}Ca$(\alpha,\gamma)^{44}$Ti. The result of the AMS measurements are shown on the far right and compared with the measurements by prompt γ next to the level scheme. Figure taken from [NPG+04].

2 Description of the Experiment

The ^{40}Ca$(\alpha,\gamma)^{44}$Ti reaction will be measured in inverse kinematics using the DRAGON recoil separator. A layout of the spectrometer is shown in Figure 4, details of the setup are presented in [HBB$^+$03]. Stable ^{40}Ca beam will be provided by ISAC-I [Lax01].

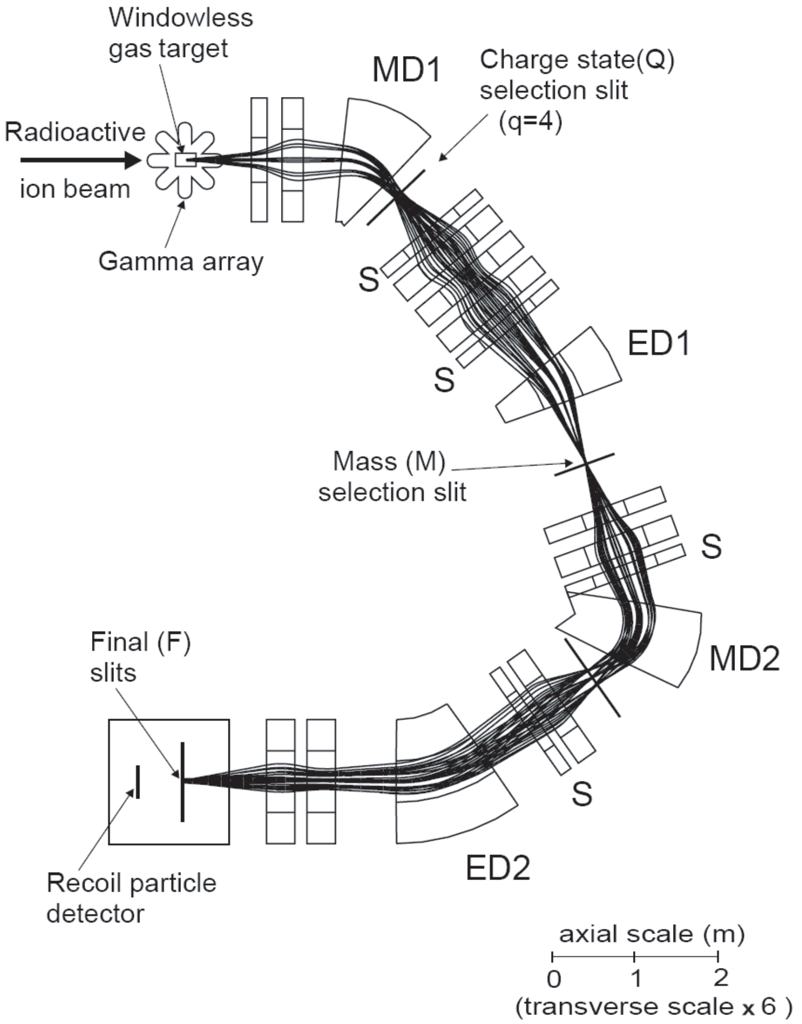

Fig. 4 Layout of the DRAGON setup. Figure taken from [HBB$^+$03].

^{40}Ca beam will be produced by the off-line ion source OLIS and charge state 2+ has to be extracted to meet the requirements for further acceleration through radio frequency quadrupole RFQ, which are $A/q < 30$. Since other already proposed experiments such as the ^{12}C$(\alpha,\gamma)^{16}$O experiment E952 would gain from higher charge states from OLIS the production of multiple charge states should be investigated.

^{40}Ca has ^{40}Ar and ^{40}K as stable isobars, which will be a contamination of the ^{40}Ca beam. The isotopic abundance of ^{40}K is 0.0117% and thus it should be negligible, but ^{40}Ar is the most abundant isotope of Ar and common in gas ion sources. However, in a surface ion source Ar should not be ionized due to its high first ionization potential.

The ^{40}Ar contamination is not critical for ^{44}Ti production, but high intensities of ^{40}Ar can cause problems with stripper foil lifetimes and beam normalization, especially if the ^{40}Ca/^{40}Ar ratio is not constant.

Subsequent to the RFQ at the medium energy beam transport (MEBT) ^{40}Ca^{2+} has to be stripped to charge state 7+ for acceleration through the drift tube linac (DTL). According to the semi-empirical formula from Sayer [Say77] the mean charge state for ^{40}Ca at 153 keV/u is 7.3, thus a stripping yield of about 30% can be expected. The DTL will accelerate the ^{40}Ca beam to the required energy. Any ^{20}Ne^{+} contamination before the DTL will be removed since it cannot reach the same m/q as ^{40}Ca in odd charge states.

The DRAGON window-less gas target will be filled with ^{4}He gas with about 1 Torr, which contains about 4×10^{17} ^{4}He atoms / cm^2, to ensure the energy loss ($\sim$ 100 keV) is larger than the energy width of the resonances. The BGO array will detect prompt γ rays from the reaction and will be used in coincidence with the detected recoil ^{44}Ti at the DRAGON end detector. The efficiency of the BGO array depends on the γ energy as well as on the γ-ray multiplicity. The single γ-ray efficiency is between 40% to 60% for γ-ray energies of 1 to 10 MeV.

The maximal opening angle of the reaction depends on the masses and the Q-value of the reaction. Due to the high masses involved the maximal opening angle is less than ±6 mrad for excitation levels above 6.5 MeV, which is much less than the nominal acceptance of DRAGON of ±20 mrad.

One limitation for the possible mass range of ions at DRAGON comes from the bending requirements of the electrostatic and magnetic dipoles. Since for magnetic dipoles the magnetic rigidity ($\propto ME/q^2$) must not exceed the maximum rigidity of the dipole only charge states equal or higher than the minimum charge state q_{min} can be used. The same is true for electrostatic dipoles with the electric rigidity ($\propto E/q$). Table 4 shows the minimum charge state q_{min} for selected recoil energies and the respective mean charge state expected for gases $\bar{q}_{gas}$. That means the full charge state distribution can not be measured in this mass range. If it turns out that this is crucial there is a possibility to use a solid state stripper to boost to higher charge states (indicated as $\bar{q}_{carbon}$). However, this method has not been tried before and the feasibility requires some testing.

Table 4 Minimum charge states q_{min} possible at DRAGON depending on recoil energy E_r (with corresponding energy level E_x in ^{44}Ti). Mean charge states for gas $\bar{q}_{gas}$ and carbon $\bar{q}_{carbon}$ are also shown (estimates based on a semi-empirical formula of Sayer [Say77].

E_r [MeV]	E_x [MeV]	q_{min}	$\bar{q}_{gas}$	$\bar{q}_{carbon}$
23.0	7.216	7	8	11
27.6	7.634	8	9	12
32.3	8.067	9	10	13
37.5	8.534	9	10	13
37.8	8.565	10	10	13
42.0	8.946	10	11	13
45.2	9.239	10	11	14

The measurement of the resonance strength $\omega\gamma$ is based on the thick target yield, Y, which is the number of recoils per incoming projectile:

$$Y = \frac{\lambda^2}{2} \frac{m_p + m_t}{m_t} \left(\frac{dE}{dx}\right)^{-1} \omega\gamma \tag{1}$$

with λ the de Broglie wavelength of the reduced mass of the compound system, m_p and m_t the mass of projectile and target, dE/dx the stopping power of the projectile in the target in the laboratory system and $\omega\gamma$ defined as:

$$\omega\gamma = \frac{2J_R + 1}{(2J_t + 1)(2J_p + 1)} \frac{\Gamma_t \Gamma_\gamma}{\Gamma} \tag{2}$$

with J_R, J_t and J_p the spins of the resonance, target and ground state of projectile, respectively, and Γ_t, Γ_γ the partial target and gamma widths of the resonance, and $\Gamma = \Gamma_t + \Gamma_\gamma$.

The reaction yield, Y, will range from $\sim 10^{-10}$ for $\omega\gamma \sim 10$ eV down to $\sim 10^{-13}$ for $\omega\gamma \sim 0.01$ eV. A suppression of the recoil spectrometer should be about 10^{10}, further suppression should come from the end detector (about 2 orders of magnitude) and the coincidence with the γ BGO array (about 3 orders of magnitude). The use of local time-of-flight (TOF) of the detected particles is here advantageous since compared to previous measurements at DRAGON with $A < 30$, heavier ions are slower at the same energy and thus better separated in TOF. The planned combination of TOF with energy (E) measurements (from the DRAGON ionization chamber) should clearly separate recoils (^{44}Ti) from leaky beam (^{40}Ca) in 2D plots.

2.1 Phase I: Measurement at $E_x \sim 9.2$ MeV

In a first stage we plan to measure the well established strong resonances around $E_x \sim 9.2$ MeV ($E_{lab}/m \sim 1.13$ MeV/u). With 1 pnA ^{40}Ca at the DRAGON gas target, expected count rates are in the order of 100/h, sufficient to study the separation capabilities of DRAGON, both for the spectrometer and the end detector. At this point it should be mentioned that recoil ^{44}Ti^{10+} has the same E/q as beam ^{40}Ca^{11+} and thus the suppression of the spectrometer may be reduced. However, charge changing or scattering processes at certain positions are still required to allow the leaky beam in the wrong charge state to pass preceding or subsequent dipoles. The high yield of these resonances should allow the study of separation capabilities of DRAGON for various charge states.

Also studies of beam contamination (especially from ^{40}Ar) should be measured at high ion energies. The DRAGON ionization chamber should be able to discriminate between ^{40}Ca and ^{40}Ar, since the difference in Z is 2 which results in a difference in stopping power of about 12% at $E_{lab}/m = 1.13$ MeV/u.

In addition one of the states ($E_x = 9.227$ MeV) is attributed $T = 1$ and it would be interesting to measure its prompt gamma decay, since (α, γ) reactions on self-conjugate $(N = Z)$ $T = 0$ nuclei are strongly suppressed by isospin selection rules [RTGW00].

2.2 Phase II: Measurement at $E_x < 9.2$ MeV

In the second stage we plan to measure the resonances of unknown states with excitation energies of $E_x < 9.2$ MeV.

For some of the resonances in this energy range no measured resonance strengths exist (see Table 5 and 6). According to [NPG$^+$04] the total resonance strength at $E_x = 6.8 - 9.2$ MeV is a factor of 8 larger than at $E_x = 9.2$ MeV alone. Thus weak resonances ($\omega\gamma < 0.1$ eV) have no significant contribution to the total resonance strength. Since we do not know where the additional resonance strength comes from, we will measure the excitation function with DRAGON starting from $E_x = 9.2$ MeV down to the lowest relevant energy of $E_x \sim 6.5$ MeV. For $\omega\gamma = 1$ eV we expect about 30 counts per hour at 1 pnA ^{40}Ca. The energy loss of ^{40}Ca in He gas is about 100 keV per 1 Torr, thus we can scan the energy range $E_{lab} \sim 45$ MeV down to $E_{lab} \sim 15$ MeV with 30 steps at 10 Torr. Since the recoil spectrometer is in first order achromatic, small energy variations are focused to the same point at the end detector. The energy acceptance of the recoil spectrometer (about $\pm 5\%$) is sufficient to accept the energy range from the energy loss of ^{40}Ca at the He target.

Depending on the result of the excitation function, single resonances will be investigated in more detail and corresponding resonance strengths $\omega\gamma$ will be measured.

Table 5 Excitation energies in ^{44}Ti (E_x) above the threshold of ^{40}Ca + α (Q-value = 5.1271 MeV), centre-of-mass resonance energies of ^{40}Ca + α (E_{cm}), assigned spin-parities and isospin and measured resonance strengths $\omega\gamma$. Data from [CS99].

E_x [keV]	E_{cm} [keV]	E_{lab}/m [keV/u]	J^π	T	$\omega\gamma$ [eV]	reference
5152	25	7.0	(6–)			
5210	83	22.8	5–			
5305	178	48.9	5–			
5421	294	80.8	3–			
5670	543	149.4	(7–)			
6030	903	248.3	2+			
6220	1093	300.5	1–			
6509	1381	379.9	(8+)			
6572	1445	397.5	(8+)			
6606	1479	406.8	2+	$T = 1$		
6805	1678	461.4	(0,2)+			
6849	1722	473.5	(6+)	$T = 1$		
6924	1797	494.1	(8–)			
6959	1832	503.8	4+	$T = 1$		
7216	2089	574.4	1+	$T = 1$		
7340	2213	608.5	3–			
7409	2281	627.4	(9–)			
7560	2433	669.0				
7634	2507	689.4			0.013 ± 0.003	[CSW77]
7670	2543	699.3	6+			
7671	2544	699.6	(10+)			
8040	2913	801.0	3–,(12+)			
8067	2940	808.5			0.022 ± 0.004	[CSW77]
8170	3043	836.8	1–			
8180	3053	839.5				
8318	3191	877.5			0.12 ± 0.02	[CSW77]
8385	3258	895.9	2+		0.52 ± 0.1	[CSW77]
8416	3289	904.4	(0+,1–)		0.33 ± 0.07	[CSW77]
8449	3322	913.5	(2+,3–)		0.28 ± 0.06	[CSW77]
8511	3384	930.6	2+		0.22 ± 0.04	[CSW77]
8534	3407	936.9	(2+,3–)		0.33 ± 0.07	[CSW77]
8565	3438	945.4	2+		0.11 ± 0.02	[CSW77]
8627	3500	962.5	2+		0.08 ± 0.02	[CSW77]
8639	3512	965.8	2+		0.23 ± 0.05	[CSW77]
8756	3629	997.9	(2+)		0.33 ± 0.07	[CSW77]

Table 6 Excitation energies in ^{44}Ti, continued.

E_x [keV]	E_{cm} [keV]	E_{lab}/m [keV/u]	J^π	T	$\omega\gamma$ [eV]	reference
8862	3735	1027.0	(10–)			
8947	3820	1050.5			0.11 ± 0.02	[DSS77]
8954	3827	1052.4	1–		0.22 ± 0.04	[DSS77]
8960	3833	1054.0	(2+,3–)		0.4 ± 0.08	[DSS77]
8987	3860	1061.5	2+		0.3 ± 0.06	[DSS77]
8992	3865	1062.8	4+		0.6 ± 0.1	[DSS77]
9073	3946	1085.1				
9100	3973	1092.5				
9120	3993	1098.0				
9140	4013	1103.5				
9180	4053	1114.5				
9215	4088	1124.2	2+		0.5 ± 0.1	[DSS80]
9227	4100	1127.5	2+	$T = 1$	5.8 ± 0.12	[DSS80]
9239	4112	1130.8	2+		2 ± 0.4	[DSS80]

3 Experimental Equipment

OLIS, ISAC, DRAGON

4 Readiness

DRAGON is ready to accept beam for this experiment.

5 Beam Time required

5.1 Phase I

Measurement	Shifts required
Beam development (^{40}Ca, charge state 2+)	(8)
Beam contamination (^{40}Ca – ^{40}Ar)	2
DRAGON suppression of leaky beam	2
$E_{lab}/m = 1.13$ MeV/u resonances	6
off resonance	2

5.2 Phase II

Measurement	Shifts required
Excitation function ($E_x = 6.8 - 9.2$ MeV) $E_{lab}/m = 1.13$ MeV/u down to 0.38 MeV/u in steps of 25 keV/u	20
measurement of single resonances plus measurement at off resonance	20

6 Data Analysis

Standard DRAGON procedures for data acquisition and data analysis.

References

[AGKP00] I. Ahmad, J. P. Greene, W. Kutschera, and M. Paul, *Measurement of the ^{44}Ti Half-Life and its Significance for Supernovae*, pp. 203–210, Kluwer Academic, 2000.

[CS99] John A. Cameron and Balraj Singh, *Nuclear Data Sheets for A = 44*, Nucl. Data Sheets **88** (1999), 199–416.

[CSW77] E. L. Cooperman, M. H. Shapiro, and H. Winkler, *Helium Burning of ^{40}Ca*, Nucl. Phys. **A 284** (1977), 163–176.

[DSS77] W. R. Dixon, R. S. Storey, and J. J. Simpson, *Levels of ^{44}Ti from the ^{40}Ca$(\alpha,\gamma)^{44}$Ti reaction*, Phys. Rev. **C 15** (1977), 1896–1910.

[DSS80] ______, *An isospin-mixed triplet in ^{44}Ti*, Can. J. Phys. **58** (1980), 1360–1366.

[GDI^{+}01] R. Georgii, R. Diehl, A. Iyudin, G. G. Lichti, V. Schönfelder, and A. Strong, *Prospects of the observations with SPI in the light of the ^{44}Ti γ-rays*, ESA SP-459: Exploring the Gamma-Ray Universe, 2001, pp. 59–63.

[HBB^{+}03] D. A. Hutcheon, S. Bishop, L. Buchmann, M. L. Chatterjee, A. A. Chen, J. M. D'Auria, S. Engel, D. Gigliotti, U. Greifef, D. Hunter, A. Hussein, C. Jewett, N. Khan, A. Lamey, W. Liu, A. Olin, D. Ottewell, J. G. Rogers, G. Roy, H. Sprenger, and C. Wrede, *The DRAGON facility for nuclear astrophysics at TRIUMF-ISAC*, Nucl. Instr. Meth. **A 498** (2003), 190–210.

[HPB^{+}] S. K. Hui, M. Paul, D. Berkovits, E. Boaretto, S. Gehlberg, M. Hass, A. Hershkowitz, and E. Navon.

[IDB^{+}94] A. F. Iyudin, R. Diehl, H. Bloemen, W. Hermsen, G. G. Lichti, D. Morris, J. Ryan, V. Schoenfelder, H. Steinle, M. Varendorff, C. de Vries, and C. Winkler, *COMPTEL observations of Ti-44 gamma-ray line emission from CAS A*, Astron. Astrophys. **284** (1994), L1–L4.

[Lax01] R. E. Laxdal, *ISAC at TRIUMF: Status of the Post-Accelerator*, Int. Workshop on production of radioactive ion beams (PRORIB 2001), Pui, India, 200, URL: www.triumf.ca/download/lax/prorib2000/prorib2001_paper/prorib2000_3.pdf (2001).

[MK04] Yuko Motizuki and Shiomi Kumagai, *^{44}Ti radioactivity in young supernova remnants: Cas A and SN 1987A*, New Astr. Reviews **48** (2004), 69–73.

[NAZ^{+}96] L. R. Nittler, S. Amari, E. Zinner, S. E. Woosley, and R. S. Lewis, *Extinct ^{44}Ti in Presolar Graphite and SiC: Proof of a Supernova Origin*, Astrophy. J. **462** (1996), L31–L34.

[NPG^{+}04] H. Nassar, M. Paul, S. Ghelberg, A. Ofan, N. Trubnikov, Y. Ben-Dov, M. Hass, and B. S. Nara Singh, *Study of the supernova nucleosynthesis ^{40}Ca$(\alpha,\gamma)^{44}$Ti reaction: progress report*, Proceedings of NIC 8 (2004), to be published.

[PFA$^+$00] M. Paul, C. Feldstein, I. Ahmad, D. Berkovits, C. Bordeanu, J. Caggiano, S. Gehlberg, , J. Goerres, J. Greene, M. Hass, A. Heinz, D. Henderson, S. K. Hiu, R. V. F. Janssens, C. L. Jiang, S. Jiang, Y. Nirel, R. C. Pardo, T. Pennington, K. E. Rehm, G. Savard, G. Verri, R. Vondrasek, I. Wiedenhover, and M. Wiescher, *Counting ^{44}Ti nuclei from the $^{40}Ca(\alpha,\gamma)^{44}Ti$ reaction*, Nucl. Phys. **A 718** (2000), 239c–242c.

[RTGW00] T. Rauscher, F.-K. Thielemann, J. Goerres, and M. Wiescher, *Capture of α particles by isospin-symmetric nuclei*, Nucl. Phys. **A 675** (2000), 695–721.

[Say77] R. O. Sayer, *Semi-empirical formulars for heavy-ion stripping data*, Rev. de Phys. App. **12** (1977), 1543.

[TCJM98] L.-S. The, D. D. Clayton, L. Jin, and M. S. Meyer, *Nuclear reactions governing the nucleosynthesis of ^{44}Ti*, Astrophy. J. **504** (1998), 500–515.

Include publications in refereed journal over at least the previous 5 years.

1. A. Priller, T. Brandl, R. Golser, W. Kutschera, S. Puchegger, W. Rom, P. Steier, C. Vockenhuber, A. Wallner, and E. Wild, *Extension of the measuring capabilities at VERA*, Nucl. Inst. and Meth. **B 172** (2000), 100–106.
2. R. Golser, G. Federmann, W. Kutschera, A. Priller, P. Steier, and C. Vockenhuber, *The VERA heavy ion program – status and prospects*, in J.L. Duggan, I.L. Morgan (eds.), Proc. 16th Int'l. Conf. on the Application of Accelerators in Research and Industry, Am. Inst. Phys. Conf. Ser. **CP576** (2001), 627–630.
3. C. Vockenhuber, R. Golser, W. Kutschera, V. Liechtenstein, A. Priller, P. Steier, and S. Winkler, *Accelerator mass spectrometry of the heaviest long-lived radionuclides with a 3-MV tandem accelerator*, PRAMANA **59** (2002), 1041–1051.
4. A. Priller, R. Golser, W. Kutschera, P. Steier, C. Vockenhuber, and S. Winkler, *Upgrade of the analyzing beam line at the VERA laboratory*, Proceedings of the 34^{th} Symposium of North Eastern Accelerator Personnel, Lund, Sweden, R. Hellborg et al. editors, World Scientific Publishing Co. (2002), 68–80.
5. S. Winkler, R. Golser, W. Kutschera, A. Priller, P. Steier, and C. Vockenhuber, *Experimental analysis of the ions optics of the VERA facility*, Proceedings of the 34^{th} Symposium of North Eastern Accelerator Personnel, Lund, Sweden, R. Hellborg et al. editors, World Scientific Publishing Co. (2002), 216–221.
6. P. Steier, R. Golser, W. Kutschera, V. Liechtenstein, A. Priller, A. Valenta, and C. Vockenhuber, *Heavy Ion AMS with a "small" accelerator*, Nucl. Instr. Meth. **B 188** (2002), 283–287.
7. S. Kraft, A. Bleile, P. Egelhof, R. Golser, O. Kisselev, W. Kutschera, V. Liechtenstein, H. J. Meier, A. Priller, A. Shrivastava, P. Steier, C. Vockenhuber, and M. Weber, *Calorimetric low temparature detectors for mass identification of heavy ion*, in F.S. Porter et al., eds., Low Temperature Detectors, Amer. Inst. Phys. Conf. Ser. **CP605** (2002), 405–408.
8. C. Vockenhuber, I. Ahmad, R. Golser, W. Kutschera, V. Liechtenstein, A. Priller, P. Steier, and S. Winkler, *Accelerator mass spectrometry of heavy long-lived radionuclides*, Int. J. Mass Spec. **223-224** (2003), 713–732.
9. C. Vockenhuber, C. Feldstein, M. Paul, N. Trubnikov, M. Bichler, R. Golser, W. Kutschera, A. Priller, P. Steier, and S. Winkler, *Search for live* ^{182}*Hf in deep-sea sediments*, New Astr. Rev. **48** (2004), 161–164.
10. S. Winkler, I. Ahmad, R. Golser, W. Kutschera, K. A. Orlandini, M. Paul, A. Priller, P. Steier, and C. Vockenhuber, *Anthropogenic* ^{244}*Pu in the Environment*, New Astr. Rev. **48** (2004), 151–154.
11. Hong-Chien Yuan, Walter Kutschera, Tze-Yue Lin, Peter Steier, Christof Vockenhuber, and Eva Maria Wild, *Investigation of a Chinese Ink Rubbing by* ^{14}*C AMS Analysis*, Radiocarbon **45** (2004), 1–7.

12. Hubert Gnaser, R. Golser, W. Kutschera, A. Priller, P. Steier, C. Vockenhuber, and S. Winkler, *Detection of sputtered molecular doubly charged anions: a comparison of secondary-ion mass spectrometry (SIMS) and accelerator mass spectrometry (AMS)*, Applied Surface Science **231-232** (2004), 117–121.
13. S. Kraft, V. Andrianov, A. Bleile, P. Egelhof, R. Golser, A. Kiseleva, O. Kisselev, W. Kutschera, H. J. Meier, A. Priller, A. Shrivastava, P. Steier, and C. Vockenhuber, *First application of calorimetric low temperature detectors in accelerator mass spectrometry*, Nucl. Inst. and Meth. **A 520** (2004), 63–66.
14. V. K. Liechtenstein, T. M. Ivkova, E. D. Olshanski, R. Golser, W. Kutschera, P. Steier, C. Vockenhuber, R. Repnow, R. von Hahn, M. Friedrich, and U. Kreissig, *Recent investigations and applications of thin diamond-like carbon (DLC) foils*, Nucl. Inst. and Meth. **A 521** (2004), 197–202.
15. V. K. Liechtenstein, N. V. Eremin, R. Golser, W. Kutschera, A. A. Paskhalov, A. Priller, P. Steier, C. Vockenhuber, and S. Winkler, *First tests of a thin natural diamond detector as an energy spectrometer for low-energy heavy ions*, Nucl. Inst. and Meth. **A 521** (2004), 203–207.
16. P. Steier, R. Golser, W. Kutschera, A. Priller, C. Vockenhuber, and S. Winkler, *VERA, an AMS facility for "all" isotopes*, Nucl. Instr. Meth. **B 223-224** (2004), 67–71.
17. P. Steier, R. Golser, W. Kutschera, A. Priller, V. Liechtenstein, C. Vockenhuber, and S. Winkler, *First tests with a Natural Diamond Detector (NDD) – a possibly powerful tool for AMS*, Nucl. Instr. Meth. **B 223-224** (2004), 205–208.
18. R. Golser, Hubert Gnaser, W. Kutschera, A. Priller, P. Steier, C. Vockenhuber, and S. Winkler, *Analysis of doubly-charged negative molecules by accelerator mass spectrometry*, Nucl. Instr. Meth. **B 223-224** (2004), 221–226.
19. S. Winkler, I. Ahmad, R. Golser, W. Kutschera, K. A. Orlandini, M. Paul, A. Priller, P. Steier, A. Valenta, and C. Vockenhuber, *Developing a detection method of environmental* ^{244}Pu, Nucl. Inst. Meth. **B 223-224** (2004), 817–822.
20. C. Vockenhuber, M. Bichler, R. Golser, W. Kutschera, V. Liechtenstein, A. Priller, P. Steier, and S. Winkler, ^{182}Hf*, a new isotope for AMS*, Nucl. Inst. and Meth. **B 223-224** (2004), 823–828.
21. I. Ahmad, J. P. Greene, E. F. Moore, W. Kutschera, C. Vockenhuber, R. J. Gehrke, and R. G. Helmer, *Absolute intensities of* ^{182}Hf γ *rays*, Phys. Rev. **C 70** (2004), 047301.
22. C. Vockenhuber, F. Oberli, M. Bichler, I. Ahmad, G. Quitté, M. Meier, A. N. Halliday, D.-C. Lee, W. Kutschera, P. Steier, R. J. Gehrke, and R. G. Helmer, *New half-life measurement of* ^{182}Hf*: Improved chronometer for the early solar system*, Phys. Rev. Lett. **93** (2004), 0172501.