Direct determination of the half-life of ^{41}Ca. G. Jörg[1,2], Y. Amelin[3], K. Kossert[4] and C. L. v. Gostomski[1], [1]Radiochemie München (RCM), Technische Universität München, Walther-Meißner-Str. 3, 85748 Garching, Germany, [2]Klinik und Poliklinik für Nuklearmedizin, Universitätsklinikum Würzburg, Oberdürrbacher Straße 6, 97080 Würzburg, Germany (joerg_g@klinik.uni-wuerzburg.de), [3]Research School of Earth Sciences, Building 61, Mills Road, The Australian National University, Canberra ACT 0200 Australia, [4]Physikalisch-Technische Bundesanstalt (PTB), Bundesallee 100, 38116 Braunschweig, Germany.

Introduction: Radionuclides with half-lives between 10^5 and 10^8 years that were synthesized shortly before, or simultaneously with the formation of the Sun and our Solar System, are used to study the time-scale of accretion [1, 2] and the stellar environment of the Solar System's formation [3, 4]. The time resolution of these "extinct" nuclide chronometers depends on the half-life of the parent radionuclide: the shorter the half-life, the finer the bits of time that can be resolved. Since the time span from the formation of the central protostellar object to the pre-main sequence (classical T Tauri) stage of stellar evolution and formation of the protoplanetary disk is less than one million years [5, 6], extinct radionuclides with the shortest half-lives, suitable for resolving the fine temporal structure of this period, have a special value in the studies of the early Solar System.

^{41}Ca has the shortest half-life, about 10^5 years, among the radionuclides commonly used as "extinct nuclide" chronometers, but due to the progress of analytical techniques, the uncertainty of its half-life is increasingly becoming a limiting factor in chronological interpretations.

Numerous determinations of the half-life of ^{41}Ca were reported (Table 1). These data show that the half-life of ^{41}Ca is not reliably known: the values range from 7.7 to 19.0×10^4 years, and all values suffer from large uncertainties. Klein et al. [7] critically re-evaluated the published data and came up with substantially larger values for the half-life, and also used a novel alternative approach by linking content and activity to ^{36}Cl in Antarctic meteorites. Their methodology, however, also relies on critical assumptions about the process of ^{41}Ca/^{36}Cl production in the meteorites (i.e. saturation) and the sample history. Paul et al. [8] took one step closer to an analysis less parameter-dependent by determining the number of ^{41}Ca nuclei by mass spectrometry. However, they still carried the experimental drawbacks of X-ray measurements over into the result. As a result of methodological and experimental difficulties, all the reported values suffer from uncertainties as large as 10-30 %. Their low precision is an obstacle to the efficient use of this nuclide.

Here we report a new determination of the ^{41}Ca half-life with the set of techniques intended to achieve the best possible precision and accuracy.

Methods: Radiochemically pure ^{41}Ca was extracted from borosilicate glass from the absorber rods of a decommissioned pressurized water reactor. In order to maximize the ^{41}Ca/^{40}Ca ratio, calcium was separated without addition of inactive Ca carrier. The concentration of separated calcium and the ^{41}Ca/^{40}Ca ratio were measured by thermal ionization mass spectrometry with a ^{42}Ca-^{48}Ca double spike, exponential normalization, and an independently determined absolute isotopic composition of Ca. The activity was measured by a liquid scintillation counting technique exploiting the triple-to-double coincidence ratio method, using the counting efficiencies computed following [9].

Results: The results of two independently processed and analysed samples of ^{41}Ca are presented in Table 2, together with a breakdown of uncertainty components. These two determinations yielded statistically indistinguishable values. Their average value of $(9.937\pm0.146)*10^4$ y is proposed as the new half-life value.

Discussion: The new half-life value overlaps the uncertainty interval of the previously accepted value of $(10.2\pm0.7)*10^4$ y [10], therefore it does not call for an immediate re-interpretation of the existing ^{41}Ca-^{41}K data. Furthermore, the ^{41}Ca-^{41}K method is still in the early stage of development and application, and the existing data are not particularly precise. With future refinements of the ^{41}Ca-^{41}K techniques, the significance of a more precisely and accurately known ^{41}Ca half-life will increase.

References: [1] Kita N.T. et al. (2005) Chondrites and the Protoplanetary Disk. *ASP Conf. Ser. 341,* pp. 558–587. [2] Huss G.R. et al. (2009) *GCA 73*, 4922–4945. [3] Adams F.C. (2010) *Annual Rev. Astron. Astrophys. 48,* 47–85. [4] Dauphas N. and Chaussidon M. (2011) *Annual Rev. Earth Planet. Sci. 39*, 351-386. [5] André P. (2002) *Star Formation and the Physics of Young Stars,* pp. 1–38. Les Ulis, Fr.: EDP Sci. [6] Reipurth B. (2005) *Chondrites and the Protoplanetary Disk.* ASP Conf. Ser. 341, San Francisco, pp. 54–77. [7] Klein J. et al. (1991) *EPSL 103*, 79-83. [8] Paul M. et al. (1991) *Z. Phys. A 340*, 249-254 [9] Kossert K. and Grau Carles A. *(2010) Appl. Radiat. Isot. 68,* 1482-1488. [10] Cameron J. A. and Singh B. (2001) *Nucl. Data Sheets 94*, 429-603.

Table 1. The half-life values of ^{41}Ca reported in literature.

Reference	Half-life in 10^4 y	Relative standard uncertainty in %	Method
Sailor and Floyd (1951)[a]	---	---	First experiments with X-ray
Brown et al. (1953)	11.0(30)	27.3	n.-irr. of ^{40}Ca-enriched Ca ($n_{^{41}Ca}$); X-ray ($A_{^{41}Ca}$)
Drouin and Yaffe (1962)	7.7(11)	14.3	n.-irr. of Ca ($n_{^{41}Ca}$); X-ray ($A_{^{41}Ca}$)
Wahlin (1966)[b]	12.0	---	
Emery et al. (1972)	13.0(20)	15.4	
Mabuchi et al. (1974)	10.3(4)	3.9[g]	n.-irr. of ^{40}Ca-enriched Ca ($n_{^{41}Ca}$); X-ray ($A_{^{41}Ca}$)
Browne and Firestone (1986)	10.3(4)	3.9	Decay data evaluation
Paul et al. (1991)[c,#,§]	10.1(10)	9.9	„standard MS techniques“ ($n_{^{41}Ca}$); X-ray ($A_{^{41}Ca}$)
Klein et al. (1991)	10.3(7)	6.8	Ratio ^{41}Ca/^{36}Cl in Antarctic meteorites
Klein et al. (1991)[d]	19.0(60)	32	Updated values for neutron capture cross section of ^{40}Ca and fluorescence yield of X-rays
Klein et al. (1991)[e]	16.0(25)	16	
Klein et al. (1991)[f]	11.4(5)	4.4[g]	
Cameron and Singh (2001)	10.2(7)	6.9	Decay data evaluation
This work	**9.937 (146)**	**1.47**	**TIMS and LSC**

(a) declare only "several months"
(b) this work is quoted by Emery et al. (1972)
(c) additional re-evaluations of earlier results in accordance with Klein et al. (1991)
(d) re-evaluation of Brown et al. (1953)
(e) re-evaluation of Drouin and Yaffe (1962)
(f) re-evaluation of Mabuchi et al. (1974)
(g) according to an evaluation by Kutschera et al. (1989), at least 30 % are more realistic
a complete report of the study tentatively described by Kutschera et al. (1989)
§ a recalculation by Kossert et al. (2009) yields 10.3 x 10^4 y
n.-irr.: neutron irradiation
$n_{^{41}Ca}$: number of atoms of ^{41}Ca
$A_{^{41}Ca}$: activity of ^{41}Ca

Table 2: Total uncertainty budget of the experimental data for calculation of the half-life of ^{41}Ca.

Component	**Rel. uncertainty in %**		**Parameter**	**Sample No. 1**	**Sample No. 2**
LSC	1.46		Total activity A ^{41}Ca in Bq	1529 ± 22	2076 ± 30
TIMS/Isotope dilution	0.08		Total content Ca in mg	1.360 ± 0.001	1.844 ± 0.001
			Specific Activity a ^{41}Ca in Bq/mg	1124 ± 16	1126 ± 16
TIMS	0.14		Isotopic concentration $n_{^{41}Ca}$ in nmol/mg	8.452 ± 0.014	8.452 ± 0.014
Square root of the sum of quadratic components	**1.47**		**Half-life in 10^4 y[d]**	**9.946 ± 0.146**	**9.929 ± 0.146**