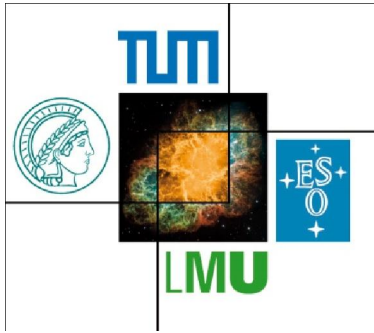


Lehrstuhl E12

Half-Life of ^{60}Fe

Georg Rugel
supported by DFG (EXC 153)



Nuclei in the Cosmos XI, July 19th-23th 2010, Heidelberg

KARLSRUHER NUKLIDKARTE

7. Auflage 2006

CHART OF THE NUCLIDES, 7th Edition 2006

CARTE DES NUCLÉIDES, 7^{ème} Edition 2006

CARTA DE NUCLEIDOS, 7ª Edición 2006

Таблица радионуклидов, 7-е издание 2006

核素图, 第7版

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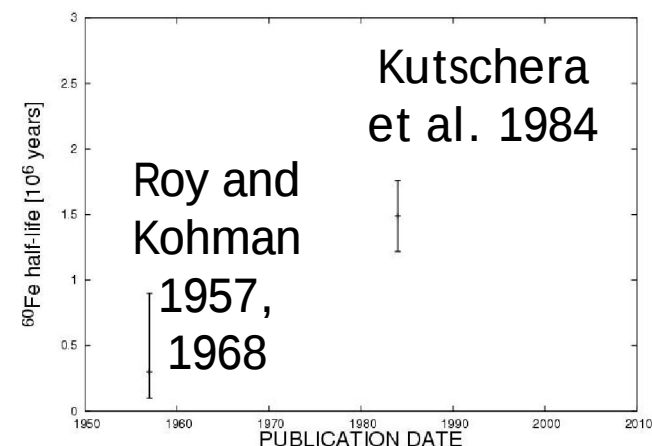
© European Communities, 2006

Status $T_{1/2}$ (^{60}Fe) 02/2009

Fe 60
 $1.5 \cdot 10^6$ a
 $\beta^- 0.1$ m

Zn 57 40 ms β^+ pp 1.92; 2.53; 4.57 γ 2701*	Zn 58 84 ms β^+ γ 203; 848 pp ?	Zn 59 182 ms β^+ 8.1... γ 491; 914 pp 1.78; 2.09; 1.82; 1.38...	Zn 60 2.4 m β^+ 2.5; 3.1... γ 670; 61; 273; 1.82; 1.38...	Zn 61 1.5 m β^+ 4.4... γ 475; 1660; 970...	Zn 62 9.13 h β^+ 0.7 γ 41; 597; 548; 508...	Zn 63 38.1 m β^+ 2.3... γ 670; 962; 1412...	Zn 64 48.268 α 0.74 $\sigma_{n,\alpha}$ 1.1E-5 $\sigma_{n,p}$ <1.2E-5	Zn 65 244.3 d ϵ ; β^+ 0.3 γ 1115... σ 66 $\sigma_{n,\alpha}$ 2.0	Zn 66 27.975 α 0.9 $\sigma_{n,\alpha}$ <2E-5	Zn 67 4.102 α 6.9 $\sigma_{n,\alpha}$ 0.0004	Zn 68 19.024 α 0.072 ± 0.8 $\sigma_{n,\alpha}$ <2E-5
Cu 56 78 ms β^+ γ 2701; 1225; 2506; 2783	Cu 57 199 ms β^+ 7.7... γ 1112	Cu 58 3.20 s β^+ 7.5... γ 1454; 1448; 40...	Cu 59 82 s β^+ 3.8... γ 1332; 1792; 339; 485...	Cu 60 23 m β^+ 2.0; 3.9... γ 1302; 878; 826...	Cu 61 3.4 h β^+ 1.2... γ 283; 556; 67; 1186...	Cu 62 9.74 m β^+ 2.9... γ (1173...)	Cu 63 69.15 α 4.5	Cu 64 12.700 h ϵ ; β^- 0.6 β^+ 0.7 γ (1346) σ ~270	Cu 65 30.85 α 2.17	Cu 66 5.1 m β^- 2.6... γ 1039; (834...) σ 140	Cu 67 61.9 h α 0.4; 0.6... γ 185; 93; 91...
Ni 55 209 ms β^+ 7.7... γ 2919; 2976; 3303	Ni 56 6.075 d ϵ ; no β^+ γ 158; 812; 750; 480; 270...	Ni 57 36.0 h ϵ γ 1378; 1920; 127...	Ni 58 68.0769 α 4.6 $\sigma_{n,\alpha}$ <0.00003	Ni 59 7.5 · 10 ⁴ a ϵ ; β^+ ... no γ ; σ 77.7 $\sigma_{n,\alpha}$ 14; $\sigma_{n,p}$ 2 σ_{fission} 92	Ni 60 26.2231 α 2.9	Ni 61 1.1399 α 2.5 $\sigma_{n,\alpha}$ 0.00003	Ni 62 3.6345 α 15	Ni 63 100 a α 0.07 σ 20	Ni 64 0.9256 α 1.6	Ni 65 2.52 h α 2.1... γ 1482; 1115; 366...	Ni 66 54.6 h β^- 0.2 no γ
Co 54 1.48 m 1932 ms β^+ 4.3 γ 411; 1130; 1407	Co 55 17.54 h β^+ 1.5... γ 931; 477; 1409...	Co 56 77.26 d ϵ ; β^+ 1.5... γ 847; 1238; 2598; 1771; 1038...	Co 57 271.79 d ϵ γ 122; 136; 14	Co 58 70.86 d ϵ ; β^+ 0.5... γ 811 σ 140000 σ 1900	Co 59 100 α 20.7 ± 16.5	Co 60 5.272 a β^- 0.5; 1.6... γ 1099; 1292... σ 13	Co 61 1.6 h β^- 1.2... γ 67; 909...	Co 62 14.0 m 1.5 m β^- 2.9... γ 1175; 1173; 1163; 2302; 366... σ 1129	Co 63 27.5 s β^- 3.6... γ 87; 982...	Co 64 0.3 s β^- 7.0... γ 1346; 931	Co 65 1.14 s β^- 6.0... γ 1142; 311; 964...
Fe 53 2.5 m β^+ 2.8... γ 378; 1011; 2340...	Fe 54 8.51 m ϵ 2.3 $\sigma_{n,\alpha}$ 1E-5	Fe 55 2.73 a ϵ σ 13 $\sigma_{n,\alpha}$ 0.01	Fe 56 91.754 α 2.8	Fe 57 2.119 α 1.4	Fe 58 0.282 α 1.3	Fe 59 44.503 d β^- 0.5; 1.6... γ 1099; 1292... σ 13	Fe 60 1.5 · 10 ⁶ a β^- 0.1	Fe 61 6.0 m β^- 2.6; 2.8... γ 1205; 1027; 298...	Fe 62 68 s β^- 5.05 γ 506 g	Fe 63 6.1 s β^- 6.7... γ 995; 1427; 1299...	Fe 64 2.0 s β^- > 3.7 γ 356
Mn 52 21 m 5.6 d β^+ 2.6... γ 1434; 936; 14738	Mn 53 3.7 · 10 ⁶ a ϵ no γ σ 70	Mn 54 312.2 d ϵ γ 835 σ <10	Mn 55 100 α 13.3	Mn 56 2.58 h β^- 2.9... γ 847; 1811; 2113...	Mn 57 1.5 m β^- 2.6... γ 14; 122; 692...	Mn 58 3.0 s β^- 3.9... γ 811; 1323... γ 1447; 172... 2433...	Mn 59 4.6 s β^- 4.4; 4.8... γ 726; 473; 571...	Mn 60 0.28 s β^- 5.7... γ 826; 1150; γ 272 1532	Mn 61 0.71 s β^- 6.4... γ 629; 207...	Mn 62 92 ms 625 ms β^- 8.77; 942; 1299...	Mn 63 0.25 s β^- > 3.7 γ 356
Cr 51 27.70 d ϵ γ 320 σ <10	Cr 52 83.789 α 0.8	Cr 53 9.501 α 18	Cr 54 2.365 α 0.36	Cr 55 3.50 m β^- 2.6 γ (1528...)	Cr 56 5.9 m β^- 1.5 γ 83; 26	Cr 57 21.1 s β^- 5.1... γ 83; 850; 1752; 1535...	Cr 58 7.0 s β^- γ 683; 126; 290; 520... m	Cr 59 1.05 s β^- γ 1238; 1900; 112; 663...	Cr 60 0.49 s β^- 6.7... γ 349; 410; 758 g	Cr 61 0.27 s β^-	Cr 62 209 ms β^- γ 285; 355; 640... m

(1.49 ± 0.27) Myr

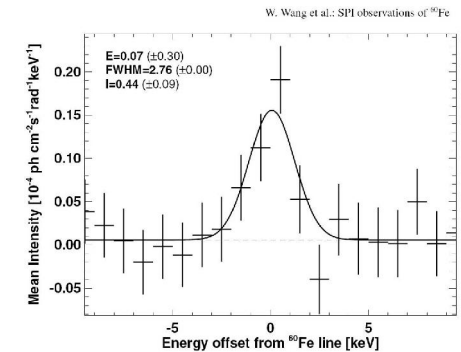
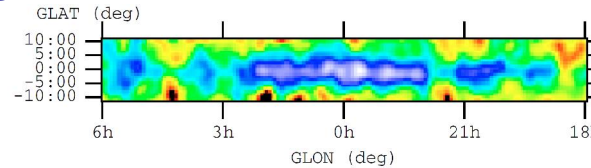


Motivation $T_{1/2}^{60\text{Fe}}$



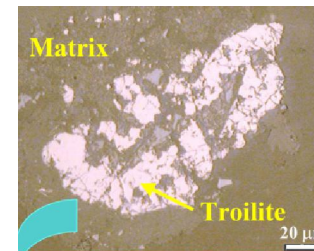
- Nucleosynthesis in the Galaxy**

see e.g talk NIC_XI_333 R. Diehl

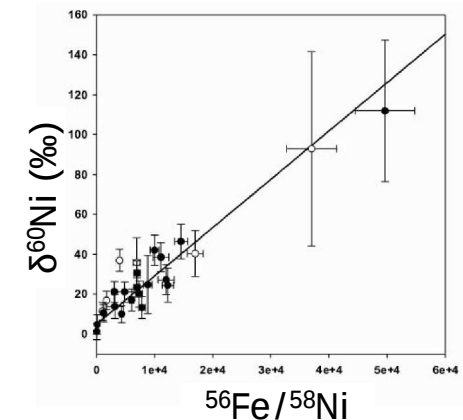


- History of the Early Solar System**

e.g. A. Shukolyukov and G.W. Lugmair, Science 1993

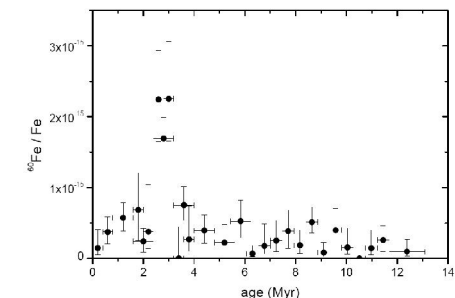


e.g: S. Mostefaoui et al., 2005



- Deposits of supernova ejecta on Earth**

e.g. K. Knie et al., PRL 2004;
C. Fitoussi et al., PRL 2008

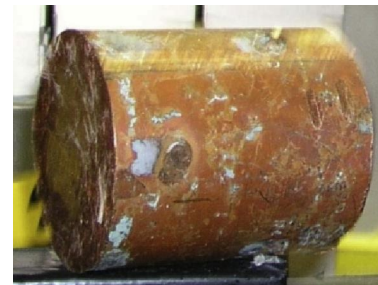


We need ^{60}Fe !

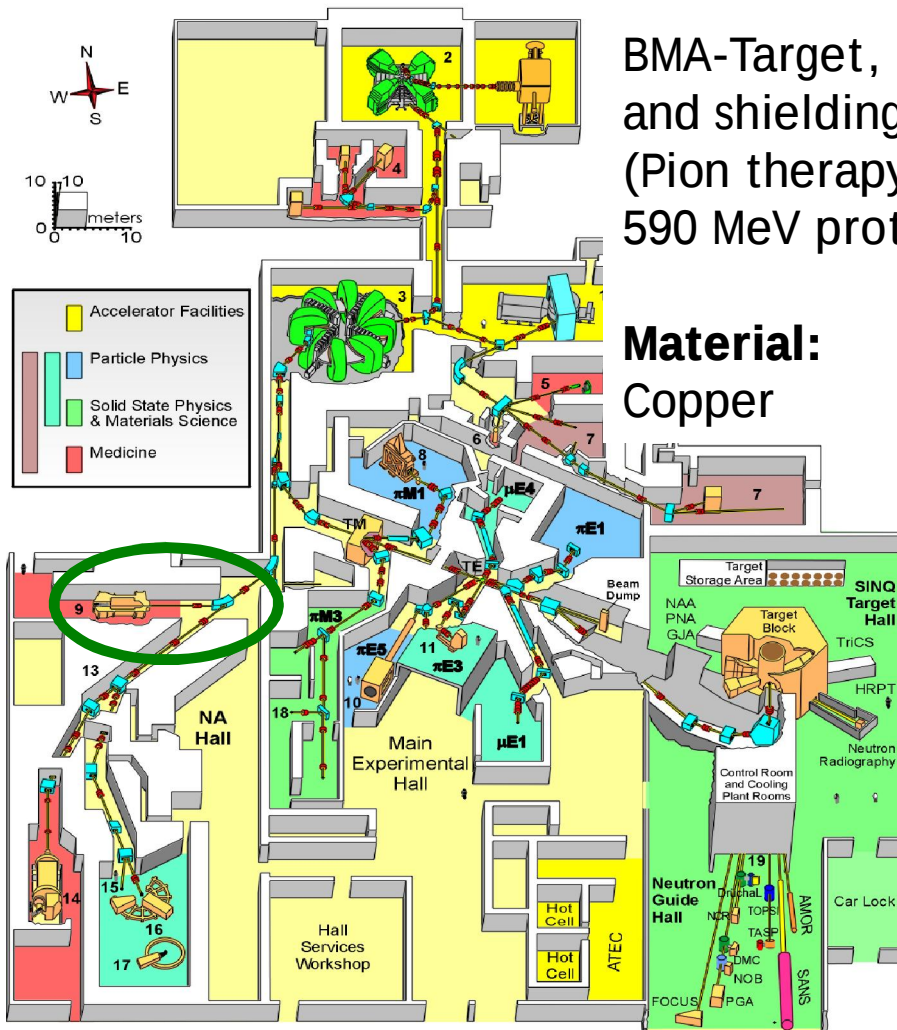
$$A_{^{60}\text{Fe}} = \lambda_{^{60}\text{Fe}} \cdot N_{^{60}\text{Fe}} = \frac{\ln(2)}{T_{1/2}(^{60}\text{Fe})} \cdot \frac{N_{^{60}\text{Fe}}}{N_{\text{Fe}}} \cdot N_{\text{Fe}}$$

BMA-Target, Beam dump and shielding
(Pion therapy station,
590 MeV protons, 0.1Ah)

Material:
Copper



Irradiated from
1980 till Sept. 1992

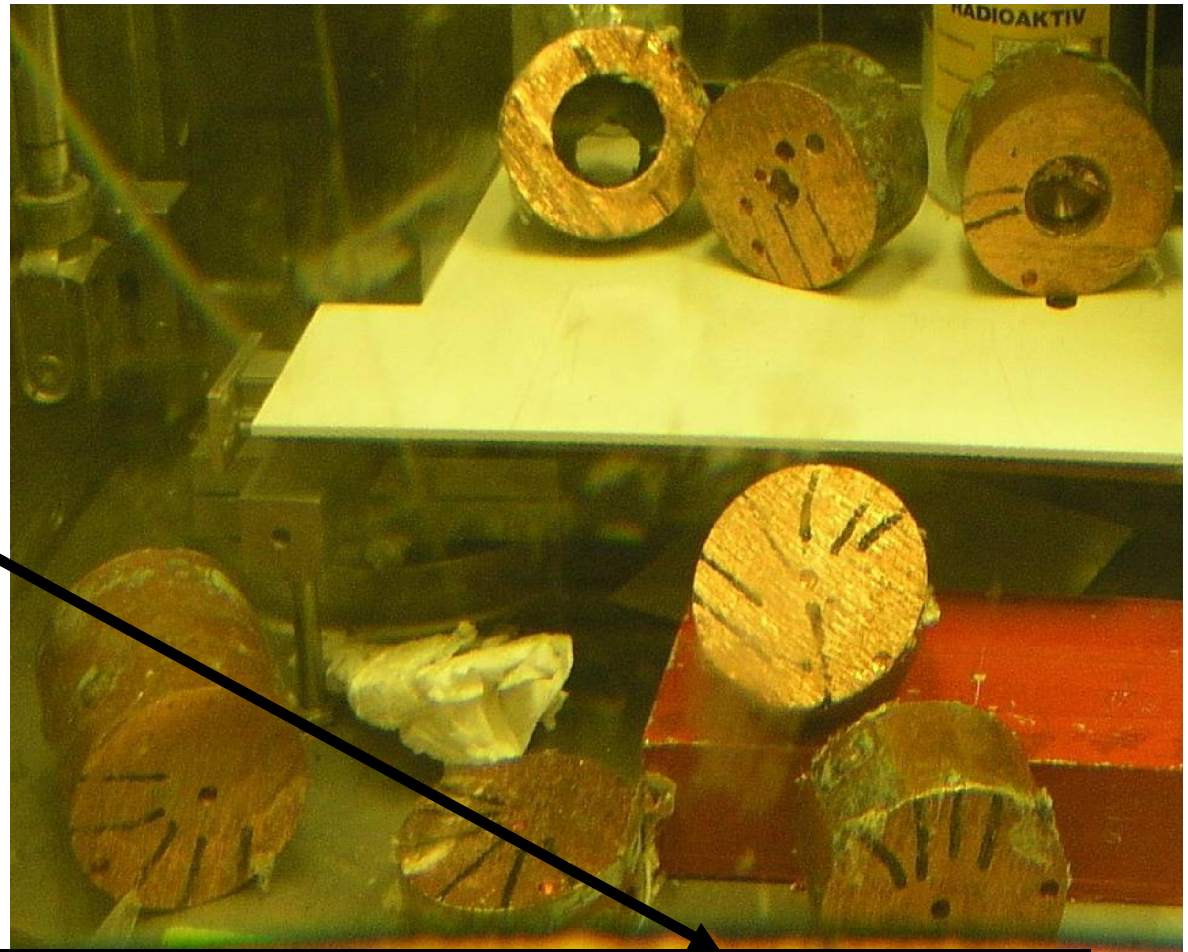


Zn 58 84 ms β^+ 8.1... γ 203, 848 β ?	Zn 59 182 ms β^+ 8.1... γ 491, 914 β 1.78; 2.09; 1.82; 1.38...	Zn 60 2.4 m β^+ 2.5; 3.1... γ 670; 61; 273; 334...	Zn 61 1.5 m β^+ 4.4... γ 475; 1660; 970...	Zn 62 9.13 h β^+ 0.7... γ 41; 597; 548; 508...	Zn 63 38.1 m β^+ 2.3... γ 41; 597; 548; 1412...	Zn 64 48.268 α 0.74 α_n, α 1.1E-5 α_n, α <1.2E-5	Zn 65 244.3 d β^+ 0.3... γ 1115... α 66 α_n, α 2.0	Zn 66 27.975 α 0.9 α_n, α <2E-5	Zn 67 4.102 α 6.9 α_n, α 0.0094	Zn 68 19.024 α 0.072 + 0.8 α_n, α <2E-5
Cu 57 169 ms β^+ 7.7... γ 1112	Cu 58 3.20 s β^+ 7.5... γ 1454; 1448; 40...	Cu 59 82 s β^+ 3.8... γ 1302; 878; 339, 465...	Cu 60 23 m β^+ 2.0; 3.9... γ 1332; 1792; 826...	Cu 61 3.4 h β^+ 1.2... γ 283; 656; 67; 1186...	Cu 62 9.74 m β^+ 2.9... γ (1173...)	Cu 63 69.15 α 4.5	Cu 64 12.700 h β^+ 0.6... β 0.7... γ (1346) α ~270	Cu 65 30.85 α 2.17	Cu 66 5.1 m β^- 2.6... γ 1039; (834...) α 140	Cu 67 61.9 h β^- 0.4; 0.6... γ 185; 93, 91...
Ni 56 6.075 d ϵ ; no β^+ γ 158, 812; 750; 880; 270	Ni 57 36.0 h ϵ ; β^+ 0.8... γ 1376; 1920; 127	Ni 58 68.0769 ϵ ; β^+ ... α 4.6 α_n, α <0.00003	Ni 59 7.5 · 10 ⁴ a ϵ ; β^+ ... γ 77.7 α_n, α 14; α_n, α 2 α 82	Ni 60 26.2231 α 2.9	Ni 61 1.1399 α 2.5 α_n, α 0.00003	Ni 62 3.6345 α 15	Ni 63 100 a β^- 0.07 α 20	Ni 64 0.9256 α 1.6	Ni 65 2.52 h β^- 2.1... γ 1482; 1115; 366... α 22	Ni 66 54.6 h β^- 0.2
Co 55 17.54 h β^+ 1.5... γ 931; 477; 1409...	Co 56 77.26 d ϵ ; β^+ 1.5... γ 847; 1238; 2508; 1771; 1038...	Co 57 271.79 d ϵ ; β^+ ... γ 122; 136; 14	Co 58 8.94 h 70.86 d ϵ ; β^+ 0.5... γ 811 α 140000 α 1900	Co 59 100 α 20.7 + 16.5	Co 60 10.5 m 5.272 a β^- 0.3... γ 59 β 0.3... γ 1332; 1173 α 25 α 2003, 1129...	Co 61 1.65 h β^- 1.2... γ 67; 909...	Co 62 14.0 m 1.5 m β^- 2.9... γ 1173; 1103, 2302; γ 67; 982...	Co 63 27.5 s β^- 3.6... γ 1346; 931	Co 64 0.3 s β^- 7.0... γ 1142; 311; 964...	Co 65 1.14 s β^- 8.0... γ 1142; 311; 964...
Fe 54 5.845 α 2.3 α_n, α 1E-5	Fe 55 2.73 a α 1.5... α_n, α 0.01	Fe 56 91.754 α 2.8	Fe 57 2.119 α 1.4	Fe 58 0.282 α 1.3	Fe 59 44.503 d β^- 0.5; 1.6... γ 1099; 1292... α 13	Fe 60 1.5 · 10 ⁶ a β^- 0.1 α 1	Fe 61 6.0 m β^- 2.6; 2.8... γ 1205; 1027; 298...	Fe 62 68 s β^- 2.5 γ 506 1299...	Fe 63 6.1 s β^- 6.7... γ 995; 1427; 1299...	Fe 64 2.0 s β^- > 3.7 γ 356
Mn 53 3.7 · 10 ⁶ a ϵ ; no γ α 70	Mn 54 312.2 d ϵ ; γ 835 α <10	Mn 55 100 α 13.3	Mn 56 2.58 h β^- 2.9... γ 847; 1811; 2113...	Mn 57 1.5 m β^- 2.6... γ 14; 122; 692...	Mn 58 55.3 s 3.0 s β^- 3.9... γ 811; 1323 α 72; α 3433...	Mn 59 4.6 s β^- 4.4; 4.8... γ 726; 473; 571...	Mn 60 1.77 s 0.28 s β^- 5.7... γ 811; 1323 α 72; α 1502	Mn 61 0.71 s β^- 6.4... γ 629; 207...	Mn 62 92 ms 625 ms β^- 6.7... γ 811 1299...	Mn 63 0.25 s β^- > 3.7 γ 356

Drilling a hole into
central part:

3.86g copper

Activation measurement
of 2kg of the beamdump:



Date	Activity ^{60}Co [Bq]	^{60}Co atoms	Initial sample ^{60}Co	
			[Bq]	atoms
01.09.1992	7×10^9	1.8×10^{18}	1.4×10^7	3.5×10^{15}
08.07.2005	1.4×10^9	3.3×10^{17}	2.6×10^6	6.4×10^{14}



$$A_{60\text{Fe}} = \lambda_{60\text{Fe}} \cdot N_{60\text{Fe}} = \frac{\ln(2)}{T_{1/2}(^{60}\text{Fe})} \cdot \frac{N_{60\text{Fe}}}{N_{\text{Fe}}} \cdot N_{\text{Fe}}$$

Volume: 4000 μl
from master solution ($\sim 1\text{nHCl}$)
Weight: 4.036 g
+ 1000 μl H_2O

→ Germanium detector

Same material used for ICP-MS
(March 2008)





$$A_{60\text{Fe}} = \lambda_{60\text{Fe}} \cdot N_{60\text{Fe}} = \frac{\ln(2)}{T_{1/2}(^{60}\text{Fe})} \cdot \frac{N_{60\text{Fe}}}{N_{\text{Fe}}} \cdot N_{\text{Fe}}$$

Efficiency calibration of the detector:

Avoiding geometrical corrections etc.

Calibration source (^{60}Co) with
the same geometry:

5ml 0.1 nHCl

102.0 (± 1.5) Bq ^{60}Co

(all uncertainties 1 sigma)



Germanium detector





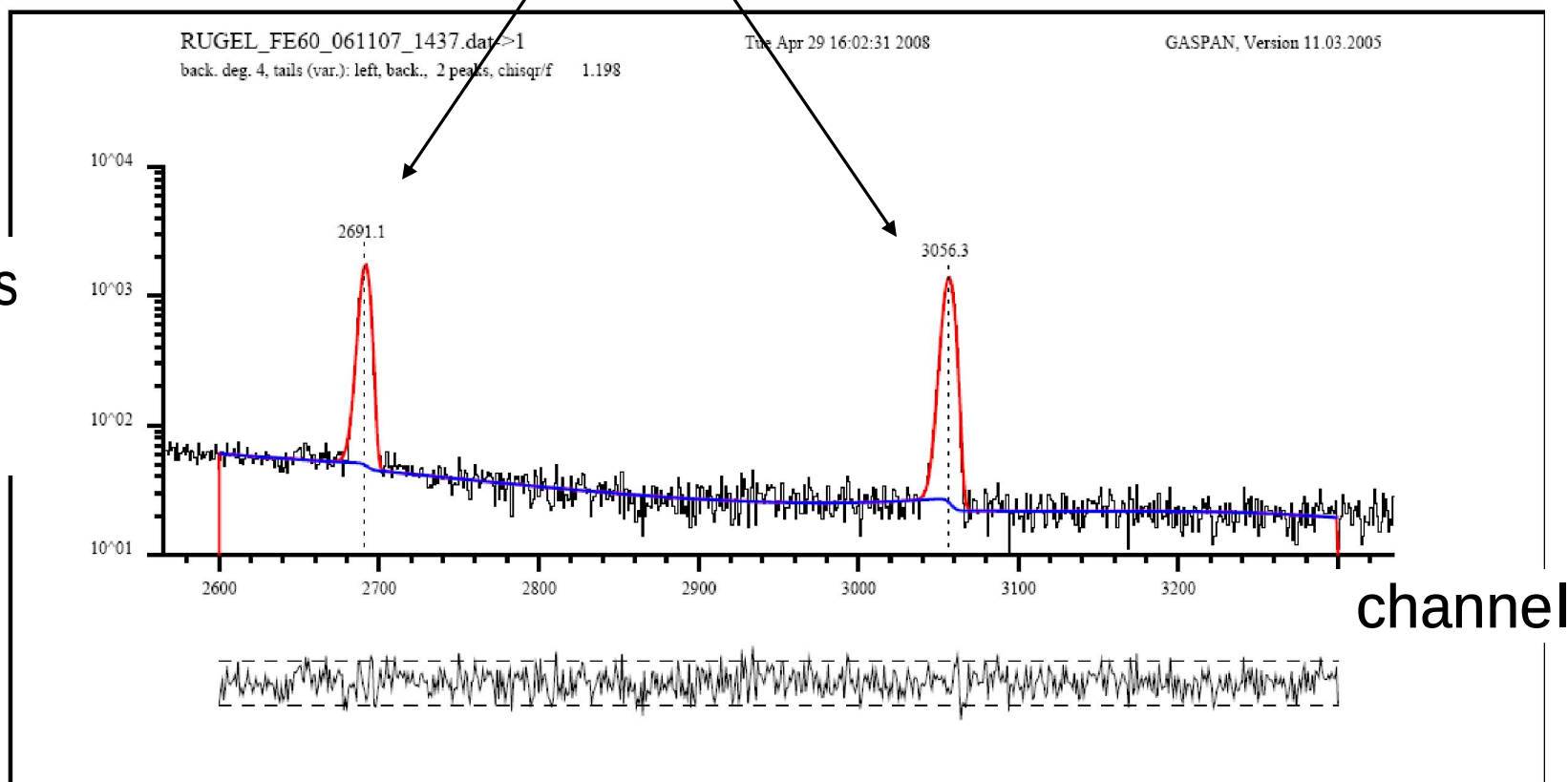
$$A_{60\text{Fe}} = \lambda_{60\text{Fe}} \cdot N_{60\text{Fe}} = \frac{\ln(2)}{T_{1/2}(^{60}\text{Fe})} \cdot \frac{N_{60\text{Fe}}}{N_{\text{Fe}}} \cdot N_{\text{Fe}}$$

^{60}Co

12710±130 cts

11450±120 cts

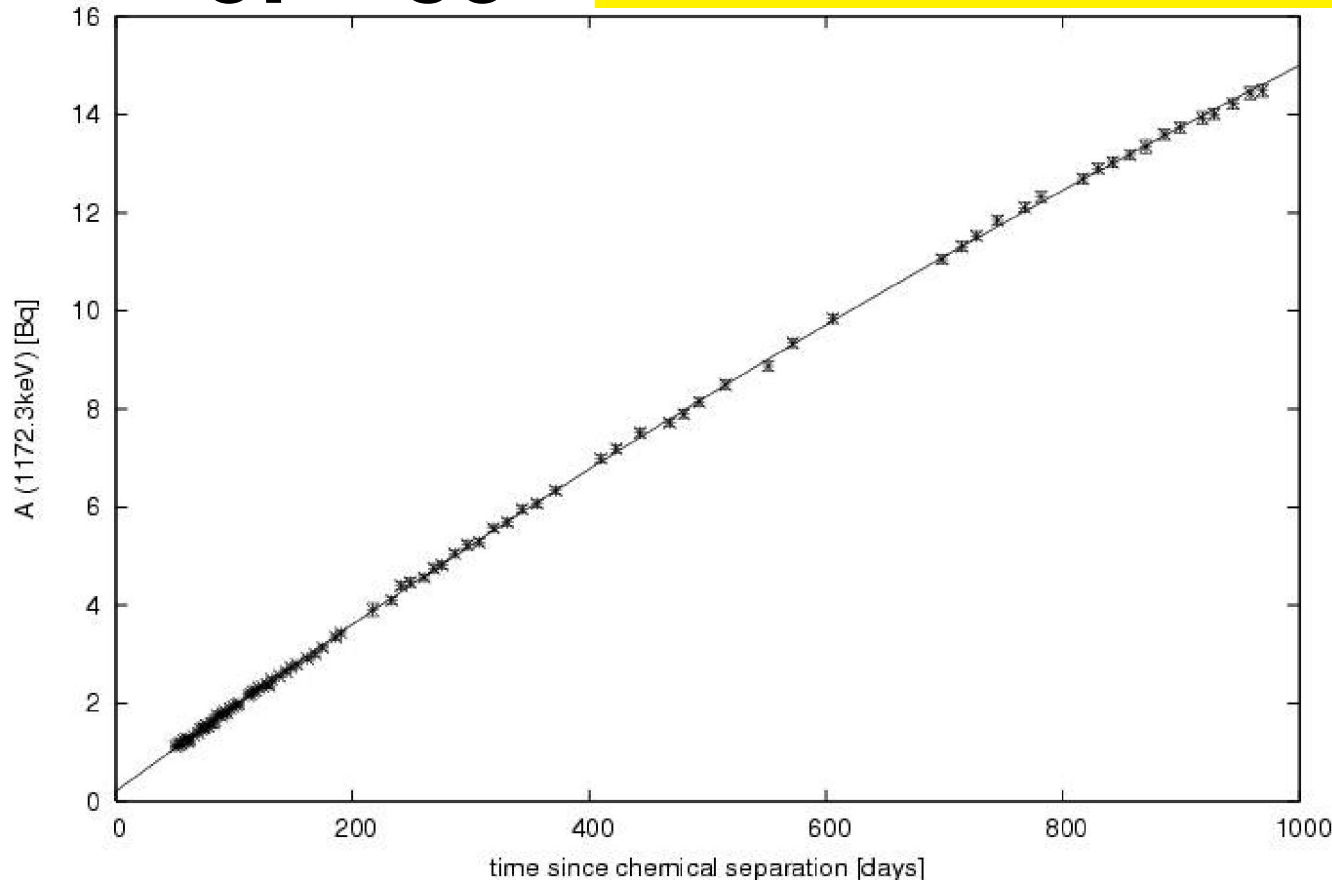
Counts
log
scale





Build-up of ^{60}Co

$$A_{^{60}\text{Fe}} = \lambda_{^{60}\text{Fe}} \cdot N_{^{60}\text{Fe}} = \frac{\ln(2)}{T_{1/2}(^{60}\text{Fe})} \cdot \frac{N_{^{60}\text{Fe}}}{N_{\text{Fe}}} \cdot N_{\text{Fe}}$$



$T=0$

$^{60}\text{Co} \sim 0.2 \text{ Bq}$

***Chemical
reduction at
least 10^7 !***

***Saturation
activity***

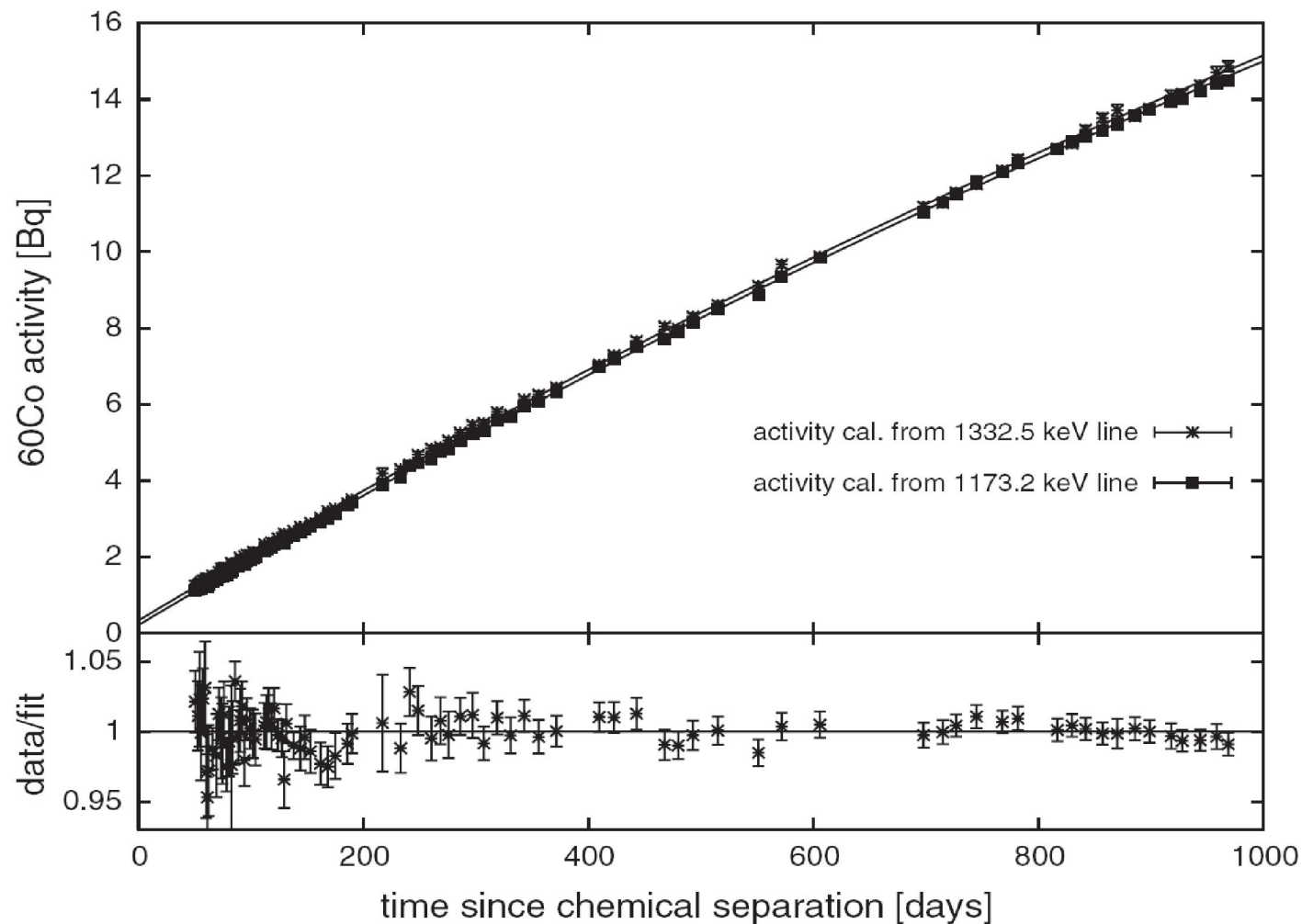
$49.14 \pm 0.08 \text{ Bq}$

$$A_{^{60}\text{Co}} = N_{^{60}\text{Fe}} \lambda_{^{60}\text{Fe}} \cdot (1 - e^{-\lambda_{^{60}\text{Co}} \cdot t})$$

$$\approx N_{^{60}\text{Fe}} \cdot \lambda_{^{60}\text{Fe}} \cdot \lambda_{^{60}\text{Co}} \cdot t$$

for $t \ll T_{1/2, ^{60}\text{Co}}$

Lower Data Normalized to the Fit



Combined result: 49.19 ± 0.11 Bq



**Master Sample
(TUM)
transferred to
PSI**

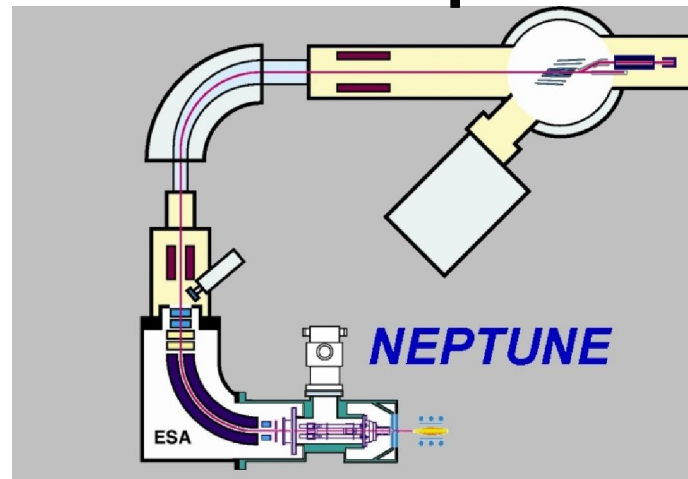
$$A_{60\text{Fe}} = \lambda_{60\text{Fe}} \cdot N_{60\text{Fe}} = \frac{\ln(2)}{T_{1/2}(^{60}\text{Fe})} \cdot \frac{N_{60\text{Fe}}}{N_{\text{Fe}}} \cdot N_{\text{Fe}}$$

Determination of N
Subsamples taken
gravimetrically after opening

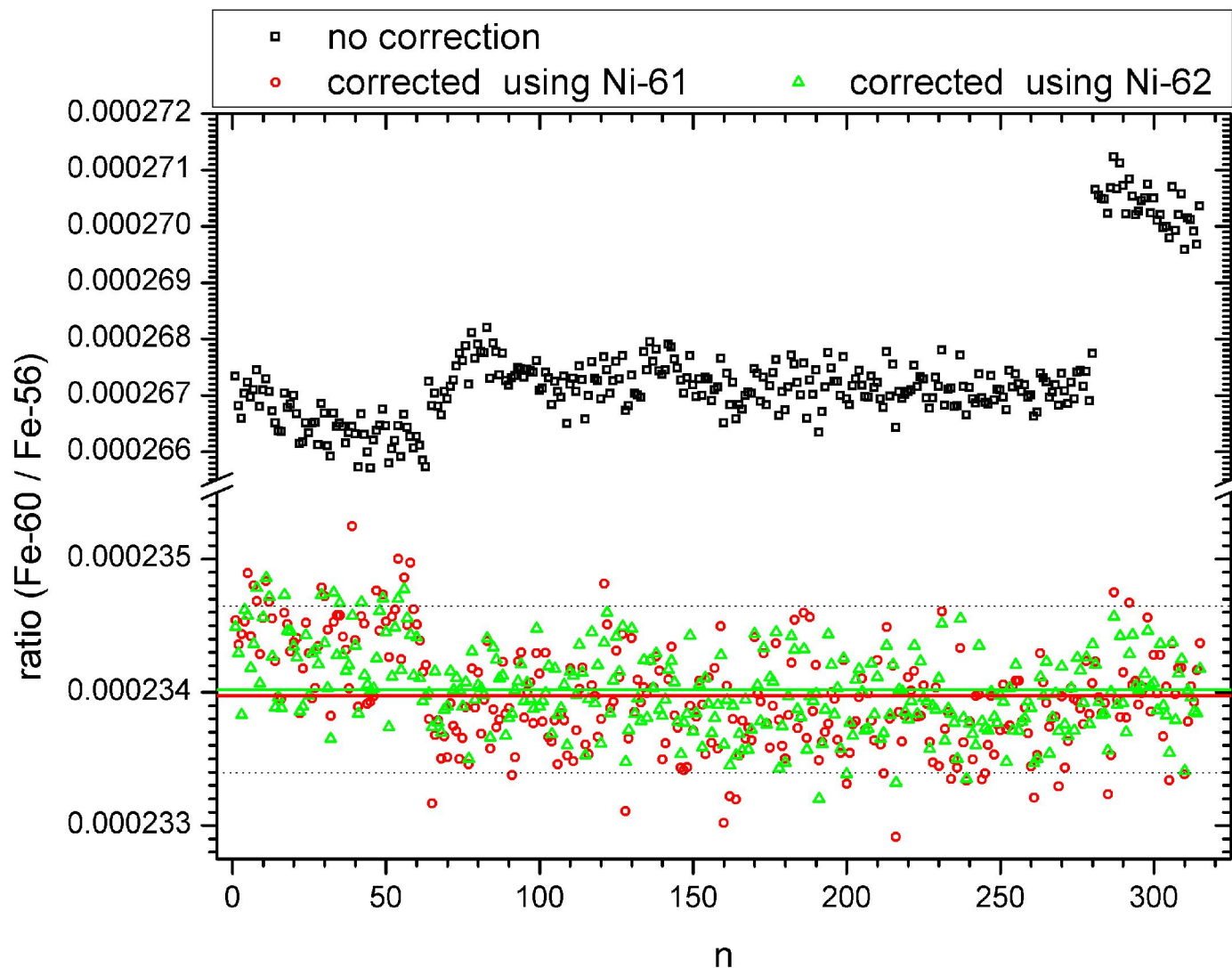
$$\frac{N_{60\text{Fe}}}{N_{\text{Fe}}}$$

$$\cdot N_{\text{Fe}}$$

**Multicollector - Inductively Coupled
Plasma Mass Spectrometry MC-ICP-MS**



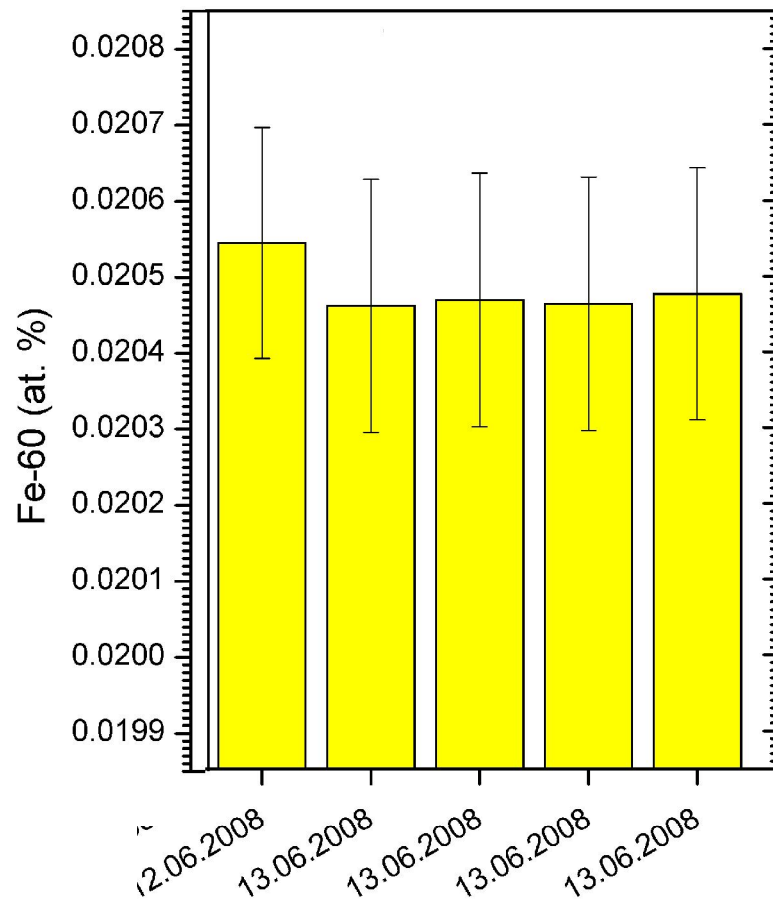
^{60}Ni interference correction



**Uncertainty:
0.17% !**

Isotopic composition

$$A_{60\text{Fe}} = \lambda_{60\text{Fe}} \cdot N_{60\text{Fe}} = \frac{\ln(2)}{T_{1/2}(^{60}\text{Fe})} \cdot \frac{N_{60\text{Fe}}}{N_{\text{Fe}}} \cdot N_{\text{Fe}}$$

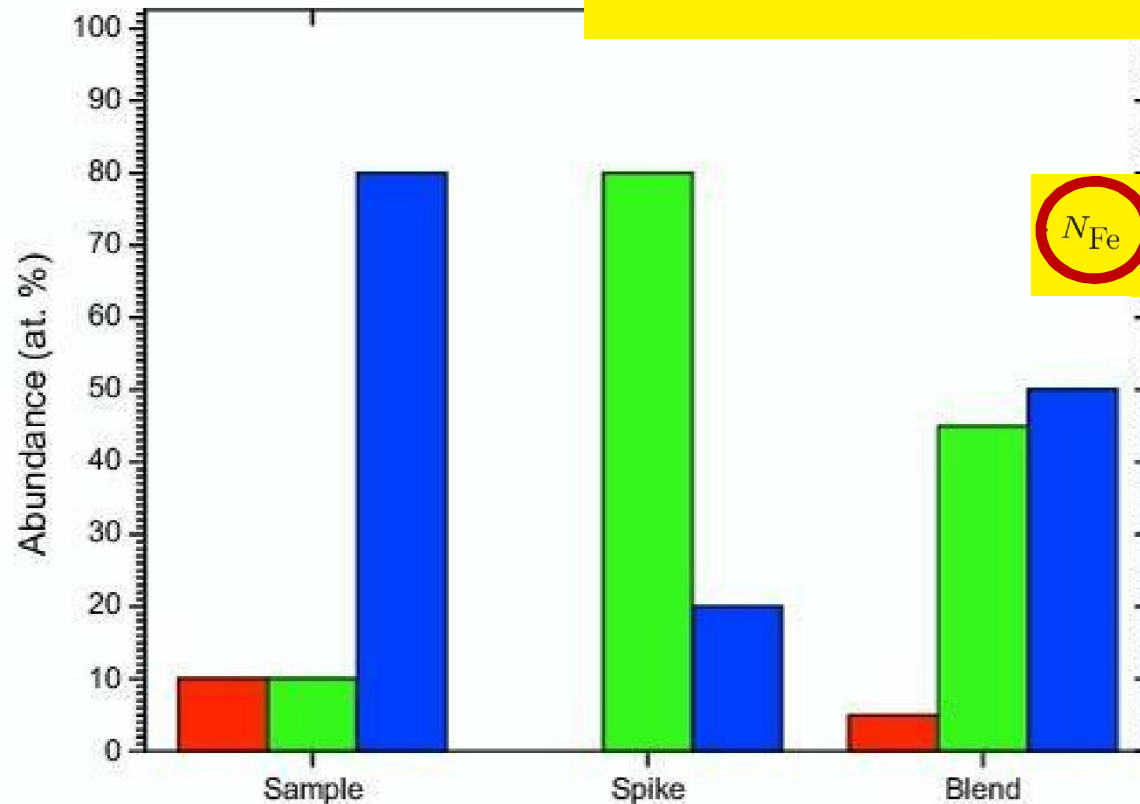


$(2.0483 \pm 0.0035) \times 10^{-4}$

Isotope Dilution MS

isotope	⁵⁴ Fe	⁵⁶ Fe	⁵⁷ Fe	⁵⁸ Fe
percentage [%]	-	3.11	95.10	1.79

$$A_{60\text{Fe}} = \lambda_{60\text{Fe}} \cdot N_{60\text{Fe}} = \frac{\ln(2)}{T_{1/2}({}^{60}\text{Fe})} \cdot \frac{N_{60\text{Fe}}}{N_{\text{Fe}}} \cdot N_{\text{Fe}}$$



$$N_{\text{Fe}} (2.662 \pm 0.009) \text{ mg}$$

$$A_{60\text{Fe}} = \lambda_{60\text{Fe}} \cdot N_{60\text{Fe}} = \frac{\ln(2)}{T_{1/2}(^{60}\text{Fe})} \cdot \frac{N_{60\text{Fe}}}{N_{\text{Fe}}} \cdot N_{\text{Fe}}$$

TABLE II: The various contributions to the uncertainty (1σ) of the three measurements are listed.

	Rel. Uncertainty [%]	
	stat.	syst.
$A_{60\text{Fe}}$ (<i>master sample</i>)		
^{60}Co standard		1.5%
fit	0.23%	
N_{Fe} (<i>ID sample</i>)		
weighing		0.18%
ID-ICP-MS	0.28%	
$N_{60\text{Fe}}/N_{\text{Fe}}$ (<i>N sample</i>)		
ICPMS	0.18%	
total	0.4%	1.51%

Combination

$$A_{60\text{Fe}} = \lambda_{60\text{Fe}} \cdot N_{60\text{Fe}} = \frac{\ln(2)}{T_{1/2}(^{60}\text{Fe})} \cdot \frac{N_{60\text{Fe}}}{N_{\text{Fe}}} \cdot N_{\text{Fe}}$$

$$(2.62 \pm 0.04) \times 10^6 \text{ yr}$$

PRL **103**, 072502 (2009)

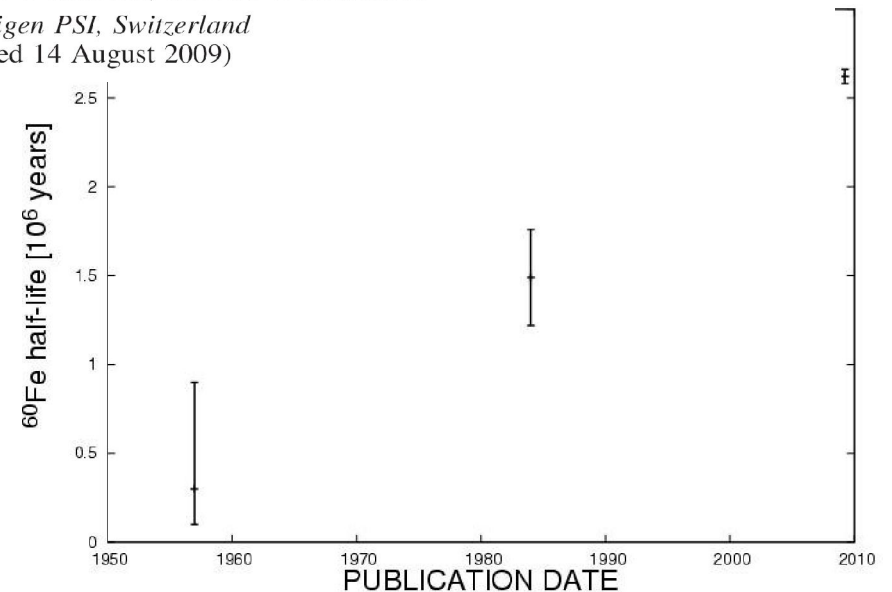
PHYSICAL REVIEW LETTERS

week ending
14 AUGUST 2009

New Measurement of the ^{60}Fe Half-Life

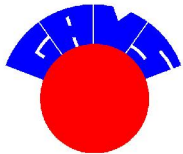
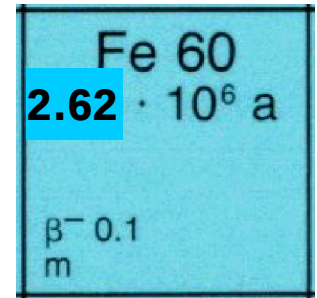
G. Rugel, T. Faestermann, K. Knie,* G. Korschinek, and M. Poutivtsev
Technische Universität München, D-85748 Garching, Germany

D. Schumann, N. Kivel, I. Günther-Leopold, R. Weinreich, and M. Wohlmuther
Paul Scherrer Institut, CH-5232 Villigen PSI, Switzerland
(Received 25 March 2009; published 14 August 2009)



TOI: $T_{1/2}(^{60}\text{Fe}): (1.49 \pm 0.27) \text{ Myr}$

Thanks to my colleagues



Georg Rugel, Thomas Faestermann, Klaus Knie,
Gunther Korschinek, Mikhail Poutivtsev
Technische Universität München



Dorothea Schumann, Regin Weinreich, Ines Günther-Leopold,
Niko Kivel, Michael Wohlmuther
Paul Scherrer Institut, Villigen, Switzerland