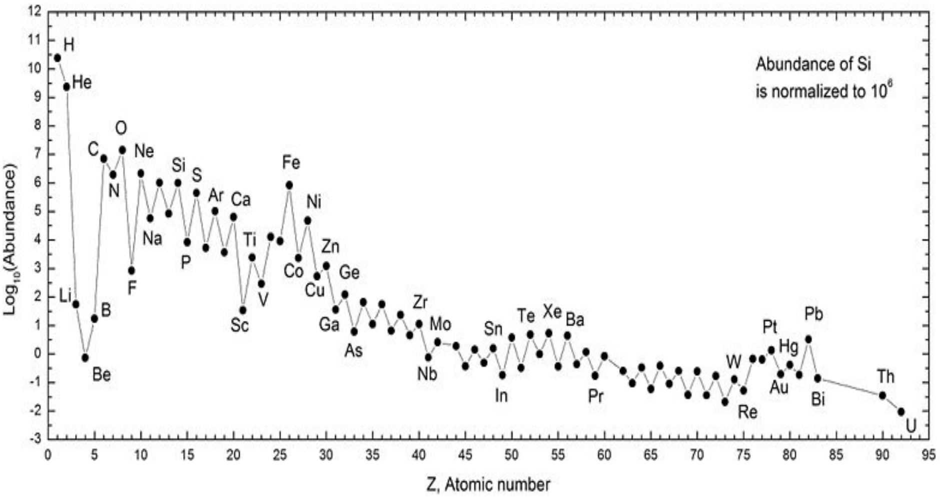
DUST-BUSTER– A new instrument of laser ionization of secondary neutrals time-of-flight mass spectrometer for isotopic analysis of pre-solar grains

Chun-Yen Chen[1], Typhoon Lee[1], Jason J-S. Shen[1]
Wally F. Calaway[2], Igor V. Veryovkin[2], Michael J. Pellin[2]
Norbert Thonnard[3]
1: Institue of Earth Sciences, Academia Sinica, Taipei, Taiwan
2: Materials Science Division, Argonne National Laboratory, Argonne, IL 60439, USA
3:University of Tennesse, Knoxville, TN 37996, USA

Presented at NTHU on June 8th, 2010

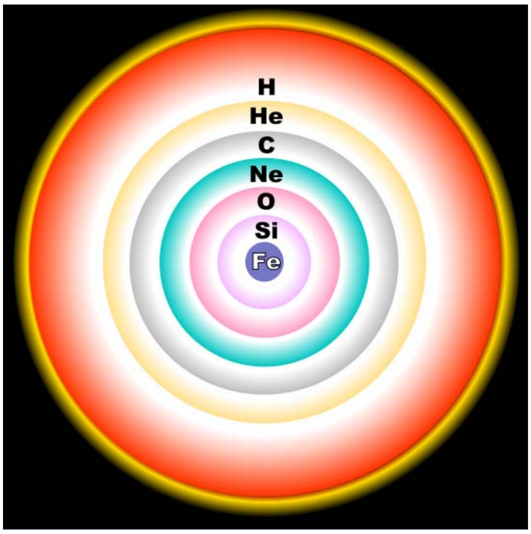
Relative abundance of the chemical elements in the solar system



http://upload.wikimedia.org/wikipedia/en/7/70/SolarSystemAbundances.jpg

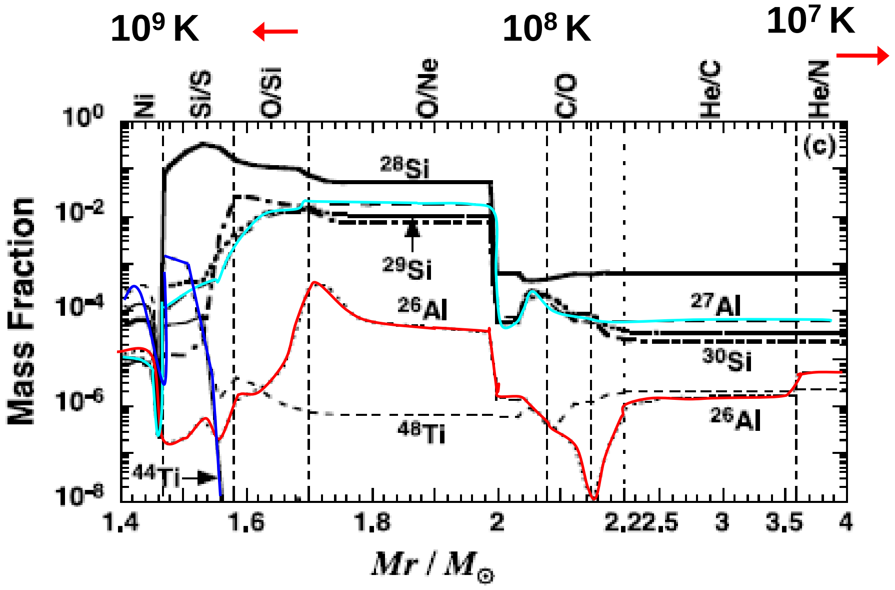
Understanding the origin of the chemical elements : where and how?

General understandings:
Big Bang nucleosynthesis : P, D, He, Li, Be
Stellar nucleosynthesis:
Elements from C to Fe : fusion processes
Heavier than Fe :
    neutron rich elements: S-process--AGB
        R-process--SNe
    proton rich elements: Rp-process--accreting binary stars
        P-process—photo-disintegration-- SNe



http://upload.wikimedia.org/wikipedia/commons/thumb/3/37/Evolved_star_fusion_shells.svg/550px-Evolved_star_fusion_shells.svg.png

Model calculation of nucleosynthesis from the beginning of core He-burning to supernova explosion for a $4M_{\odot}$ He star (Yoshida, T. 2004, ApJ, 606, 592)



中央研究院
Academia Sinica
地球科學研究所
Institute of Earth Sciences

Proofs of the theoretical predictions by astronomy observations

Evidence of nucleosynthesis in stars: Detection of Technetium absorption lines in certain red giants

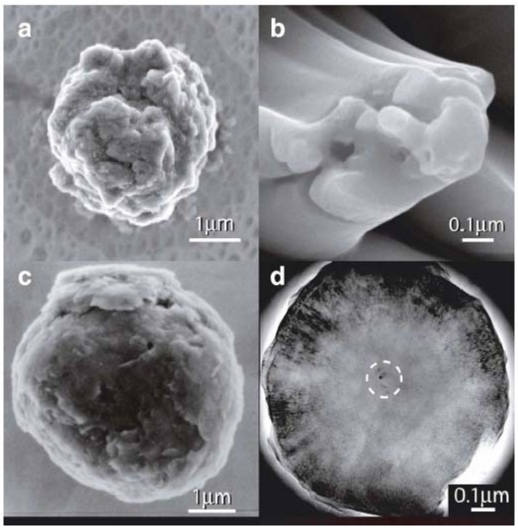
(Paul R. Merrill : “Spectroscopic observations of stars of class S ; Astrophysical Journal, vol. 116, p.21 (1952))

Tc has no stable isotopes; longest half-life ~ Myrs;
→Tc isotopes are synthesized fresh in the stars

Evidence of supernova nucleosynthesis: Detection of ^{56}Co and ^{57}Co gamma-ray lines from supernova 1987A.

Explosive Si-burning produces large amounts of ^{56}Ni, ^{44}Ti
^{56}Ni ($t_{1/2}$ ~ 6 days) → ^{56}Co ($t_{1/2}$~77days)→^{56}Fe

STAR DUSTS : Fossils of stars



3 µm
SiC grain

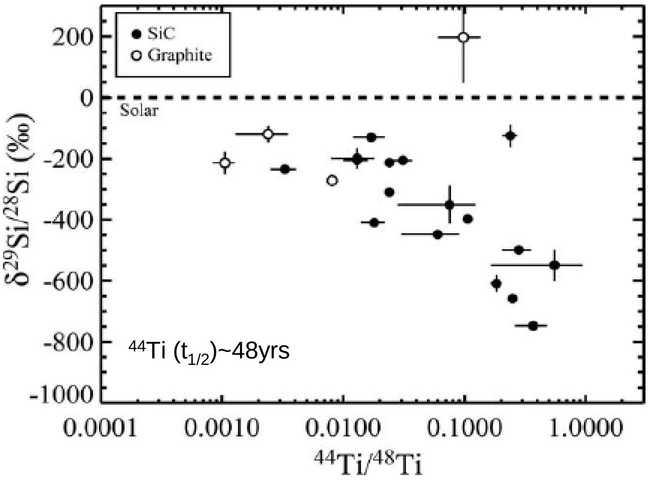
5 µm
graphite grain

TEM image of a
100nm thick slice of a
1 µm graphite grain

Dotted circle:
TiC subgrains

Larry R. Nittler: EPSL 209 (2003) 259-273

Laboratory experiments to prove supernova nucleosynthesis



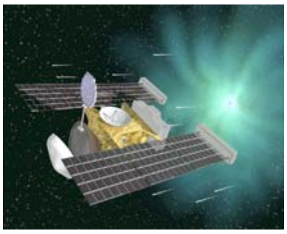
^{44}Ti ($t_{1/2}$)~48yrs

Figure 6 $\delta^{29}Si$ values plotted versus inferred $^{44}Ti/^{48}Ti$ ratios for supernova SiC and graphite grains (Besmehn & Hoppe 2003, Hoppe et al. 2000, Nittler et al. 1996). The presence of extinct ^{44}Ti in the grains proves a supernova origin.

Annu. Rev. Astro. Astrophys. 2004. 42:39-78 D. D. Clayton and L.R. Nittler

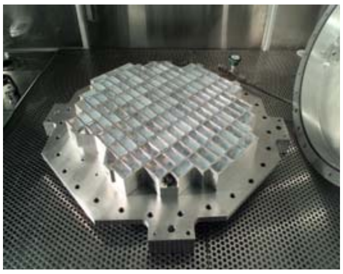
NASA STARDUST comet sample return mission

Cometary dusts collected : Jan. 2, 2004
Earth returned : Jan. , 2006



Description by artist about STARDUST spacecraft flying by comet Wild-2

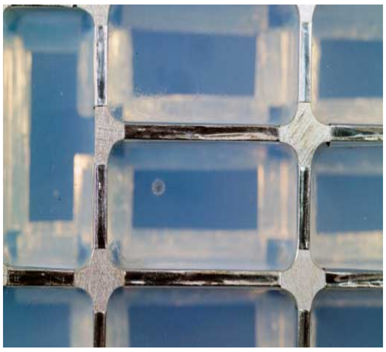
http://stardust.jpl.nasa.gov



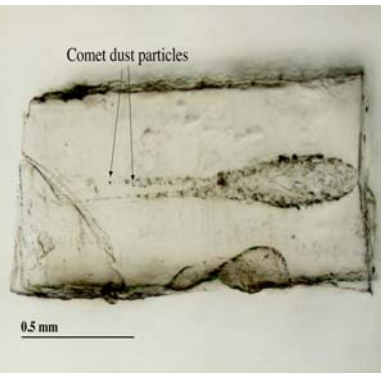
Aerogel collector; porous silica

Sample Return Capsule landed in Utah. Jan. 2006

View of a cometary impact into aerogel



X-ray Tomography Images of Wild-2 Comet Particles and Tracks in Aerogel (images by NASA/JPL)



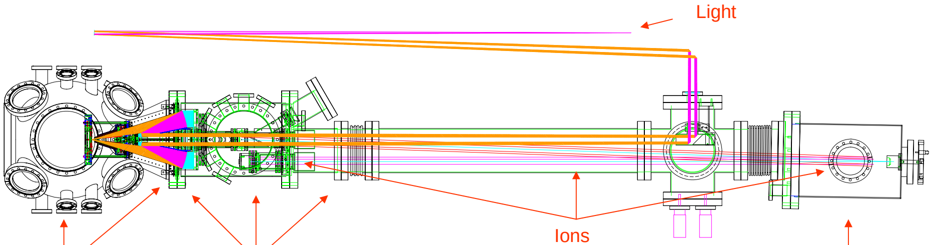
Goal : look for large isotope effect in small grains

Cover as many as isotope ratios over large mass range in order to examine the structure of individual source star of solar system nuclides.

Technical challenge

Dust size < 1 μm
Weight ~10^{-12} gram
Atom numbers ~ 10^{10}
3σ ~ 10% effect

The new laser-SNMS instrument for Genesis by ANL



Light

Ions

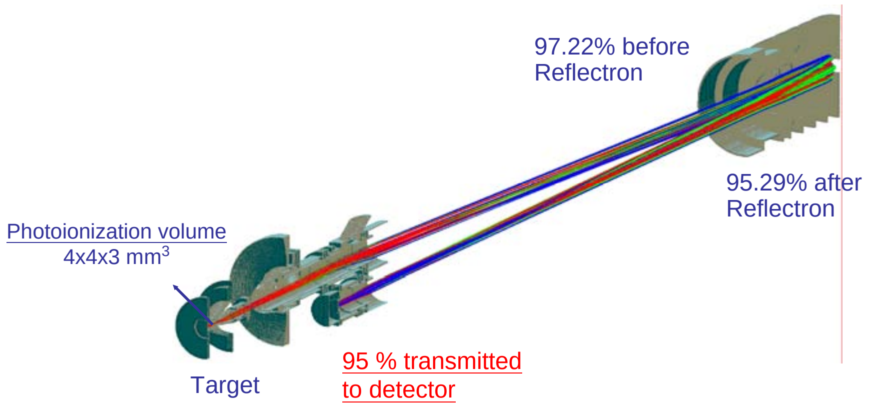
Main chamber

Ion optics and detectors housing chamber

Reflectron chamber

Ion optics simulation of the new instrument design

3D SIMION software was used to simulate, predict transmission and useful yield for the new reflectron time-of-flight (TOF) mass spectrometer.



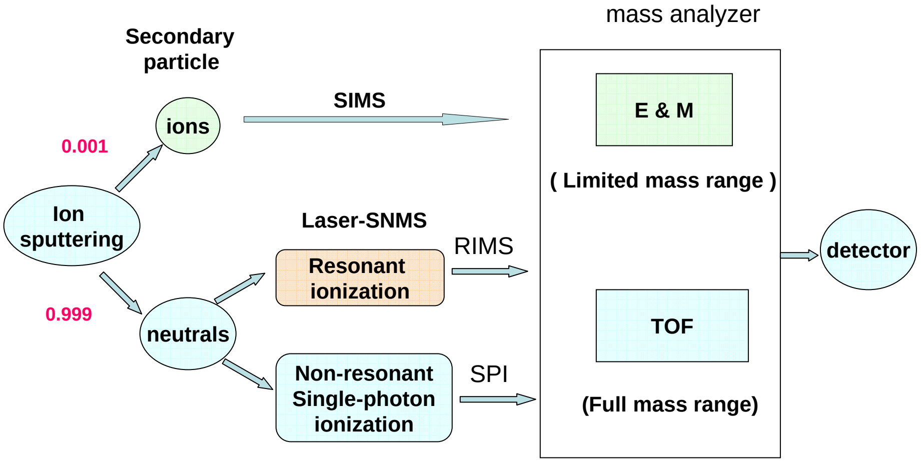
97.22% before Reflectron

95.29% after Reflectron

Photoionization volume 4x4x3 mm^3

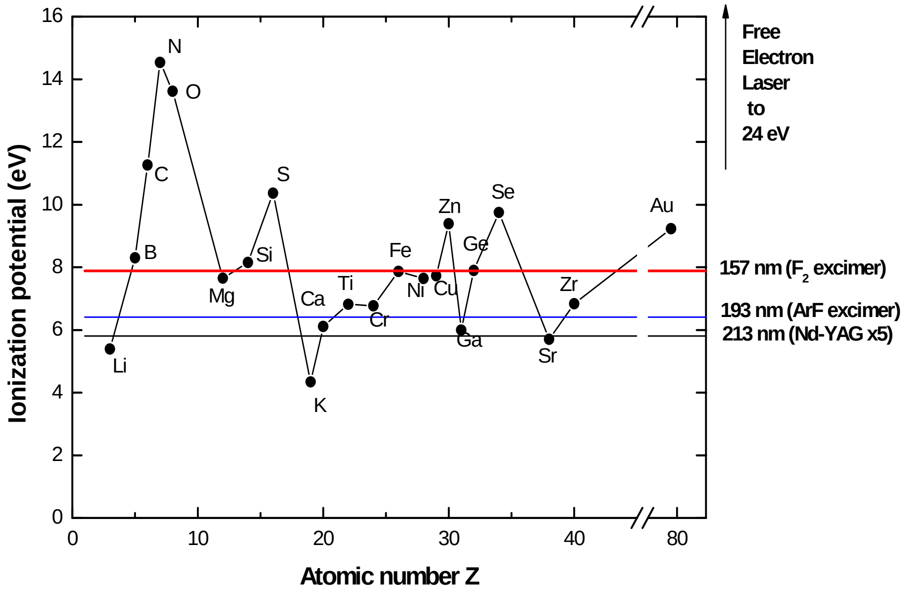
Target

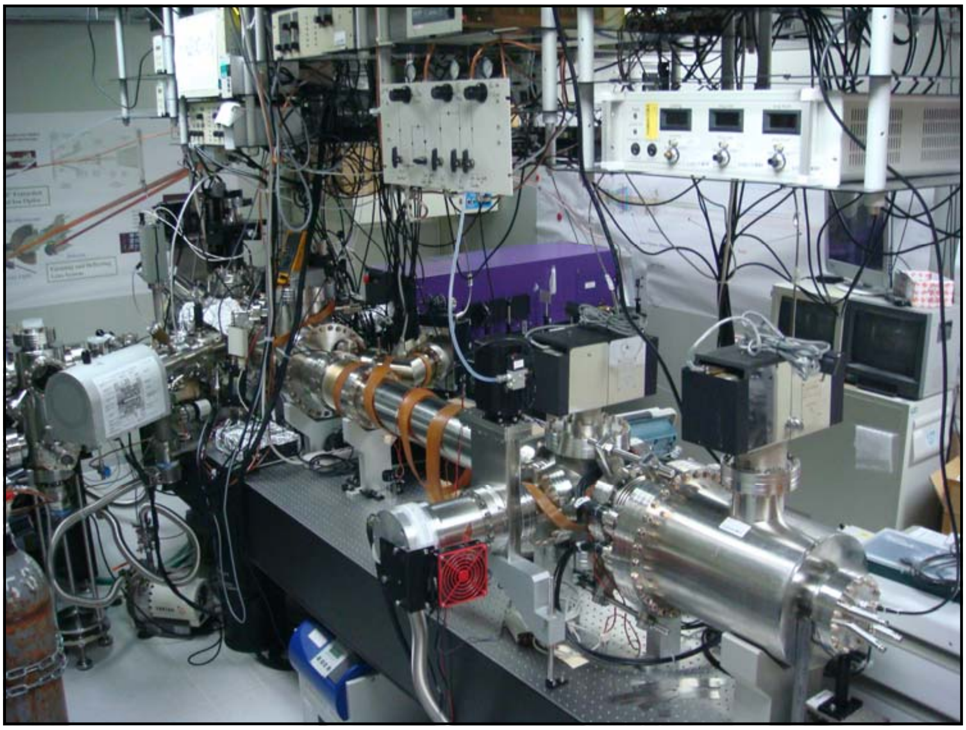
95 % transmitted to detector



Goal : instrument efficiency ($\frac{\text{\# of ions detected}}{\text{\# of atoms consumed}}$) ≥ 30%

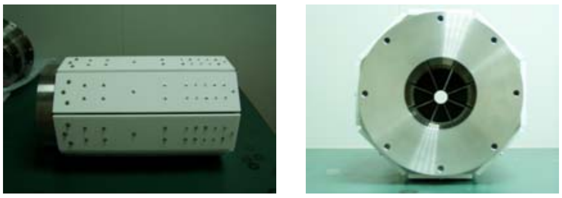
Ionization potentials of atomic elements vs. laser wavelength



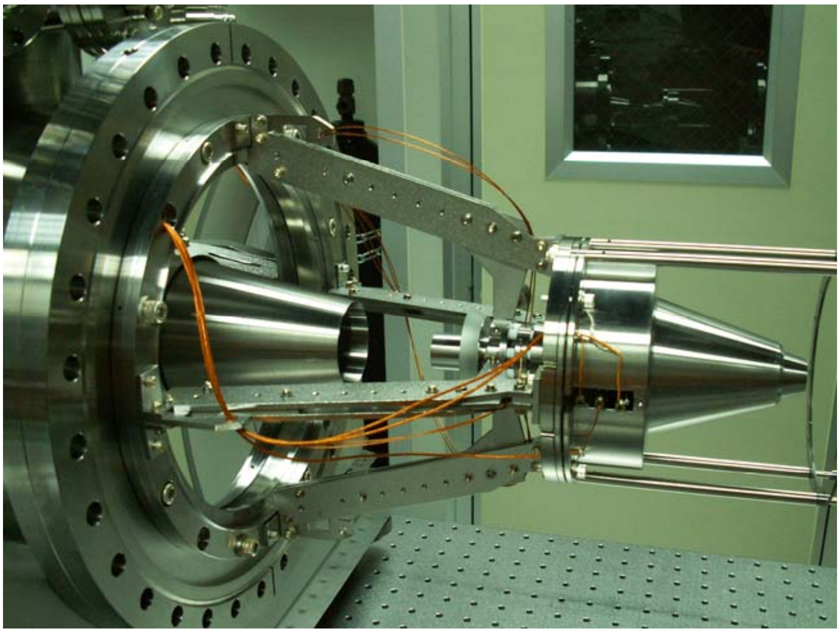


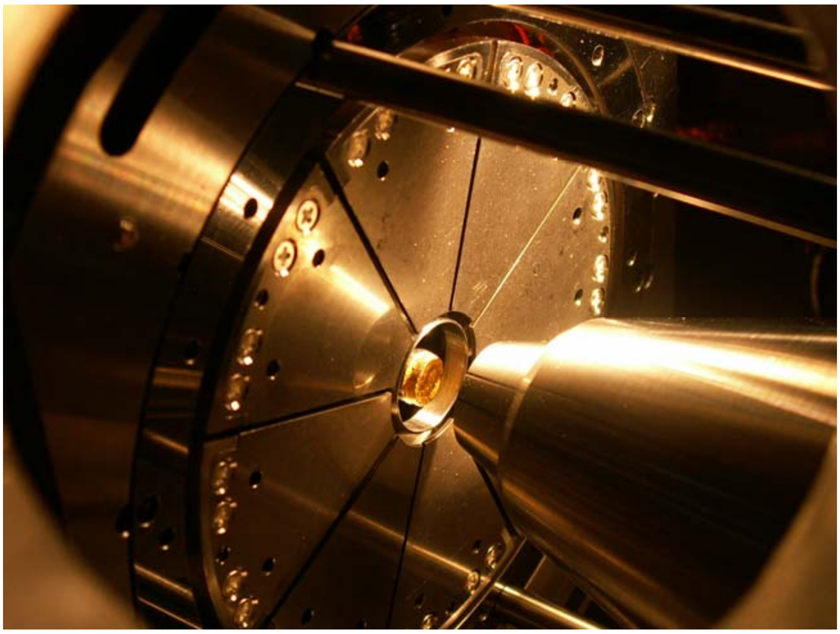
Assembled ion optics:
front end photo-ion
extraction system

Assembled ion optics :
Photo-ion bending &
detection housing

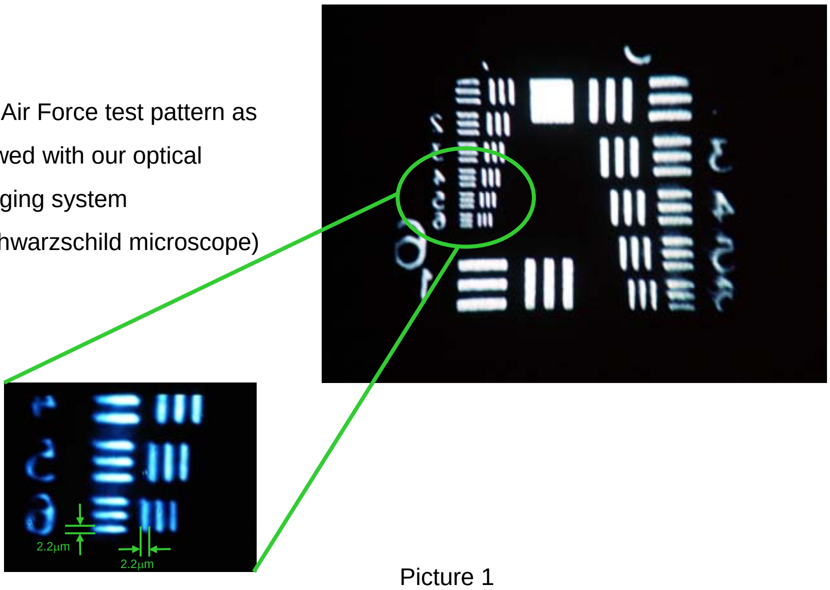


Assembled ion optics:
Reflectron system;
side & front views

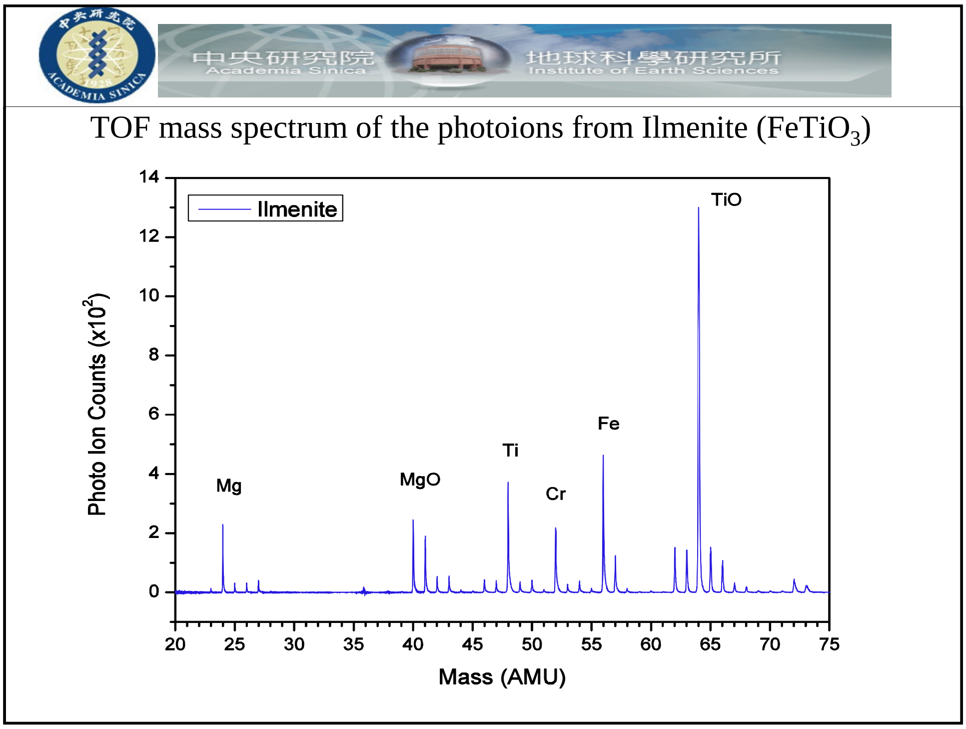




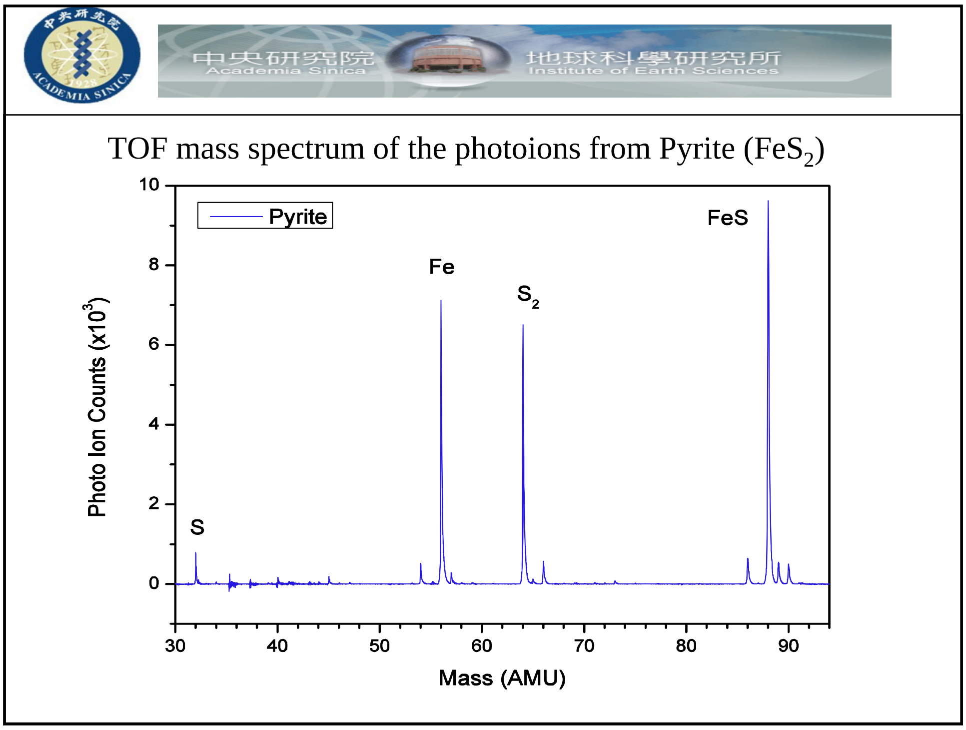
US Air Force test pattern as viewed with our optical imaging system (Schwarzschild microscope)



Picture 1



TOF mass spectrum of the photoions from Ilmenite ($FeTiO_3$)



TOF mass spectrum of the photoions from Pyrite (FeS_2)

Data Analysis :

result:100% x $[({}^{25}Mg/{}^{24}Mg)_{experiment}/\ ({}^{25}Mg/{}^{24}Mg)_{terrestrial}\ -1]$

Correction :assumptions:

$^{24}MgH/^{24}Mg = {}^{25}MgH/^{25}Mg = {}^{26}MgH/^{26}Mg = R$

Intensity at mass 25 = $^{25}Mg + {}^{24}MgH = m25$

Intensity at mass 26 = $^{26}Mg + {}^{25}MgH = m26$

Intensity at mass 24 = $^{24}Mg = m24$

Abundance $^{24}Mg{:}^{25}Mg{:}^{26}Mg = 78.99{:}10.00{:}11.01$

Then, expected intensity

at mass 25 = $(m25)_{expected} = ({}^{25}Mg^+)_{expected} + R\times ({}^{24}Mg^+)_{expected}$

at mass 26 = $(m26)_{expected} = ({}^{26}Mg^+)_{expected} + R\times ({}^{25}Mg^+)_{expected}$

at mass 24 = $(m24)_{expected} = (m24)_{measured}$

R is found by minimizing

$$[(m24)_{measured}-(m24)_{expected}]^2+[(m25)_{measured}-(m25)_{expected}]^2+[(m26)_{measured}-(m26)_{expected}]^2$$

$$({}^{x}Mg^+)_{corr} = m(x)_{measured} - R\times m({}^{(x-1)}Mg^+)_{corr}\ ;\ x=25,\ 26$$

Mg-Isotope Ratio

Isotope ratio	w/o correction		with correction	
	Mg^+ (%)	MgO^+ (%)	Mg^+ (%)	MgO^+ (%)
$^{25}Mg/^{24}Mg$	11.7 ± 3.1	528.9 ± 8.6	-0.1 ± 0.3	0.1 ± 0.2
$^{26}Mg/^{24}Mg$	2.1 ± 2.1	59.2 ± 7.4	0.7 ± 2.1	-1.6 ± 7.2

Ti-Isotope Ratio

Isotope ratio	w/o correction		with correction	
	Ti^+ (%)	TiO^+ (%)	Ti^+ (%)	TiO^+ (%)
$^{47}Ti/^{46}Ti$	4.0 ± 5.1	6.1 ± 3.2	1.7 ± 5.2	0.7 ± 3.0
$^{48}Ti/^{46}Ti$	0.7 ± 3.2	0.7 ± 1.3	0.5 ± 3.2	0.3 ± 1.3
$^{49}Ti/^{46}Ti$	27.9 ± 5.3	65.0 ± 4.1	-0.2 ± 2.8	-0.4 ± 1.2
$^{50}Ti/^{46}Ti$	12.4 ± 5.4	16.2 ± 2.4	10.3 ± 5.5	11.2 ± 2.3

Isotope ratio	Cr^+ (%)	Isotope ratio	Fe^+ (%)
$^{53}Cr/^{52}Cr$	4.6 ± 5.6	$^{54}Fe/^{56}Fe$	1.5 ± 1.8

S-Isotope Ratio

Isotope ratio	S^+ (%)	S_2^+ (%)	FeS^+ (%)
$^{34}S/^{32}S$	9.6 ± 3.8	-0.5 ± 1.0	3.8 ± 1.7

Fe-Isotope Ratio

Isotope ratio	Fe^+ (%)	FeS^+ (%)
$^{54}Fe/^{56}Fe$	3.3 ± 1.5	1.3 ± 0.9

Conclusions: the isotope ratios of the isotopes which have suffered less interferences from hydrides or hydroxides such as those of $^{48}Ti/^{46}Ti$, $^{54}Fe/^{56}Fe$ in $FeTiO_3$ and $^{34}S/^{32}S$, $^{54}Fe/^{56}Fe$ …can be measured at a level that its deviation to the terrestrial ratio is within 1.5% at one sigma uncertainty level of better than 3%.

Things to be improved to make the DUST-BUSTER instrument ready for analyzing pre-solar grains:
1: up the instrument sensitivity… >10%
2: implement a different type of ion gun—Ga^+ gun for less than micron-sized beam spot size

Technical challenge

Small sample size
~ 10^{-12} gram
<1 μm^3
10^{10} atoms

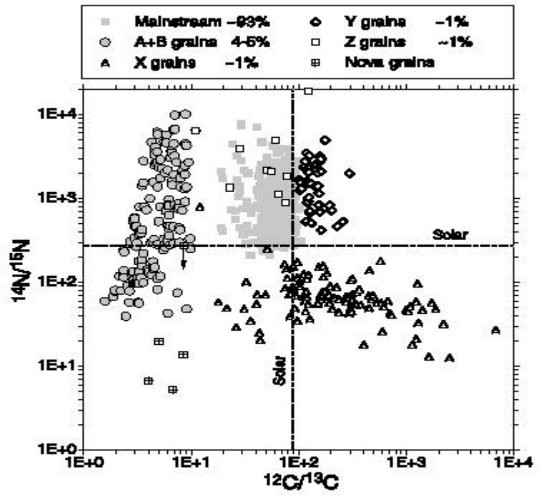
Isotopic measurement techniques

TIMS: thermal ionization mass spectrometry
system sensitivity can be >10^{-2}, but ionization efficiency is element dependent

ICP-MS: inductively coupled plasma mass spectrometry
System sensitivity ~ 10^{-3}, element less dependent

SIMS :secondary ion mass spectrometry
System sensitivity usually <10^{-4} , element dependent

DUST-BUSTER
laser ionization secondary neutral TOF mass spectrometry
System sensitivity expected > 10%



Carbon and Nitrogen isotopic ratios of different populations of presolar SiC grains from Murchison carbonaceous meteorite.

S. Amari et al. APJ, Vol 559, P559, 2001