ANALYSIS OF EXTRA-TERRESTRIAL MATERIALS BY MUON CAPTURE – DEVELOPING A NEW TECHNIQUE FOR THE ARMORY. I. C. Lyon[1], Y. Matsuda[2] AND P. Strasser[3]. [1]School of Earth, Atmospheric and Environmental Sciences, The University of Manchester, UK, M13 9PL, Ian.Lyon@manchester.ac.uk [2]Advanced Meson Science Laboratory, RIKEN Wako Institute, RIKEN, Japan. [3]Muon Science Laboratory, IMSS, KEK, Tsukuba, Japan

Introduction: The aim of this project is to study the feasibility of using negative muon capture to measure major and trace element abundances of meteorites and other extra-terrestrial samples such as solar wind trapped in Genesis collectors. This is achieved by detecting x-rays and gamma rays emitted during muonic cascades in constituent atoms in the samples. Negative muons have identical properties to electrons except for a mass 207 times that of the electron. When they are captured by an atom they are free to rapidly cascade to the lowest muonic 1s groundstate unaffected by the exclusion principle that prevents decay of electrons. The innermost muonic states (n<14) have a Bohr radius that is well inside the Bohr radius of the 1s electronic orbitals and so the muon is captured to an orbital that has a mean radius very close to the nucleus and is considerably affected by nuclear properties such as shape and size. Isotope shifts are significant. Transitions between muonic states result in the emission of characteristic x-rays and gamma rays that can be used to quantify elemental abundances. Isotope shifts for many elements are sufficiently large that different isotopes may be resolved and abundances may be quantified. For light atoms, after the mean muon lifetime of 2.2μs, the muon decays to an electron leaving the atom in its original state or, for heavier atoms there is a significant probability that the muon will be captured by the nucleus and be transformed. There is thus the potential for an (almost) non-destructive technique for isotopic and elemental analysis.

The main aim of this present work was as a feasibility demonstration to test the possibility of using negative muons for analytical purposes. A future extension would be to use a high intensity flux of low energy muons (keV energy range) which would penetrate the surface of a sample and be captured within a selectable depth tens of nm below the surface to measure the abundance of solar wind elements implanted into Si and CVD wafers returned by the Genesis spacecraft.

Experimental Procedure: The samples were suspended using gold wire into the negative muon beam at RIKEN-RAL port 4 at the Rutherford-Appleton Laboratory, UK [1]. Backward-decay negative muons with a momentum 27MeV/c were used. The muon beam was collimated to approximately 4cm in diameter and the samples were oriented at 45^o to the beam. The potential advantage of this approach is that ~4MeV negative muons have a stopping distance of approximately 1mm so that a true bulk average value can be obtained for the meteorite composition potentially allowing the accurate determination of trace element abundances such as chlorine that are difficult to obtain by other means. Of necessity, the analyses were performed parasitically upon existing equipment leading to far from ideal conditions with high background levels. This severely restricted the lower abundance limit for elements that could be detected with this configuration.

A SiLi detector recorded low energy x-rays at 90^o to the beam and a coaxial Ge detector (20% relative efficiency) measured high energy gamma rays. The meteorite samples comprised a 4cm*x*2cm approximately oval section of the Allende (CV3) carbonaceous chondrite with a flat face, a 2.5cm*x*1.5cm square piece of the Murchison (CM2) carbonaceous chondrite with flat face and a 3cm*x*2.5cm square piece of the Camel Donga (Eucrite) meteorite. In addition, samples of NIST 610 standard glass, aluminum sheet, stainless steel sheet and magnesium fluoride were placed into the beam for calibration purposes. These latter samples allowed us to obtain energies and relative intensities of the various emission lines from iron, aluminum, chromium, fluorine and magnesium. The muon beam width was in nearly all cases larger than the sample sizes resulting in characteristic gamma ray spectra from the surrounding copper walls of the containment vessel and air. To assess the contribution to measured spectra from this source, spectra were also obtained when there was no sample present. Muon capture and radiative decay occurs on a rapid timescale (<1ns). This meant that time resolved data were able to discriminate against many background sources in the detectors by taking advantage of the pulse structure at the RIKEN-RAL muon station. Only 'prompt' spectra were analyzed. The prompt gamma ray spectrum obtained from the NIST 610 glass is shown in Figure 1.

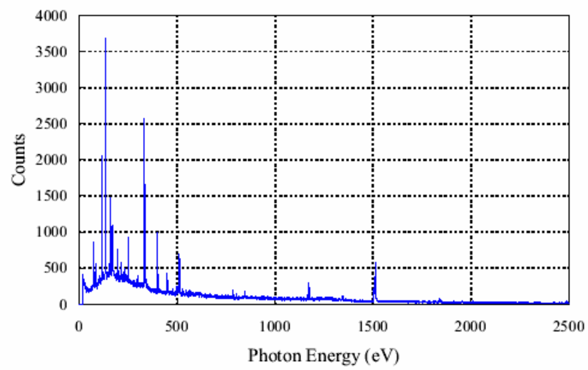

Figure 1. Gamma ray emission spectrum from the NIST 610 glass standard.

A large background arising from Compton scattering and bremsstrahlung was observed which masked lower intensity lines. Many of the lines observed also arise from the walls of the experimental vessel (mainly copper). Subtraction of the spectrum obtained with no sample present allows us to identify those lines due to the sample. Many peaks remain unidentified but probably arise from neutron effects in the detectors and surrounding materials. The nominal matrix of this glass was 72% SiO_2, 12% CaO, 14% Na_2O and 2% Al_2O_3 with approximately 500ppm by weight of >60 elements, some of which had certified abundances. However, the large background count rate obscured transitions from lower abundance elements and caused large uncertainties in the abundance measurements of the lower abundance elements such as Al. Shown in Table 1 are the measured energies and relative intensities of transition lines from the major elements. The peaks areas were integrated to obtain the total number of relative gamma ray captures from each element and corrected to 100% efficiency using a Ge detector efficiency curve.

Table 1. Measured energies and relative intensities of muonic transition lines in NIST 610 glass.

Transition	Energy (keV)	Stoichiome-tric Ratio (X/Si)	Measured Ratio (X/Si)
μO(2p-1s)	133.20	2.40	2.41(1)
μSi(2p-1s)	400.16	1	1
μNa(2p-1s)	250.29	0.38	0.38(1)
μCa(2p-1s)	784.47	0.67	0.18()
μAl(2p-1s)	348.60	0.09	0.03()

The detector efficiency curve has an approximate plateau between 100-400keV so that correction of intensities of emission lines that fall into this energy range is unlikely to introduce significant error. Corrected intensities of emission lines that fall outside this range however may be significantly in error. Error bars given are derived from the peak statistics background noise levels and do not include possible systematic errors particularly from correction of abundances for detector efficiency.

Table 2

Element abun-dances /Si	Murchison	Allende	Camel Donga
O	4.9	3.8	2.96
Fe32	1.7	1.59	0.69
Fe21	-	3.3	0.98
Mg	0.82	1.0	0.19
Al	0.31	0.19	0.16
Ca	–	–	0.9

Measured elemental abundances from the 3 meteorite samples are shown in table 2. The Murchison and Allende meteorites are similar to unaltered material in the forming solar system. They therefore have high abundances of oxygen, iron and magnesium relative to silicon and the measured element ratios compare favorably with the known actual abundances. Camel Donga is a eucrite of basaltic composition which means that the material from which it is made has undergone severe chemical processing whilst on its parent body (possibly asteroid Vesta). The relative proportions of iron and magnesium are therefore lower relative to silicon and calcium is much more significant.

Conclusions:

X-ray and gamma ray emission lines resulting from muonic capture in meteorite samples and terrestrial samples were obtained. Relative abundances of major elements were determined in 3 different meteorite types with measured differences that reflect their different origins. Muonic capture spectra were also obtained from stainless steel, aluminum and magnesium fluoride and measurements obtained of muonic cascades allowing comparison with modeling of cascade branching ratios.

The experimental conditions were far from ideal in this project because the surrounding vessels could not be removed. A better target geometry would improve the signal/noise ratio and therefore the sensitivity. A high flux, low energy muon beam would allow the selective analysis of near-surface layers and much lower abundance detection limits could be achieved.

References:

1) Matsuzaki T., Ishida K., Nagamine K., Watanabe I., Eaton G.H. and Williams W.G. (2001) The RIKEN-RAL pulsed Muon Facility. Nucl. Inst. Method **A 465**, 365-383