First results from the DORN experiment onboard the Chang'E 6 mission.

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Historical overview: Since the Apollo missions, the Moon is known to have a very tenuous exosphere, classified as a surface boundary exosphere (SBE), resulting from a balance between sources and sinks [1]. The short lifetime of atoms and molecules in the lunar exosphere implies their rapid regeneration. One of the sources of the lunar exosphere is the release of endogenic gases from the lunar interior, in particular those produced by radioactive decay (^{4}He, ^{40}Ar, ^{222}Rn). Since the early stages of the lunar exploration, ^{222}Rn and its progeny (^{218}Po, ^{214}Po, ^{210}Pb and ^{210}Po) have been identified as key tracers of the present-day lunar exosphere, as well as seismic and venting activity. Measurements of their concentration performed both on the surface of the Moon (α-scattering experiments on Surveyor 5, 6 and 7) [2], from the orbit (Alpha Particle Spectrometers (APS) onboard Explorer 35, Apollo 15, 16 and Lunar Prospector) [3-5], and on returned samples (lunar fines from Apollo 11, 14 and 15, camera visor from the Surveyor 3 spacecraft and solar-wind composition foils from Apollo 12, 14, 15 and 16) [e.g., 6] have revealed large temporal and spatial variations. The latter were attributed to the presence of active degassing spots, of time-variable outgassing intensities, which radon and its progeny can help locate. Enrichment of ^{210}Po at the Mare/Highlands boundary and ^{222}Rn anomalies over "young" craters (Aristarchus, Grimaldi, Kepler) have been observed. A statistical analysis has revealed a strong correlation between the locations of ^{222}Rn and ^{210}Po anomalies and regions where Transient Lunar Phenomena (TLP) have been observed [7], which suggests that these TLPs could be caused by the sporadic release of gases and dust from the lunar interior. This analysis also reveals a correlation between the locations of deep and shallow moonquakes and the Mare/Highlands boundary. Together with the correlation that exists between the ^{40}Ar degassing rate and the occurrence of shallow moonquakes [8], there is converging evidence that the present day lunar degassing activity may be controlled by seismicity and-or the presence of fractures, which can help ^{222}Rn and other gases transit from the lunar interior. In the last two decades, lunar radon gained renewed interest with the Kaguya-Selene (Alpha Radon Detector, ARD) and Chandrayaan-1 (High-Energy X-Ray Spectrometer, HEX) missions. The ARD experiment showed, once again, time variations and radon anomalies associated with the Aristarchus and Kepler craters [9]. Finally, exhalation of radon from the lunar surface was recently reported by [10], using the KPLO gamma-ray spectrometer.

However, despite the number of experiments that attempted to measure this gas, it is still presently difficult to have a fully consistent and comprehensive picture of radon outgassing and transport on the Moon from all these datasets. The Surveyor experiments were not designed and therefore not optimized to measure these radionuclides (large background due to an onboard ^{254}Es calibration source and very small FOV). Data acquired from the orbit had a large footprint and limited temporal coverage. Moreover, some of these measurements were degraded due to a contamination of the detectors by ^{210}Po or ^{241}Am sources used for their calibration, and the APS background increased significantly after failure of one of its light filters. The ARD suffered from noise in some of its channels and its anticoincidence detectors dysfunctioned.

The DORN experiment onboard Chang'E 6: To fill in the gap between orbital and laboratory measurements, the DORN instrument was proposed to conduct the first dedicated measurements of radon and polonium at the surface of the Moon, with the following scientific objectives:

- Study the lunar outgassing and transport of gases through the lunar regolith, hence providing constraints on the physical and thermal properties of the regolith, by measuring the exhalation rate of ^{222}Rn and ^{220}Rn.
- Provide data to improve models of transport of gases in the lunar exosphere
- Constrain the rate/efficiency of dust lifting (by measuring the ^{222}Rn/^{210}Po ratio)
- Providing ground-truth for past and future orbital measurements of radon and polonium
- Improve orbital measurements of uranium

It was also aimed at comparing radon levels measured on the Moon, Earth, Mercury and Mars [11,12].

After an agreement was signed in 2019 between the French and Chinese Space Agencies (CNES and CNSA) to foster collaboration in the field of space exploration, the DORN instrument was selected to be part of the Chang'E 6 mission payload. It was developed and built at IRAP in the following 3.5 years, and the Proto Flight Model was delivered to CNSA in the summer of 2023. This was followed by a few months of Assembly, Integration and Tests activities at the CAST facilities in Beijing and then on the launch site in Wenchang, where the instrument was reassembled with the spacecraft.

DORN is an alpha spectrometer measuring charged particles in the 0.6-12 MeV range (Fig. 1). It is made of 8 detection units (DU). Each DU consists of a pair of 5.3 cm^2 silicon detectors in a telescope configuration, to reject and characterize solar and galactic particles coming from the rear-side and from the front-side with penetrating energies. Its front detectors are also surrounded by plastic collimators to passively screen protons with grazing incidence angles that could deposit energy in the 5-10 MeV range of interest (range of energy where ^{222}Rn and ^{220}Rn and their progeny emit alpha particles). The 8 DU are arranged in two subsets of 4 DU with different tilt angle wrt the surface, to cover the near- and far-fields around the lander and gain a better understanding of the background and radon signals (surface vs. sky) (Fig. 1). A small ^{209}Po calibration source was mounted in front of each DU to allow energy calibration and to monitor the status of health and the performance of the detectors (both on the ground and in flight) (Fig. 2).

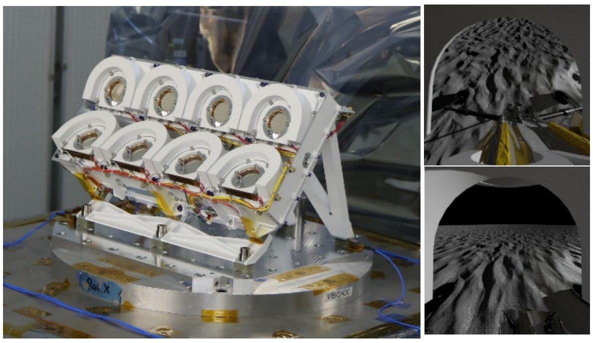

Fig. 1: DORN Proto Flight Model, with its 8 Detection Units organized in two rows to cover different fields of view, as simulated in the right panel (Top: Near-Field, to measure polonium implanted in the lunar surface; Bottom: Far-field, to measure exospheric radon and polonium present in the far-field, far from possible lander disturbances)

In total, the weight of the instrument was ~4.5 kg and its power need ~12W. The large total surface area of the detectors (42 cm^2) was necessary to ensure a low limit of detection for a very short-lived mission like Chang'E 6 (expected Minimum Detectable Activity of polonium ~1 atom·m^{-2}·s^{-1}, i.e., an order of magnitude better than previous orbital measurements).

DORN was conceived as a demonstrator, as the Chang'E 6 mission profile restricted its use two less than 48h at the lunar surface, therefore recording only one snapshot of the expected radon daily cycle. Carried onboard long-lived missions, it could record its full diurnal cycle and possibly detect time anomalies associated to outgassing events. Because of the infinite range of α particles in vacuum, it could also be used to characterize remotely (e.g., from the rim of shadowed craters) the trapping efficiency of very cold spots such as Permanently Shadowed Regions (PSR), possibly associated to radon and polonium enrichments. The renewed interest for lunar exploration could provide several new opportunities for DORN deployment.

DORN operations during the Chang'E 6 mission:

Chang'E 6 was launched on May 3rd, 2024, and landed in the Apollo Crater within the South Polar Aitken Basin, at a latitude of -41.6°S, on June 2nd. The instrument was switched on several times during the course of the mission. First, during the Chang'E 6 Earth-Moon transfer (for 10 hours), then in an ellipitical orbit (for 32 hours) and in a circular orbit at an altitude of ~200 km (for 111 hours) (Fig. 2), in the wake of a strong solar storm. After Chang'E 6 landing, it collected 19 hours of data and was switched off a few hours before the liftoff of the ascent module, which occurred on June 4th. DORN was thus able to perform both orbital and surface data, although no orbital data from the Chang'E 6 landing site were acquired.

Initial results from DORN: We will present at the conference the initial results obtained by DORN and compare them with previous measurements of radon and polonium made from the orbit, and will discuss discrepancies found between the very low activity levels measured *in situ* and the results of a transport model of radon in the lunar environment that we developed to estimate time and space variations of radon flux and exospheric abundances across the lunar globe [13]. Differences with levels of radon concentrations measured on Earth, Mars and Mercury will also be discussed. Finally, developments of analytical techniques aimed to analyse low-mass lunar samples (including CE'5 samples, and CE'6 in the future) are underway to extract properties such as bulk uranium content, radon emanation and adsorption coefficients, which are important to explain the observed discrepancies and to improve transport models [14].

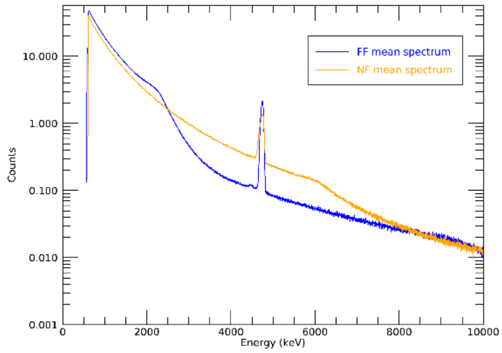

Fig. 2: Mean spectra acquired by DORN Far-Field and Near-Field detectors in lunar orbit (including when the instrument was poiting away from the Moon). The peak at 4.8 MeV is produced by the onboard ^{209}Po calibration source.

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