Feasibility Study for an Active $^{238}$UF$_6$ Gas Target for Photo-Fission Experiments

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Abstract

A series of fission experiments in the actinide region has been started at the superconducting Darmstadt linear accelerator S-DALINAC. For detailed investigations on, e.g., the energy dependence of fission modes, the population of fission isomers, or even the search for parity non-conservation effects (PNC) in the photon-induced fission process of $^{238}$U, high luminosities are needed. Increasing target thickness reduces mass and angular resolutions. One possible solution is the utilization of an active gas target containing UF$_6$. In order to test UF$_6$ as an admixture to standard counting gases (e.g. argon) and to study its properties, an ionization chamber has been built at Technische Universität Darmstadt.

After testing the chamber with pure argon as a counting gas to evaluate signal quality and to determine the drift velocity, gaseous UF$_6$ was filled into the chamber in steps of one mass-percent uranium for each measurement, where both signal quality and drift velocity at different admixtures have been determined. Up to two percent of uranium in the counting gas one finds that the drift velocity increases with UF$_6$ content, while overall a good signal quality and energy resolution of the ionization chamber is preserved.

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1. Photofission experiments at the S-DALINAC

Since its discovery in the late 1930s, nuclear fission has been used in a variety of technical applications. Despite its technical use, a detailed microscopic theoretical understanding of the fission process has not been achieved yet [1]. In order to gain insight into the fission process, e.g., fissioning shape isomers may be investigated, and the determination of mass and total kinetic energy (TKE) distributions - often parameterized in the fission-mode concept developed by Brosa et al. [2] - as well as fragment angular distributions are pursued. Detailed data on these quantities may

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help elucidate the structure of intermediate states as well as the shape of the fission barrier. This, in turn, may guide theoretical studies for a microscopic description of fission dynamics.

Results on the mass and TKE distributions from photon-induced fission of $^{234,238}$U have been obtained recently [3] at the 10 MeV bremsstrahlung facility [4] of the superconducting Darmstadt electron linear accelerator S-DALINAC [5]. These experiments use a twin Frisch-grid ionization chamber with a solid target located at the common cathode [6]. An important step in the analysis is the determination of the fragment emission angle with respect to the target. This is obtained from the measurement of the electron drift times to the anode [7]. For a significant improvement on such data, higher luminosities are desirable, which would result in a longer measurement campaign with the present set-up.

Another point of interest is the search for parity non-conservation (PNC) in the reaction $^{238}$U($\gamma,f$). From the ratio of the coupling constants of weak and strong interaction, a PNC strength of $10^{-7}$ is expected. Previous experiments with neutron-induced fission show an enhancement to $10^{-4}$ [8], which is proposed to arise from the high level density and the selective excitation of states by low angular momentum transfer [9]. For an improved understanding of these enhancement effects, studies with other probes are needed. Flambaum and Gribakin [10] as well as Wettig and Weidenmüller [11] have argued, that even in the case of a broad excitation spectrum, detectable effects may persist. With the newly installed source of spin-polarized electrons [12] it will be possible to produce bremsstrahlung that is circularly polarized close to the electron beam energy to search for forward-backward asymmetries originating from PNC.

For a PNC experiment to become feasible, even higher luminosities are required. As the beam currents of the S-DALINAC are limited to 60 $\mu$A with an option for an upgrade to about 150 $\mu$A [13], increasing target thickness is mandatory. For a solid target, however, the mass and angular resolutions deteriorate with increasing target thickness. Therefore, as a possible alternative to this dilemma, an active gas-target containing uranium atoms inside the counting gas is investigated. Hence different admixtures of UF$_6$, available as gas at temperatures above 56 °C, with common counting gases, e.g. argon, are studied [14].

2. Set-up for an active UF$_6$ gas-target feasibility study

A Frisch-grid ionization chamber for testing UF$_6$ as a gas-admixture has been built. The chamber was designed with a distance $D = 4.2$ cm between cathode and grid, and a distance of 1 cm between grid and anode. A schematic sketch of the chamber geometry can be found in Fig. 1. The electrons, created by the energy loss of charged particles inside the active gas volume, produce a signal at the anode (A), which is proportional to the deposited energy. Taking into account the shielding inefficiency of the grid, an energy calibration of the chamber may be obtained.

For a typical charged particle inside the active volume, the center of gravity of its charge distribution is denoted by $\overline{X}$ as depicted in Fig. 1. With the distance $D$ between cathode (C) and grid (G), one obtains the ratio $\overline{X}/D$, which defines the suppression of the signal induced at the cathode relative to the anode signal, and consequentially one can deduce the emission angle of the charged particle.

As UF$_6$ is highly hygroscopic and can form hydrofluoric acid, all appliances have to be baked out in order to reduce the water content, and they must be resistant against corrosion. The same is true for elastomer materials, where only those with a fluorine content do resist hydrofluoric acid. Hence, due to these safety reasons, all conducting parts inside the chamber are made out of stainless steel (AISI 316L), and all insulators are made out of polytetrafluorethylene (PTFE).

Leak tests were carried out showing an integral helium leak rate of $9.1 \cdot 10^{-10}$ (mbar $\cdot$ l)/s. After flushing with argon in order to avoid gas impurities, such as air, the chamber was then filled with argon of purity 6.0 equivalent to a volume of 950 mln (volume in ml under normal conditions).

For energy calibration purposes a triple alpha source is used containing $^{239}$Pu, $^{241}$Am and $^{244}$Cu, which emit alpha particles at energies of 5155 keV, 5480 keV and 5795 keV, respectively. The alpha source is mounted on a stainless steel disk in the cathode plane inside the ionization chamber and fixed with a PTFE fitting.

3. Experimental Results

First the functionality of the chamber at different temperatures between 30 °C and 70 °C was demonstrated. Special attention has been payed on the signal quality, which can be seen in Fig. 2(a). Only low-energy alpha particles are
completely stopped inside the argon, due to the dimensions of the chamber. The produced electrons induce a signal on the cathode and drift along the field lines towards the anode. Clearly separated signals are visible in the two-dimensional plot. This indicates a high resolution due to the pure argon atmosphere with no air impurities. In this set-up, argon gas was flowing continuously through the ionization chamber. From the events in Fig. 2(a) an energy spectrum may be created that allows for energy calibration, see Fig. 3(a).

Another quantity that was derived was the drift velocity of the electrons in the active volume. It was measured at a temperature of $70^\circ C$ and a gas volume of 950 mln. The results for different electric field strengths normalized to the pressure are shown in Fig. 4(a). A typical behavior for the drift velocity in argon, with a peak value at a small strength of the reduced electric field around $100 \text{ V/(cm} \cdot \text{atm)}$ and saturation at higher field strengths, is visible, see Fig. 4(a).

In the next step different mixtures of argon gas and small amounts of UF$_6$ were investigated. We started with one mass per cent of uranium, added as UF$_6$ to an argon volume of 1055 mln, and increased the content to two mass percent, in order to study the behavior of the gas mixture with respect to signal quality and electron drift velocity. Figure 2(b) gives an indication of the signal quality with an amount of two mass per cent uranium in the system. Adding UF$_6$ to the argon gas obviously distorts the signals. We note that in this case the mean free range of the alpha particles from the calibration source exceeds the dimensions of the chamber. The alpha particles are not completely stopped, and consequently the signals are washed out. Two lines with lower intensity can be seen at lower energies, as well. They originate from the alpha decays of $^{238}$U and $^{234}$U, respectively, which takes place close to or on the surface of the electrodes. As the UF$_6$ is spread out over the entire active volume, many events may be identified. They create a background in the energy spectrum. Events with low cathode pulse height are probably due to UF$_6$ molecules which have frozen out on the electrodes.

Figure 3(b) shows the energy spectrum of the calibration source obtained with an argon / UF$_6$ mixture (two mass per cent uranium). Apart from a higher background, which is due to the alpha radioactivity in the counting gas, one finds that the visible energy peak for $^{238}$U is about two orders of magnitude lower than for the calibration source, although their activities are in the same order of magnitude. The activity of the calibration source nuclides is around 1 kBq each. With a specific activity of 12.2 kBq/g and an estimated mass of 60 mg, the alpha activity of the $^{238}$U content in the chamber should be about 730 Bq. Since this value could not be confirmed by comparing the peak intensities from the calibration source and $^{238}$U, one may assume that only a small amount of UF$_6$ has stuck to the electrodes.

The observed anti-correlation between anode and the cathode pulse height (cf. Fig. 2(b)) might be explained by air impurities inside the chamber, which occurred during the gas filling process. However, this issue is still under investigation and may be suppressed in a second measurement campaign, when the gas mixture is renewed.

For two different UF$_6$ concentrations inside the active volume the results from the electron drift-velocity measure-
ments are shown in Fig. 4(b), as a function of reduced field strength. Corresponding values for pure argon are included as reference. All three measurements exhibit similar behavior at small field strengths. At higher field strength the drift velocity increases with uranium concentration, eventually leading to saturation.

4. Discussion and Outlook

The feasibility of an ionization chamber operated with a gas mixture of argon with up to two mass per cent uranium in the form of UF$_6$ has been demonstrated. Signals from a mixed alpha source are well resolved after adding UF$_6$ to the gas mixture. During the UF$_6$ filling procedure the signals became distorted, an effect, which seems to recover after some time. In the near future, the counting-gas properties of Ar + UF$_6$ at even higher uranium concentrations will be elucidated. If the uranium mass exceeds 60 mass per cent in the present set-up, the thickness of the active target would be comparable to a target with a thickness of around 1 mg/cm$^2$ required for high-quality photo-fission data, and also for the search for PNC effects. Another issue to be investigated is the purity of the gas and the performance of the active target over a long period of time as well as the reproducibility of the gas behavior. Some efforts may also be taken to improve the data collection procedure, e.g. by sampling the signals with fast ADCs, and the granularity of the signal. Therefore segmented electrode designs are currently under investigation, and a readout system for a larger number of channels is under construction.
Figure 4: Measured electron drift velocities as a function of reduced field strength in (a) a pure Ar atmosphere (950 mln) and (b) Ar (1055 mln) with different admixtures of UF₆, both at 70 °C.

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