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Search for the Inelastic Scattering of Weakly Interacting Massive Particles on the ^{178m2}Hf Isomer

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In this report we present the results of our experimental search for dark matter using the ^{178m2}Hf isomer [1]. The use of long-lived nuclear isomers as targets to study exothermic reactions for the detection of dark matter was proposed in 2020 [2]. And the first experiment aimed at the search for dark matter using the ^{178m2}Hf isomer was conducted in 2023 [3].

The idea to detect dark matter using nuclear isomers is the following: during inelastic scattering of WIMPs on the long-lived excited nuclear state some specific excited states can be populated that are not populated during the spontaneous decay of this isomer. And if the excitation energy, as in the case of the ^{178m2}Hf isomer, is very high (E = 2446.05 keV, Fig. 1), such excited states can also have high energy and decay with the emission of high-energy γ-rays. This can significantly increase the sensitivity of dark matter detection experiments, since the natural background at high energies is much lower.

In [3], 11 excited levels of 178Hf were selected, which are the most attractive in the search for dark matter. For each of them, based on the obtained upper limit on the intensity of depopulating γ-transition, the corresponding half-lives for dark-matter-induced transitions were estimated. As a result, the longest half-life was obtained as T1/2 > 1.79 × 105 years.

Our ^{178m2}Hf isomer target has an activity < 100 Bq, which allows measurements to be carried out in zero geometry. In addition to the 178m2Hf isomer a number of long-lived nuclides and isomers such as 60Co, 101Rh, 102mRh, 108mAg, 133Ba, 150Eu, 152Eu, 154Eu, 158Tb, 173Lu, 174Lu, 172Hf and 179Ta are present in the target [4]. The γ-spectrum of our ^{178m2}Hf isomer target was measured for 106 s using a CANBERRA® BE2825 HPGe detector shielded only by 2 cm Pb (Fig. 2). The efficiency calibration curve from 334 to 1344 keV was obtained using 150Eu and from 1344 to 2000 keV - using B-Spline extrapolation.

Fig. 1. The scheme of the spontaneous decay of the ^{178m2}Hf isomer with only the most intense γ-transitions. Two excited levels of 178Hf, which might be populated during inelastic scattering of weakly interacting massive particles on the ^{178m2}Hf isomer, are shown.

Fig. 2. The γ-spectrum of the ^{178m2}Hf isomer (blue) and the background spectrum (red). Isomer peaks and its sum peaks are marked in dark blue, while background peaks and the strongest peaks of isotopes present in the target are labeled in dark red.

We reviewed the list of 178Hf levels that may be the most attractive for the search for dark matter, i.e. the levels which decay by γ-rays with energies above 1000 keV and branching ratios greater than 27%. There are more than 50 such levels, and more than 60 corresponding γ-transitions. 17 most promising transitions were analyzed in detail. In general, we obtained the best estimate of T1/2j, which slightly exceeds 9×10^5 yr, for the transitions with energies of 1340.460 and 1893.17 keV.

For further improvement of such experiments, it is required:
- a much stronger (104 - 105 Bq) isomer target allowing:
– less critical dependence on background radiation;
– measurements in a non-zero geometry minimizing the sum peaks;
– $\gamma - \gamma$ coincidence measurements.
- radiochemical removal of other nuclides present in the isomer target;
- passive and active protection of the detector against background radiation;
- an experiment conducted in low background conditions of an underground laboratory.

Bearing this in mind, we went forward and performed the next series of experiments. First, AntiCompton spectrometer was used in the AntiCoincidence [5] and Coincidence modes (the last experiment is still ongoing). Secondly, the ultra-low background experiment was performed at Gran Sasso National Laboratory (Italy) last summer, while its results are still processed.

The AntiCompton spectrometer consists of (Fig. 3):
- GR1519 HPGe detector and NaI detector placed cup-to-cup with small cavity for a source;
- Additional 4 NaI detectors are placed symmetrically around the crystal of the HPGe detector for the effective Compton scattering detection.

As a result, γ-rays from the excited levels of 178Hf, which might be populated during inelastic scattering of WIMPs on the ^{178m2}Hf isomer and which correspond to transitions to the 8-, 2+ та 0+ excited levels of 178Hf, present in the spontaneous decay scheme of the ^{178m2}Hf isomer, do not fall into any coincidences. Therefore, such γ-rays would be accumulated in the AntiCoincidences spectrum, which significantly improves the background conditions (Fig. 4). In fact, there are 31 such levels and 35 corresponding γ-transitions.

Fig. 3. Schematic representation of the AntiCompton spectrometer shows the approximate location of the HPGe detector, the central NaI detector, two of the four side NaI detectors and the applied filters.

Fig. 4. Traditional (red) and $\gamma - \gamma$ AntiCoincidence (blue) γ-spectra. The ^{178m2}Hf Isomer peaks and its sum peaks (blue) plus the peaks of background and other nuclides (dark red) are shown.

Of those 11 transitions recognized as promising in [3], only one transition is in our list, namely the transition with energy of 1678.82 keV. For this transition we improved the $_{1/2}$ estimate by almost 30 times (from 1.79×10^5 yr to 53.14×10^5 yr). The best estimate of $_{1/2}$, which reaches 99.27×10^5 yr, was obtained for the transition with energy of 1715.06 keV (more than 55 times higher than the best estimate in [3]).
As for the preliminary result of our ultra-low background experiment, the limits on $_{1/2}$ of the dark-matter-induced transitions are improved by about 70 times and reached $T_{1/2} > 124 \times 10^5$ years.
Further progress of such experimental efforts will be discussed.

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