

Search for inelastic scattering of dark matter particles on ^{83}Kr nuclei with excitation of a low-lying nuclear level

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A search for excitation of the first nuclear level with an energy of 9.4 keV in the ^{83}Kr nuclide by massive weakly interacting dark matter particles was performed with a gas proportional counter filled with the ^{83}Kr isotope. The experiment was conducted in the Baksan Neutrino underground laboratory of the Institute for Nuclear Research of the Russian Academy of Sciences. As a result, a new upper limit on the nuclear level excitation cross section was established: for 20 GeV mass particles — $\sigma_0^{\text{SD}} \leq 3.4 \cdot 10^{-35} \text{ cm}^2$ at a 90% confidence level.

Keywords: dark matter, weakly interacting massive particles, WIMPs, inelastic scattering.

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Weakly interacting massive particles (WIMPs), and in particular the lightest supersymmetric particles, remain the leading candidate dark matter particles. Most experiments, such as XENON, LZ, PandaX, CDMS, DarkSide, etc., are aimed at searching for elastic coherent spin-independent scattering of WIMPs on nuclei where the recoil nucleus is detected [1]. At the same time, inelastic spin-dependent scattering of WIMPs with excitation of low-lying nuclear levels is also feasible. Although the expected cross section of this reaction is smaller, it has an obvious advantage in allowing one to detect X-ray and gamma quanta and conversion and Auger electrons arising during the decay of a low-lying nuclear level with a characteristic energy spectrum and delayed by the level lifetime relative to the signal from the recoil nucleus.

The search for inelastic scattering was performed in the ELEGANT V [2], DAMA [3,4], and COSINE [5] experiments for ^{127}I nuclei (with NaI detectors) and the XMASS [6–8] and XENON [9,10] experiments for ^{129}Xe nuclei (with liquid xenon time projection chambers). In addition to ^{127}I and ^{129}Xe [11], the expected cross sections were examined theoretically for ^{125}Te [12], ^{83}Kr [13], and several other nuclei [14].

Transitions to excited states [11,13] are normally suppressed energetically. The exceptions here are certain odd (in mass number A) nuclei with low-lying excited states and the possibility of transitions to excited states due to spin-dependent interactions. In the present study, we analyzed the energy spectrum of a large gas proportional counter filled with the ^{83}Kr isotope, which has a nuclear level with an energy of 9.4 keV. The ^{83}Kr nucleus has an odd number of neutrons and should be sensitive to the WIMP–neutron spin-dependent interaction. The transition from the first excited $7/2^+$ state to the ground $9/2^+$ state corresponds to

the $M1$ -transition with a small admixture ($\delta = 0.0129$) of the $E2$ transition. The lifetime of the level is 212 ns, which allows one to use delayed coincidences in liquid scintillation or solid-state detectors, but is ill-suited for their application in gas counters due to a long ($\sim 1 \mu\text{s}$) charge collection time.

According to the standard halo model of our Galaxy, the density of dark matter in the region of the Solar System is $0.2\text{--}0.6 \text{ GeV}/\text{cm}^3$ and the velocity distribution of WIMPs corresponds to the Maxwell–Boltzmann $f(v)$ distribution that has the most probable velocity of 230 km/s and is cut off at velocities greater than 530 km/s [15]. To calculate WIMP fluxes in the vicinity of the Earth, the $f(v)$ distribution must be transformed to take into account the Earth’s motion with a velocity of 230 km/s as part of the Solar System [16,17]. The average kinetic energy of WIMPs in a laboratory system is $\sim 0.5 \cdot 10^{-6}$ of WIMP mass m_W , which is sufficient to excite nuclear levels with an energy of $\sim 10 \text{ keV}$ at large values of m_W . To excite a nuclear level with energy E_{ex} in a nucleus with mass m_A , the WIMP mass must exceed $m_{W \text{ min}} = m_A / (m_A v_{esc}^2 / 2E_{ex})$. The $m_{W \text{ min}}$ value for ^{83}Kr and halo escape velocity $v_{esc} = 600 \text{ km/s}$ is 5 GeV. This value should be compared with $m_{W \text{ min}} = 39$ and 21 GeV for ^{127}I and ^{129}Xe nuclei, respectively. The experiment with ^{83}Kr allows one to expand significantly the range of studied possible WIMP masses.

In inelastic scattering with the transition of a nucleus to an excited state, the energy of the recoil nucleus must exceed a certain minimum energy, which depends on excitation energy E_{ex} , nucleus mass m_A , and WIMP mass m_W and escape velocity v_{esc} . The minimum and maximum energies potentially transferred to the ^{83}Kr recoil nucleus in scattering of a 20 GeV WIMP are 0.05 and 50 keV, respectively [13].

The expected shape of the energy spectrum of recoil nuclei $S(E_i)$ in a detector in scattering of WIMPs with velocities v_k is calculated as follows:

$$S(E_i) = \frac{\rho_W}{m_W} \sum_{k_{\min}}^{k_{\max}} \sigma_{ex}(E_i, v_k) f(v_k) v_k \Delta v_k, \quad (1)$$

where $\rho_W = 0.3 \text{ GeV/cm}^3$ is the local dark matter density and σ_{ex} is the cross section of inelastic WIMP scattering with excitation of the nuclear level. The sum is calculated in steps of Δv_k from the minimum velocity v_{\min} needed to excite ^{83}Kr nuclei to the maximum velocity v_{\max} . In inelastic scattering with excitation of a nuclear level, the v_{\min} value increases from the minimum velocity $v_0 = (m_A E_i / 2\mu^2)^{1/2}$, which is needed for the recoil nucleus to acquire energy E_i in the case of elastic scattering, to $v_{\min} = v_0 + v_{thr}^2 / 4v_0$. Here, $\mu = m_A m_W / (m_A + m_W)$ is the reduced mass of the nucleus and WIMPs and $v_{thr} = (2E_{ex} / \mu)^{1/2}$ is the minimum velocity required to excite a nuclear level. The ^{83}Kr isotope has an advantage over the above-mentioned ^{127}I and ^{129}Xe isotopes in having lower values of v_{\min} and $m_{W \min}$, which helps expand the range of studied masses and velocities of WIMPs.

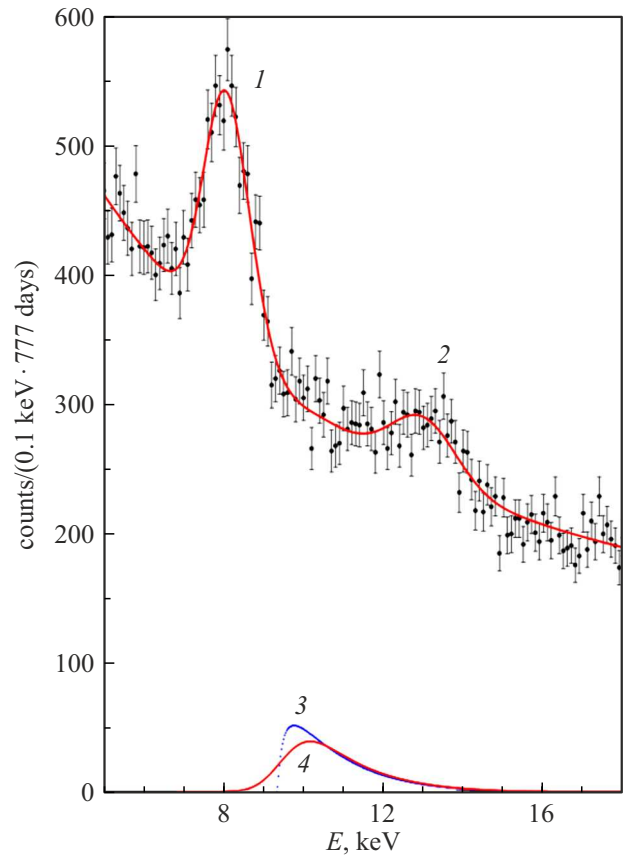
In the standard spin-dependent interaction, the interaction cross section is inversely proportional to the WIMP velocity squared [1]:

$$\sigma_{ex}(E_i, v_k) = \frac{m_{\text{Kr}}}{2\mu^2 v_k^2} \sigma_0^{SD} F_{SD}^2(E_i), \quad (2)$$

where σ_0^{SD} is the spin-dependent cross section in the limit of zero momentum transfer and F_{SD} is the nuclear structure factor [18]. To obtain a real spectrum from expressions (1) and (2), one needs to take into account the quenching of the ionization signal from recoil nuclei and the finite energy resolution of the detector.

A low-background setup with a krypton proportional counter, passive protection for suppressing external gamma and neutron radiation, and active plastic scintillator protection for detection of cosmic muons was located in the underground Baksan Neutrino Observatory of the Institute for Nuclear Research of the Russian Academy of Sciences. The cylindrical counter body is made of copper and has an internal diameter of 137 mm and a length of 745 mm; the total volume is 10.8 l. The counter is filled with krypton (enriched in ^{83}Kr to 99.9%) at a pressure of 1.8 bar. The mass of krypton in the working volume of the counter (8.77 l) is 58 g. The detector spectrum recorded over 777 days of actual („live“) measurement time is shown in the figure. The experiment was initially performed to search for resonant absorption of solar axions with excitation of the first nuclear level of ^{83}Kr . It was discussed in more detail in [19–21].

The characteristic time of electron collection in a gas counter is close to $1 \mu\text{s}$, which exceeds significantly the lifetime of the considered nuclear level of ^{83}Kr . Therefore, the signal of inelastic interaction of WIMPs with a ^{83}Kr



Kr counter spectrum and results of fitting two Gaussian peaks with the sum of the background characterized by an exponential function and the detector response function for inelastic scattering of WIMPs. 1 — Copper X-ray peak; 2 — peak associated with the ^{81}Kr isotope decay; 3 — spectrum expected from excitation of the 9.4 keV level in inelastic scattering of 20 GeV WIMPs with account for quenching of the ionization signal; 4 — spectrum 3 with account for the energy resolution of the detector.

nucleus is a sum of signals from the recoil nucleus and particles (X-ray and gamma radiation and conversion and Auger electrons) produced in the course of decay of the 9.4 keV level.

Conversion electrons from the L , M , and N shells (the ratio of probabilities of emission of a conversion electron and a γ -quantum is $e/\gamma = 14.1$) and X-ray radiation accompanying them in transitions to the L -shell are the primary products of a nuclear level decay. Only the γ -quanta may actually escape the working volume of the counter; all photons of the L series and conversion and Auger electrons are recorded by the detector. The resulting response function of the Kr counter detecting particles with an energy of 9.4 keV is a Gaussian peak at the same energy with a width determined by the energy resolution of the detector ($\sigma = 420 \text{ eV}$).

Ionization in gas induced by a recoil nucleus with energy E_r is weaker than the one induced by an electron with the same energy. Recorded energy E_{vis} for an event producing an electron and a nucleus with energies E_e

and E_r , respectively, is written as $E_{vis} = E_e + q(E_r)E_r$, where $q(E_r)$ is the energy-dependent ionization quenching factor for recoil nuclei. We used the quenching factor for ^{83}Kr nuclei determined using the Lindhard model [22,23]. The value of $q(E_r)$ varies from 0.2 to 0.3 as E_r changes from 4 to 100 keV. Average value $q(E_r) = 0.25$ was used for all energies. The figure shows the calculated expected inelastic scattering energy spectrum for a WIMP with mass $m_W = 20 \text{ GeV}$ (curve 4). This spectrum was plotted with account for the energy resolution of the Kr counter.

The measured counter spectrum was fitted with an expression characterizing the continuous background, two Gaussian functions with a known energy, and the sought-for response function for WIMPs with a mass of 20 GeV. The fitting results are presented in the figure. Two well-defined Gaussian peaks are associated with X-ray emission from copper (material of the counter body) and decays of the ^{81}Kr long-lived radioactive isotope. No statistically significant response function was found for 20 GeV WIMPs; the upper limit on the number of events in the peak was $S_{\text{lim}} = 140$ counts at 90% confidence level (C.L.).

Expected number of detected inelastic WIMP scattering events $S = T N \varepsilon \sum S(E_i)$ is specified by the product of WIMP flux $\Phi_W = (\rho_W/m_W)\langle v \rangle$ ($\langle v \rangle$ is the average velocity of WIMPs), the cross section of inelastic spin-dependent interaction, measurement time $T = 6.71 \cdot 10^7 \text{ s}$, number of ^{83}Kr atoms in the counter $N = 4.19 \cdot 10^{23}$, and event detection efficiency $\varepsilon \approx 1$. Taken together with expressions (1) and (2) and the assumption that nuclear structure factor $F_{SD} \approx 1$, condition $S \leq S_{\text{lim}}$ allows one to put an upper limit on σ_0^{SD} :

$$\sigma_0^{SD} \leq 3.4 \cdot 10^{-35} \text{ cm}^2 \text{ (90\% C.L.)}. \quad (3)$$

Constraint (3) is less strict than the constraints obtained in the DAMA [4], COSINE [5], XMASS [7], and XENON [10] experiments, which used the above-mentioned scintillation and liquid xenon detectors focused on the search for elastic scattering of WIMPs on nuclei and having a significantly larger mass. An experimental search for excitation of the 9.4 keV level of ^{83}Kr nuclei has been performed for the first time. To expand the research toward smaller WIMP masses, we plan to analyze the data from an experiment with a low-temperature microcalorimeter based on a thulium garnet ($\text{Tm}_3\text{Al}_5\text{O}_{12}$) crystal that contains the ^{169}Tm isotope with a nuclear level with an energy of just 8.4 keV [24].

The energy spectrum of a large gas proportional counter filled with ^{83}Kr was analyzed in order to search for the excitation of a low-lying nuclear level with an energy of 9.4 keV by dark matter particles. The Kr counter of the low-background setup in the Baksan Neutrino Observatory of the Institute for Nuclear Research of the Russian Academy of Sciences was used to detect conversion and Auger electrons and gamma and X-ray quanta produced by decay of this level. The background spectrum was measured within the range of 4–20 keV with an energy resolution of 420 eV (σ). The spectrum obtained over 777 days

using the counter with 58 g of ^{83}Kr was analyzed to set a new constraint on the inelastic scattering cross section for WIMPs with a mass of 20 GeV: $\sigma_0^{SD} \leq 3.4 \cdot 10^{-35} \text{ cm}^2$ (90% C.L.).

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Conflict of interest

The authors declare that they have no conflict of interest.

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