Article

Electrodisintegration of Deuteron into Dark Matter and Proton Close to Threshold

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Abstract: We discuss an investigation of the dark matter decay modes of the neutron, proposed by Fornal and Grinstein (2018–2020), Berezhiani (2017, 2018) and Ivanov et al. (2018) for solution of the neutron lifetime anomaly problem, through the analysis of the electrodisintegration of the deuteron d into dark matter fermions χ and protons p close to threshold. We calculate the triple-differential cross section for the reaction $e^- + d \rightarrow \chi + p + e^-$ and propose to search for such a dark matter channel in coincidence experiments on the electrodisintegration of the deuteron $e^- + d \rightarrow n + p + e^-$ into neutrons n and protons close to threshold with outgoing electrons, protons, and neutrons in coincidence. An absence of neutron signals should testify to a detection of dark matter fermions.

Keywords: dark matter decay modes; neutron lifetime anomaly; deuteron electrodisintegration

PACS: 11.10.Ef; 13.30a; 95.35.+d; 25.40.Fq

Citation: Ivanov, A.N.; Höllwieser, R.; Troitskaya, N.I.; Wellenzohn, M.; Berdnikov, Y.A. Electrodisintegration of Deuteron into Dark Matter and Proton Close to Threshold. *Symmetry* **2021**, *13*, 2169. <https://doi.org/10.3390/sym13112169>

Academic Editors: Yuri A. Kamyshev, Zurab Berezhiani and Rabindra Mohapatra

Received: 14 July 2021

Accepted: 4 November 2021

Published: 12 November 2021

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1. Introduction

Recently, Fornal and Grinstein [1–5] proposed a solution to the neutron lifetime anomaly (NLA) problem, related to a discrepancy between experimental values of the neutron lifetime measured in bottle and beam experiments, through a contribution of the neutron dark matter decay mode $n \rightarrow \chi + e^- + e^+$, where χ is a dark matter fermion and $(e^- e^+)$ is the electron–positron pair. However, according to experimental data [6–8], the decay mode $n \rightarrow \chi + e^- + e^+$ is suppressed. So at first glimpse it seems that the decay mode $n \rightarrow \chi + e^- + e^+$ cannot explain the NLA problem. In order to overcome such a problem we have assumed [9] that an unobservability of the decay mode $n \rightarrow \chi + e^- + e^+$ may only mean that the production of the electron–positron pair in such a decay is below the reaction threshold, i.e., a mass m_χ of dark matter fermions obeys the constraint $m_\chi > m_n - 2m_e$, where m_n and m_e are masses of the neutron and electron (positron), respectively. Then, we have proposed that the NLA problem can be explained by the decay mode $n \rightarrow \chi + \nu_e + \bar{\nu}_e$, where $(\nu_e \bar{\nu}_e)$ is a neutrino–antineutrino pair [9]. Since neutrino ν_e and electron e^- belong to the same doublet in the Standard Electroweak Model (SEM) [10,11] (see also [12,13]), neutrino–antineutrino $(\nu_e \bar{\nu}_e)$ pairs couple to the neutron–dark matter current with the same strength as electron–positron $(e^- e^+)$ pairs [9]. We have extended this effective quantum field theory by a gauge invariant quantum field theory model of the neutron- and lepton–dark matter interactions invariant under the $U'_{Y'}(1) \times U''_{Y''}(1)$ gauge symmetry. In the physical phase the dark matter sectors with $U'_{Y'}(1)$ and $U''_{Y''}(1)$ symmetries are responsible for the effective interaction $(n\chi\ell\ell)$ [9] and interference of the dark matter into dynamics of neutron stars [14–17], respectively. The dark matter sector with $U''_{Y''}(1)$ symmetry we

have constructed in analogue with scenario proposed by Cline and Cornell [17]. This means that dark matter fermions with mass $m_\chi < m_n$ couple to a very light dark matter spin-1 boson Z'' providing a necessary repulsion between dark matter fermions in order to give a possibility for neutron stars to reach masses of about $2M_\odot$ [18], where $M_\odot$ is the mass of the Sun [10]. The corrected version of the dark matter sectors, invariant under the $U'_{Y'}(1) \times U''_{Y''}(1)$ gauge symmetry is expounded in [19].

In connection with different approaches to the explanation of the NLA, we have to mention another mechanism proposed by Berezhiani [20,21], which is not related to the decay of the neutron into a dark matter but based on the $n \longleftrightarrow n'$ transitions, where n' is a mirror neutron [22,23]. Since, such a mechanism is far from being applicable to the analysis of the electrodisintegration of the deuteron, we will not discuss it in this paper. Another mechanism for the explanation of the NLA proposed by Berezhiani [24], assuming the existence of the neutron decays into dark matter particles, is similar to that by Fornal and Grinstein [1–5]. So our approach to the NLA seems to be a modification of both Berezhiani's, and Fornal and Grinstein's mechanism.

We would like to notice that the existence of the reaction $n \rightarrow \chi + \nu_e + \bar{\nu}_e$ for the explanation of the NLA problem entails the existence of the reactions $n + n \rightarrow \chi + \chi$, $n + n \rightarrow \chi + \chi + \nu_e + \bar{\nu}_e$ and $\chi + \chi \rightarrow n + n$, which together with the reaction $n \rightarrow \chi + \nu_e + \bar{\nu}_e$ can serve as URCA processes for the neutron star cooling [25–27].

We would like to emphasize that a possibility to explain the NLA problem by the neutron dark matter decay mode $n \rightarrow \chi + \nu_e + \bar{\nu}_e$ is not innocent and demands to pay the following price. As has been pointed out in [9], the explanation of the neutron lifetime $\tau_n = 888.0(2.0)$ s [1] within the Standard Model with the axial coupling constant $g_A = 1.2764$ [28,29], reproducing the neutron lifetime $\tau_n = 879.6(4)$ s [30], is not possible and demands the account for the contributions of interactions beyond the Standard Model such as the Fierz interference term b [31–38] equal to $b = -1.44 \times 10^{-2}$ [39]. However, as has been shown in [39], the Fierz interference term $b = -1.44 \times 10^{-2}$ does not contradict the existing experimental data on the correlation coefficients and asymmetries of the neutron beta decay. It is obvious that the decay channel is $n \rightarrow \chi + \nu_e + \bar{\nu}_e$, since all decay particles are neutral. Hence, such mechanism of the NLA can be confirmed experimentally by experimental investigations of reactions, where an emission of a dark matter fermion χ is accompanied by an emission of charged standard model particles.

Having assumed that the results of the experimental data [6–8] can be also interpreted as a production of electron–positron pairs below reaction threshold, we may assume that the neutron dark matter decay $n \rightarrow \chi + \nu_e + \bar{\nu}_e$ can be confirmed, for example, in the process of the electrodisintegration of the deuteron into dark matter fermions and protons $e^- + d \rightarrow \chi + p + e^-$ close to threshold, induced by the $(n\chi e^- e^+)$ interaction [9].

The paper is organized as follows. In Section 2 we calculate the triple-differential cross section for the electrodisintegration of the deuteron $e^- + d \rightarrow \chi + p + e^-$ into dark matter fermions χ and protons p . In Section 3 we discuss the obtained results, make an estimate of the triple-differential cross section, calculated in Section 2, and propose an experimental observation of dark matter fermions in coincidence experiments on the electrodisintegration of the deuteron $e^- + d \rightarrow n + p + e^-$ close to threshold by detecting outgoing electrons, protons and neutrons in coincidence. An absence of neutron signals should testify to an observation of dark matter fermions.

2. Triple-Differential Cross Section for Electrodisintegration of Deuteron into Dark Matter Fermions and Protons $e^- + D \rightarrow \chi + P + e^-$

For the solution of the neutron lifetime anomaly problem we have proposed to use the following effective interaction [9,19]

$$\mathcal{L}_{\text{DMBL}}(x) = -\frac{G_F}{\sqrt{2}} V_{ud} [\bar{\psi}_\chi(x) \gamma_\mu (h_V + \bar{h}_A \gamma^5) \psi_n(x)] [\bar{\Psi}_e(x) \gamma^\mu (1 - \gamma^5) \Psi_e(x)], \quad (1)$$

where $G_F = 1.1664 \times 10^{-11} \text{ MeV}^{-2}$ is the Fermi weak coupling constant, $V_{ud} = 0.97370(14)$ is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element [10], extracted from the $0^+ \rightarrow 0^+$ transitions [10]. The phenomenological coupling constants h_V and $\bar{h}_A$ define the strength of the neutron-dark matter $n \rightarrow \chi$ transitions. Then, $\psi_\chi(x)$ and $\psi_n(x)$ are the field operators of the dark matter fermion and neutron, respectively. For the quantum field theoretic derivation of the interaction Equation (1) we refer to [19]. According to the SEM [10] (see also [12]), the field operator $\Psi_e(x)$ is the doublet with components $(\psi_{\nu_e}(x), \psi_e(x))$, where $\psi_{\nu_e}(x)$ and $\psi_e(x)$ are the field operators of the electron-neutrino (electron-antineutrino) and electron (positron), respectively. The leptonic current $\bar{\Psi}_e(x)\gamma^\mu(1-\gamma^5)\Psi_e(x)$ has the $V-A$ structure, since electron-neutrinos are practically left-handed. The amplitude of the reaction $e^- + d \rightarrow \chi + p + e^-$ is defined by

$$M(e^- d \rightarrow \chi p e^-)_{\sigma_e, \lambda_d}^{\sigma_\chi, \sigma_p, \sigma'_e} = -\frac{G_F}{\sqrt{2}} V_{ud} \langle p(\vec{k}_p, \sigma_p) \chi(\vec{k}_\chi, \sigma_\chi) | [\bar{\psi}_\chi(0) \gamma_\mu (h_V + \bar{h}_A \gamma^5) \psi_n(0)] | d(\vec{k}_d, \lambda_d) \rangle \times [\bar{u}_e(\vec{k}'_e, \sigma'_e) \gamma^\mu (1 - \gamma^5) u_e(\vec{k}_e, \sigma_e)], \quad (2)$$

where $\lambda_d = 0, \pm 1$ define the polarization states of the deuteron, $\bar{u}_e(\vec{k}'_e, \sigma'_e)$ and $u_e(\vec{k}_e, \sigma_e)$ are Dirac wave functions of free electrons in the final and initial states of the reaction. In the matrix element of the $d \rightarrow \chi + p$ transition $\langle p(\vec{k}_p, \sigma_p) \chi(\vec{k}_\chi, \sigma_\chi) |$ and $|d(\vec{k}_d, \lambda_d)\rangle$ are the wave functions of the dark matter fermion and proton in the final state and the deuteron in the initial one. They are defined by [40]

$$\langle p(\vec{k}_p, \sigma_p) \chi(\vec{k}_\chi, \sigma_\chi) | = \langle 0 | a_\chi(\vec{k}_\chi, \sigma_\chi) a_p(\vec{k}_p, \sigma_p) \quad (3)$$

and

$$|d(\vec{k}_d, \lambda_d = \pm 1)\rangle = \frac{1}{(2\pi)^3} \int \frac{d^3 q_p}{\sqrt{2E_p(\vec{q}_p)}} \frac{d^3 q_n}{\sqrt{2E_n(\vec{q}_n)}} \sqrt{2E_d(\vec{q}_p + \vec{q}_n)} \delta^{(3)}(\vec{k}_d - \vec{q}_p - \vec{q}_n) \times \Phi_d\left(\frac{\vec{q}_p - \vec{q}_n}{2}\right) a_p^\dagger(\vec{q}_p, \pm 1/2) a_n^\dagger(\vec{q}_n, \pm 1/2) |0\rangle, \\ |d(\vec{k}_d, \lambda_d = 0)\rangle = \frac{1}{(2\pi)^3} \int \frac{d^3 q_p}{\sqrt{2E_p(\vec{q}_p)}} \frac{d^3 q_n}{\sqrt{2E_n(\vec{q}_n)}} \sqrt{2E_d(\vec{q}_p + \vec{q}_n)} \delta^{(3)}(\vec{k}_d - \vec{q}_p - \vec{q}_n) \times \Phi_d\left(\frac{\vec{q}_p - \vec{q}_n}{2}\right) \frac{1}{\sqrt{2}} [a_p^\dagger(\vec{q}_p, +1/2) a_n^\dagger(\vec{q}_n, -1/2) + a_p^\dagger(\vec{q}_p, -1/2) a_n^\dagger(\vec{q}_n, +1/2)] |0\rangle, \quad (4)$$

where $|0\rangle$ is the vacuum wave function, $a_j^\dagger(\vec{p}_j, \sigma_j)$ and $a_j(\vec{p}_j, \sigma_j)$ are operators of creation and annihilation of a fermion $j = n, p, \chi$ with a 3-momentum $\vec{p}_j$ and polarization $\sigma_j = \pm 1/2$ obeying standard relativistic covariant anti-commutation relations [40]. Then, $\Phi_d(\vec{k})$ is the component of the wave function of the bound np -pair in the 3S_1 state defined in the momentum representation. It is normalized to unity [40] (see also [41]):

$$\int |\Phi_d(\vec{k})|^2 d^3 k / (2\pi)^3 = 1. \quad (5)$$

We neglect the contribution of the component of the wave function of the bound np -pair in the 3D_1 -state [42–44] (see also [41,45]), which is not important for the analysis of the electrodisintegration of the deuteron into dark matter fermions and protons. The wave function of the deuteron Equation (4) is normalized by [40]:

$$\langle d(\vec{k}'_d, \lambda'_d) | d(\vec{k}_d, \lambda_d) \rangle = (2\pi)^3 2E_d(\vec{k}_d) \delta^{(3)}(\vec{k}'_d - \vec{k}_d) \delta_{\lambda'_d \lambda_d}. \quad (6)$$

In the non-relativistic approximation for heavy fermions and in the laboratory frame, where the deuteron is at rest, the amplitudes of the electrodisintegration of the deuteron into dark matter fermions and protons are determined by

$$\begin{aligned}
M(e^- d \rightarrow \chi p e^-)_{\sigma_e, \lambda_d = \pm 1}^{\sigma_\chi, \sigma_p, \sigma'_e} &= -\sqrt{4m_d m_n m_\chi} G_F V_{ud} \Phi_d(\vec{k}_p) \delta_{\sigma_p, \pm 1/2} \left(h_V [\varphi_\chi^\dagger(\sigma_\chi) \varphi_n(\pm 1/2)] \right. \\
&\times [\bar{u}'_e(\vec{k}'_e, \sigma'_e) \gamma^0 (1 - \gamma^5) u_e(\vec{k}_e, \sigma_e)] - \bar{h}_A [\varphi_\chi^\dagger(\sigma_\chi) \vec{\sigma} \varphi_n(\pm 1/2)] \cdot [\bar{u}'_e(\vec{k}'_e, \sigma'_e) \vec{\gamma} (1 - \gamma^5) u_e(\vec{k}_e, \sigma_e)] \Big), \\
M(e^- d \rightarrow \chi p e^-)_{\sigma_e, \lambda_d = 0}^{\sigma_\chi, \sigma_p, \sigma'_e} &= -\sqrt{2m_d m_n m_\chi} G_F V_{ud} \Phi_d(\vec{k}_p) \left\{ \delta_{\sigma_p, +1/2} \left(h_V [\varphi_\chi^\dagger(\sigma_\chi) \varphi_n(-1/2)] \right. \right. \\
&\times [\bar{u}'_e(\vec{k}'_e, \sigma'_e) \gamma^0 (1 - \gamma^5) u_e(\vec{k}_e, \sigma_e)] - \bar{h}_A [\varphi_\chi^\dagger(\sigma_\chi) \vec{\sigma} \varphi_n(-1/2)] \cdot [\bar{u}'_e(\vec{k}'_e, \sigma'_e) \vec{\gamma} (1 - \gamma^5) u_e(\vec{k}_e, \sigma_e)] \Big) \\
&+ \delta_{\sigma_p, -1/2} \left(h_V [\varphi_\chi^\dagger(\sigma_\chi) \varphi_n(+1/2)] [\bar{u}'_e(\vec{k}'_e, \sigma'_e) \gamma^0 (1 - \gamma^5) u_e(\vec{k}_e, \sigma_e)] - \bar{h}_A [\varphi_\chi^\dagger(\sigma_\chi) \vec{\sigma} \varphi_n(+1/2)] \right. \\
&\cdot [\bar{u}'_e(\vec{k}'_e, \sigma'_e) \vec{\gamma} (1 - \gamma^5) u_e(\vec{k}_e, \sigma_e)] \Big) \Big\}, \tag{7}
\end{aligned}$$

where $\varphi_\chi(\sigma_\chi)$ and $\varphi_n(\sigma_n)$ are the Pauli wave functions of the dark matter fermion and neutron, respectively, $\vec{\sigma}$ are 2×2 Pauli matrices, $m_d = m_n + m_p + \varepsilon_d$ is the deuteron mass, m_n and m_p are masses of the neutron and proton, and $\varepsilon_d = -2.224575(9)$ MeV is the deuteron binding energy [46], and m_χ is the dark matter fermion mass. The differential cross section for the reaction $e^- + d \rightarrow \chi + p + e^-$, averaged over polarizations of the incoming electron and deuteron and summed over polarizations of the fermions in the final state, is equal to

$$\begin{aligned}
d^9 \sigma(E'_e, E_e, \vec{k}'_e, \vec{k}_e, \vec{k}_\chi, \vec{k}_p) &= (1 + 3g_A^2) \frac{G_F^2 |V_{ud}|^2}{8\pi^5} \frac{\zeta^{(\text{dm})}}{\beta_e} \left(1 + a^{(\text{dm})} \frac{\vec{k}'_e \cdot \vec{k}_e}{E'_e E_e} \right) |\Phi_d(\vec{k}_p)|^2 \delta(E'_e + E_p + E_\chi - m_d - E_e) \\
&\times \delta^{(3)}(\vec{k}_\chi + \vec{k}_p + \vec{k}'_e - \vec{k}_e) d^3 k_\chi d^3 k_p d^3 k'_e, \tag{8}
\end{aligned}$$

where $\beta_e = k_e/E_e$ is the incoming electron velocity and $g_A = 1.27641(56)$ is the axial coupling constant [28,29] introduced in [9] for convenience. The correlation coefficients $\zeta^{(\text{dm})}$ and $a^{(\text{dm})}$ are defined by [9]

$$\zeta^{(\text{dm})} = \frac{1}{1 + 3g_A^2} (|h_V|^2 + 3|\bar{h}_A|^2) = \frac{0.018}{(m_n - m_\chi)^5}, \quad a^{(\text{dm})} = \frac{|h_V|^2 - |\bar{h}_A|^2}{|h_V|^2 + 3|\bar{h}_A|^2}, \tag{9}$$

where $m_n - m_\chi$ is measured in MeV. In the non-relativistic approximation for the dark matter fermion and proton and in the center-of-mass frame of the χp -pair we transcribe Equation (8) into the form

$$\begin{aligned}
d^9 \sigma(E'_e, E_e, \vec{k}'_e, \vec{k}_e, \vec{p}, \vec{k}) &= (1 + 3\lambda^2) \frac{G_F^2 |V_{ud}|^2}{8\pi^5} \frac{\zeta^{(\text{dm})}}{\beta_e} \left(1 + a^{(\text{dm})} \frac{\vec{k}'_e \cdot \vec{k}_e}{E'_e E_e} \right) \left| \Phi_d \left(\vec{k} + \frac{m_p}{m_p + m_\chi} \vec{p} \right) \right|^2 \\
&\times \delta \left(\frac{p^2}{2M} + \frac{k^2}{2\mu} - (\mathcal{E}_0 + E_e - E'_e) \right) \delta^{(3)}(\vec{p} + \vec{k}'_e - \vec{k}_e) d^3 p d^3 k d^3 k'_e, \tag{10}
\end{aligned}$$

where $\mathcal{E}_0 = m_n - m_\chi + \varepsilon_d$, $\vec{p}$ and $\vec{k}$ are the total and relative 3-momenta of the χp -pair, related to the 3-momenta of the dark matter fermion $\vec{k}_\chi$ and the proton $\vec{k}_p$ as follows

$$\vec{k}_\chi = -\vec{k} + \frac{m_\chi}{m_p + m_\chi} \vec{p}, \quad \vec{k}_p = \vec{k} + \frac{m_p}{m_p + m_\chi} \vec{p}. \tag{11}$$

Then, $M = m_p + m_\chi$ and $\mu = m_p m_\chi / (m_p + m_\chi)$ are the total and reduced masses of the χp -pair. Having integrated over $\vec{p}$ we arrive at the expression

$$\begin{aligned}
d^6 \sigma(E'_e, E_e, \vec{k}'_e, \vec{k}_e, \vec{k}) &= \frac{\mu}{2\pi^2} \frac{\zeta^{(\text{dm})}}{\tau_n f_n \beta_e} \left(1 + a^{(\text{dm})} \frac{\vec{k}'_e \cdot \vec{k}_e}{E'_e E_e} \right) \left| \Phi_d \left(\vec{k} + \frac{m_p}{m_p + m_\chi} \vec{q} \right) \right|^2 \\
&\times \delta \left(k^2 - 2\mu(\mathcal{E}_0 + E_e - E'_e) + \frac{\mu}{M} q^2 \right) d^3 k d^3 k'_e, \tag{12}
\end{aligned}$$

where $\vec{q} = \vec{k}_e - \vec{k}'_e$ [47] and $q^2 = \vec{q}^2$, and we have used the definition of the neutron lifetime $1/\tau_n = (1 + 3g_A^2) G_F^2 |V_{ud}|^2 f_n / 2\pi^3$ [30]. Following Arenhövel [47] and Arenhövel et al. [48] we define the triple-differential cross section in the center-of-mass frame of the χp -pair and in the laboratory frame of incoming and outgoing electrons

$$\frac{d^5\sigma(E'_e, E_e, \vec{k}'_e, \vec{k}_e, \vec{n})}{dE'_e d\Omega_e d\Omega_{\vec{n}}} = \frac{\mu}{4\pi^2} \frac{\zeta^{(\text{dm})}}{\tau_n f_n \beta_e} k'_e E'_e \left(1 + a^{(\text{dm})} \frac{\vec{k}'_e \cdot \vec{k}_e}{E'_e E_e}\right) \Theta\left(m_p(\mathcal{E}_0 + E_e - E'_e) - \frac{1}{4}q^2\right) \times \sqrt{2\mu(\mathcal{E}_0 + E_e - E'_e) - \frac{\mu}{M}q^2} \left|\Phi_d\left(\vec{n}\sqrt{2\mu(\mathcal{E}_0 + E_e - E'_e) - \frac{\mu}{M}q^2} + \frac{m_p}{m_p + m_\chi}\vec{q}\right)\right|^2, \quad (13)$$

where $\Theta(z)$ is the Heaviside function, $\vec{n} = \vec{k}/k$, $d\Omega_e = 2\pi \sin\theta_e d\theta_e$ and $d\Omega_{\vec{n}} = \sin\theta d\theta d\phi$ with the standard definition of the kinematics of the electrodisintegration of the deuteron [47,48] (see Figure 1 of Refs. [47,48]), where $\vec{k}'_e \cdot \vec{k}_e = k'_e k_e \cos\theta_e$ and $\vec{n} \cdot \vec{q} = q \cos\theta$. Then, it is convenient to transcribe Equation (13) into the form

$$\frac{d^5\sigma(E'_e, E_e, \vec{k}'_e, \vec{k}_e, \vec{n})}{dE'_e d\Omega_e d\Omega_{\vec{n}}} = \frac{m_p}{8\pi^2} \frac{\zeta^{(\text{dm})}}{\tau_n f_n \beta_e} k'_e E'_e \left(1 + a^{(\text{dm})} \frac{\vec{k}'_e \cdot \vec{k}_e}{E'_e E_e}\right) \Theta\left(m_p(\mathcal{E}_0 + E_e - E'_e) - \frac{1}{4}q^2\right) \times \sqrt{m_p(\mathcal{E}_0 + E_e - E'_e) - \frac{1}{4}q^2} \left|\Phi_d\left(\vec{n}\sqrt{m_p(\mathcal{E}_0 + E_e - E'_e) - \frac{1}{4}q^2} + \frac{1}{2}\vec{q}\right)\right|^2. \quad (14)$$

For the wave function of the deuteron $\Phi_d(\vec{\ell})$ we may use the expression

$$\Phi_d(\vec{\ell}) = \sqrt{\frac{8\pi}{\sum_{i=1}^n \sum_{j=1}^n \frac{C_i C_j}{m_i m_j (m_i + m_j)^3}}} \sum_{i=1}^n \frac{C_i}{m_i^2 + \ell^2}, \quad \int \frac{d^3\ell}{(2\pi)^3} |\Phi_d(\vec{\ell})|^2 = 1 \quad (15)$$

with parameters C_i and m_i taken from the paper by Machleidt et al. [42]. Also we may follow Gilman and Gross [45] and describe the wave function $\Phi_d(\vec{\ell})$ by the expression

$$\Phi_d(\vec{\ell}) = \frac{\sqrt{8\pi\sqrt{-m_N \varepsilon_d}}}{(-m_N \varepsilon_d + \ell^2) \left(1 + \frac{\ell^2}{p_0^2}\right)} \left(1 - \frac{m_N \varepsilon_d}{p_0^2}\right)^{3/2}, \quad \int \frac{d^3\ell}{(2\pi)^3} |\Phi_d(\vec{\ell})|^2 = 1, \quad (16)$$

where $-m_N \varepsilon_d = 0.940 \times 2.224 \times 10^{-3} \text{ GeV}^2 = 2.09 \times 10^{-3} \text{ GeV}^2$ and $p_0^2 = 0.15 \text{ GeV}^2$ [45]. The squared 3-momenta ℓ^2 and q^2 are defined by

$$\begin{aligned} \ell^2 &= m_p(\mathcal{E}_0 + E_e - E'_e) + q\sqrt{m_p(\mathcal{E}_0 + E_e - E'_e) - \frac{1}{4}q^2} \cos\theta, \\ q^2 &= (\vec{k}_e - \vec{k}'_e)^2 = (k_e - k'_e)^2 + 4k'_e k_e \sin^2 \frac{\theta_e}{2}. \end{aligned} \quad (17)$$

Using the definition of the correlation coefficient $\zeta^{(\text{dm})}$ (see Equation (9)) we may rewrite the triple-differential cross section Equation (16) as follows

$$\frac{d^5\sigma(E'_e, E_e, \vec{k}'_e, \vec{k}_e, \vec{n})}{dE'_e d\Omega_e d\Omega_{\vec{n}}} = \sigma_0 \frac{k'_e E'_e}{16\pi^2 \beta_e} \left(1 + a^{(\text{dm})} \frac{\vec{k}'_e \cdot \vec{k}_e}{E'_e E_e}\right) \Theta\left(m_p(\mathcal{E}_0 + E_e - E'_e) - \frac{1}{4}q^2\right) \\ \times \sqrt{m_p(\mathcal{E}_0 + E_e - E'_e) - \frac{1}{4}q^2} \left| \Phi_d \left(\sqrt{m_p(\mathcal{E}_0 + E_e - E'_e) + q\sqrt{m_p(\mathcal{E}_0 + E_e - E'_e) - \frac{1}{4}q^2} \cos \theta} \right) \right|^2, \quad (18)$$

where all momenta and energies and the dimension of the wave function of the deuteron are measured in MeV. Then, the scale parameter σ_0 is equal to

$$\sigma_0 = 2m_p \frac{\zeta^{(\text{dm})}}{\tau_n f_n} = 6.4 \left(\frac{0.12}{m_n - m_\chi} \right)^5 \frac{\text{fb}}{\text{MeV}}. \quad (19)$$

The triple-differential cross section for the reaction $e^- + d \rightarrow \chi + p + e^-$, given by Equation (18), can be used for the analysis of the experimental data on searches for dark matter fermions in coincidence experiments [49–51]. For $(m_n - m_\chi) \simeq 0.023$ MeV (see [19]) the scale parameter σ_0 increases by four orders of magnitude $\sigma_0 \simeq 24.7$ pb/MeV.

3. Discussion

We have analyzed the electrodisintegration of the deuteron into dark matter fermions and protons $e^- + d \rightarrow \chi + p + e^-$ close to threshold. Such a disintegration is induced by the electron–neutron inelastic scattering $e^- + n \rightarrow \chi + e^-$ with energies of incoming electrons larger than the deuteron binding energy $|\varepsilon_d| = 2.224575(9)$ MeV. The strength of the reaction $e^- + n \rightarrow \chi + e^-$ is caused by the strength of the neutron dark matter decay mode $n \rightarrow \chi + \nu_e + \bar{\nu}_e$, which has been proposed in [9] for an explanation of the neutron lifetime anomaly in case of an unobservability (see [6,7]) of the dark matter decay mode $n \rightarrow \chi + e^- + e^+$ [1], where the production of the electron–positron pair can be below the reaction threshold [9]. Following such an assumption that the production of the electron–positron pair can be below the reaction threshold for a confirmation of an existence of the dark matter decay mode $n \rightarrow \chi + e^- + e^+$ we have proposed in [9] to analyze the low-energy electron–neutron inelastic scattering $e^- + n \rightarrow \chi + e^-$, which can be in principle distinguished above the background of the low-energy electron–neutron elastic scattering $e^- + n \rightarrow n + e^-$.

The effective interaction Equation (1) is supported by the effective quantum field theory model with gauge $SU_L(2) \times U_Y(1) \times U'_R(1) \times U''_L(1)$ symmetry, where the SM and dark matter sectors are described by the effective low-energy Lagrangian $\mathcal{L}_{\text{L}\&\text{M}\&\text{SET}\&\text{DM}'\&\text{DM}''}$ [19]. The SM part of this effective field theory, determined by the effective low-energy Lagrangian $\mathcal{L}_{\text{L}\&\text{M}\&\text{SET}}$ invariant under $SU(2)_L \times U_Y(1)$ gauge symmetry, is gauge invariant and renormalizable [12,13]. This has been demonstrated in [12,13] by examples of the calculation of the radiative corrections of order $O(\alpha E_e/m_N)$ to the neutron lifetime and correlation coefficients of the neutron beta decay [52]. As has been shown in [9,19] such a quantum field theory model allows (i) to derive the effective interaction Equation (1) in the tree approximation for the dark matter spin–1 boson Z' exchanges with $h_V = h_A$ (see [19]), and (ii) following the scenario by Cline and Cornell [17] to show that dynamics of dark matter fermions with mass $m_\chi < m_n \sim 1$ GeV and a light dark matter spin–1 boson Z'' , responsible for a repulsion between dark matter fermions, does not prevent neutron stars to reach masses of about $2M_\odot$. It has also been noticed [9] that the processes $n \rightarrow \chi + \nu_e + \bar{\nu}_e$, $n + n \rightarrow \chi + \chi$, $n + n \rightarrow \chi + \chi + \nu_e + \bar{\nu}_e$ and $\chi + \chi \rightarrow n + n$, allowed in such a quantum field theory model, can serve as URCA processes for the neutron star cooling [25–27]. The effective quantum field theory, described by the Lagrangian $\mathcal{L}_{\text{L}\&\text{M}\&\text{SET}\&\text{DM}'\&\text{DM}''}$ [19] is fully a low-energy theory. The application of this effective theory to the analysis of the searches of dark matter in the LHC experiments is not straightforward and demands special consideration, which we are planing to carry out in our forthcoming publication.

However, in order to have more processes with particles of the Standard Model in the initial and final states allowing to search dark matter in terrestrial laboratories we have turned to the analysis of the dark matter decay mode $n \rightarrow \chi + e^- + e^+$ through the electrodisintegration of the deuteron $e^- + d \rightarrow \chi + p + e^-$ induced by the interaction $(n\chi e^- e^+)$ [9]. We have calculated the triple-differential cross section for the reaction $e^- + d \rightarrow \chi + p + e^-$ (see Equation (18)), which can be used for the analysis of traces of dark matter in coincidence experiments on the electrodisintegration of the deuteron $e^- + d \rightarrow n + p + e^-$ close to threshold [49–51]. An important property of this cross section is its independence of the azimuthal angle ϕ between the scattering and reaction planes (see Figure 1 of Ref. [48]). Using the experimental conditions of Ref. [51]: $E_e = 50$ MeV, $E_x = E_e - E'_e = 8$ MeV, $\theta_e = 40^\circ$, $\theta = 0$ and the wave function of the deuteron Equation (16) we predict the triple-differential cross section for the reaction $e^- + d \rightarrow \chi + p + e^-$ equal to

$$16\pi^2 \frac{d^5\sigma(E'_e, E_e, \vec{k}'_e, \vec{k}_e, \vec{n})}{dE'_e d\Omega_e d\Omega_{\vec{n}}} \Big|_{E_e, E_x=8 \text{ MeV}, \theta_e=40^\circ, \theta=0} = \left(\frac{0.12}{m_n - m_\chi}\right)^5 \left\{ \begin{array}{l} 9, E_e = 50 \text{ MeV} \\ 21, E_e = 85 \text{ MeV} \end{array} \frac{\text{fb}}{\text{MeV}'} \right. \quad (20)$$

where we have set $a^{(\text{dm})} = 0$ [9]. Following [49] we define the ratio $R(\theta)$ of the triple-differential cross section at fixed E_e, E_x, θ_e and $0 \leq \theta \leq 180^\circ$ to the triple-differential cross section at fixed E_e, E_x, θ_e and $\theta = 0^\circ$. We get

$$R(\theta) = \frac{\left| \Phi_d \left(\sqrt{m_p(\mathcal{E}_0 + E_e - E'_e) + q \sqrt{m_p(\mathcal{E}_0 + E_e - E'_e) - \frac{1}{4}q^2 \cos \theta}} \right) \right|^2}{\left| \Phi_d \left(\sqrt{m_p(\mathcal{E}_0 + E_e - E'_e) + q \sqrt{m_p(\mathcal{E}_0 + E_e - E'_e) - \frac{1}{4}q^2}} \right) \right|^2}. \quad (21)$$

In Figure 1 we plot the ratio $R(\theta)$ for the experimental conditions of [51] and $0 \leq \theta \leq 180^\circ$. For $E_e = 50$ MeV and $E_e = 85$ MeV the 3-momentum transferred q is equal to $q = 0.16 \text{ fm}^{-1}$ and $q = 0.28 \text{ fm}^{-1}$, respectively.

Figure 1. The ratio $R(\theta)$ of the triple-differential cross sections for the electrodisintegration of the deuteron $e^- + d \rightarrow \chi + p + e^-$ for the energies $E_e = 50$ MeV (red curve) and $E_e = 85$ MeV (blue curve), $E_x = 8$ MeV, $E'_e = E_e - E_x$ and $\theta_e = 40^\circ$ [51].

Of course, the value of the triple-differential cross section Equation (18) is sufficiently small. Its strong dependence on the mass difference $m_n - m_\chi$ looks rather promising but cannot guarantee a real enhancement of the cross section. Nevertheless, we believe that an observation of the electrodisintegration of the deuteron into dark matter fermions and protons close to threshold can be performed in coincidence experiments on the electrodisintegration of the deuteron. Indeed, in [49,51] the electrodisintegration of the deuteron $e^- + d \rightarrow n + p + e^-$ has been investigated close to threshold detecting outgoing electrons and protons from the np -pairs in coincidence.

We propose to detect dark matter fermions from the electrodisintegration of the deuteron $e^- + d \rightarrow \chi + p + e^-$ above the background $e^- + d \rightarrow n + p + e^-$ by detecting outgoing electrons, protons, and neutrons in coincidence. Since the kinetic energies of the center-of-mass and relative motion of the np -pairs (or χp -pairs) are equal to $(T_{(n/\chi)+p} = q^2/2M = 0.28 \text{ MeV}, T_{(n/\chi)p} = k^2/2\mu = 5.61 \text{ MeV})$ and $(T_{(n/\chi)+p} = q^2/2M =$

0.83 MeV, $T_{(n/\chi)p} = k^2/2\mu = 5.06$ MeV) for $E_e = 50$ MeV and $E_e = 85$ MeV, respectively, $E_x = 8$ MeV and $\theta_e = 40^\circ$, neutrons should be detected with kinetic energies $T_{(n/\chi)p} < 6$ MeV in the direction practically opposite to the direction of protons. An absence of neutron signals at simultaneously detected signals of protons and outgoing electrons should testify to an observation of dark matter fermions in the final state of the electrodisintegration of the deuteron close to threshold. The electron-energy and angular distribution of these events with an absence of neutron signals should be compared with the distribution given by Equation (18).

Finally we would like notice that it would be very interesting to understand an influence of the reactions $n \rightarrow \chi + \nu_e + \bar{\nu}_e$, $e^- + n \rightarrow \chi + e^-$, $e^- + d \rightarrow \chi + p + e^-$, $\nu_e(\bar{\nu}_e) + n \rightarrow \chi + \nu_e(\bar{\nu}_e)$ and $\nu_e(\bar{\nu}_e) + d \rightarrow \chi + p + \nu_e(\bar{\nu}_e)$, which are caused by the same interaction Equation (1), on a formation of dark matter in the Universe during the evolution of the Universe [53–56].

Author Contributions: A.N.I.: Conceptualization, Methodology, Data Curation, Investigation, Supervision, Writing—Original draft preparation, R.H.: Methodology, Investigation, Formal analysis, Visualization, Writing—Original draft preparation, N.I.T.: Methodology, Investigation, Writing—Original draft, M.W.: Methodology, Investigation, Formal analysis, Visualization, Writing—Original draft preparation, Y.A.B.: Data Curation, Methodology, Validation. All authors have read and agreed to the published version of the manuscript.

Funding: The work of A.N.I. was supported by the Austrian “Fonds zur Förderung der Wissenschaftlichen Forschung” (FWF) under contracts P31702-N27 and P26636-N20 and “Deutsche Forschungsgemeinschaft” (DFG) AB 128/5-2. The work of R.H. was supported by the Deutsche Forschungsgemeinschaft in the SFB/TR 55. The work of M.W. was supported by the MA 23.

Acknowledgments: We are grateful to Hartmut Abele for fruitful discussions stimulating the work under this paper.

Conflicts of Interest: The authors state that there is no conflict of interest.

References

1. Fornal, B.; Grinstein, B. Dark matter interpretation of the neutron decay anomaly. *Phys. Rev. Lett.* **2018**, *210*, 191801. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Fornal, B.; Grinstein, B. Dark side of the neutron? *EPJ Web Conf.* **2019**, *219*, 05005. [\[CrossRef\]](#)
3. Fornal, B.; Grinstein, B. Dark particle interpretation of the neutron decay anomaly. *J. Phys. Conf. Ser.* **2019**, *1308*, 012010. [\[CrossRef\]](#)
4. Fornal, B.; Grinstein, B. Dark matter capture by atomic nuclei. *Phys. Lett. B* **2020**, *811*, 135869. [\[CrossRef\]](#)
5. Fornal, B.; Grinstein, B. Neutron’s dark secret. *Mod. Phys. Lett. A* **2020**, *35*, 2030019. [\[CrossRef\]](#)
6. Tang, Z.; Blatnik, M.; Broussard, L.J.; Choi, J.H.; Clayton, S.M.; Cude-Woods, C.; Currie, S.; Fellers, D.E.; Fries, E.M.; Geltenbort, P.; et al. Search for the neutron decay $n \rightarrow X + \gamma$, where X is a dark matter particle. *Phys. Rev. Lett.* **2018**, *121*, 022505. [\[CrossRef\]](#) [\[PubMed\]](#)
7. Sun, X.; Adamek, E.; Allgeier, B.; Blatnik, M.; Bowles, T.J.; Broussard, L.J.; Brown, M.P.; Carr, R.; Clayton, S.; Cude-Woods, C.; et al. Search for dark matter decay of the free neutron from the UCNA experiment: $n \rightarrow \chi + e^- + e^+$. *Phys. Rev. C* **2018**, *97*, 052501. [\[CrossRef\]](#)
8. Klopfer, M.; Jericha, E.; Märksch, B.; Saul, H.; Soldner, T.; Abele, H. Constraints on the dark matter interpretation $n \rightarrow \chi + e^+ + e^-$ of the neutron decay anomaly with the PERKEO II experiment. *Phys. Rev. Lett.* **2019**, *122*, 222503. [\[CrossRef\]](#)
9. Ivanov, A.N.; Höllwieser, R.; Troitskaya, N.I.; Wellenzohn, M.; Berdnikov, Y.A. Neutron dark matter decays. *arXiv* **2018**, arXiv:1806.10107.
10. Particle Data Group; Zyla, P.; Barnett, R.M.; Beringer, J.; Dahl, O.; Dwyer, D.A.; Groom, D.E.; Lin, C.J.; Lugovsky, K.S.; Pianori, E.; et al. Review of particle physics. *Prog. Theor. Exp. Phys.* **2020**, *2020*, 083C01. [\[CrossRef\]](#)
11. Gonoghue, J.F.; Golowich, E.; Holstein, B.R. *Dynamics of the Standard Model*, 2nd ed.; Cambridge University Press: Cambridge, UK, 2014. [\[CrossRef\]](#)
12. Ivanov, A.N.; Höllwieser, R.; Troitskaya, N.I.; Wellenzohn, M.; Berdnikov, Y.A. Radiative corrections of order $O(\alpha E_e/m_N)$ to Sirlin’s radiative corrections of order $O(\alpha/\pi)$ to the neutron lifetime. *Phys. Rev. D* **2019**, *99*, 093006. [\[CrossRef\]](#)
13. Ivanov, A.N.; Höllwieser, R.; Troitskaya, N.I.; Wellenzohn, M.; Berdnikov, Y.A. Radiative corrections of order $O(\alpha E_e/m_N)$ to Sirlin’s radiative corrections of order $O(\alpha/\pi)$, induced by hadronic structure of the neutron. *Phys. Rev. D* **2021**, *103*, 113007. [\[CrossRef\]](#)

14. McKeen, D.; Nelson, A.E.; Reddy, S.; Zhou, D. Neutron stars exclude light dark baryons. *Phys. Rev. Lett.* **2018**, *121*, 061802. [CrossRef] [PubMed]
15. Baym, G.; Beck, D.H.; Geltenbort, P.; Shelton, J. Testing dark decays of baryons in neutron stars. *Phys. Rev. Lett.* **2018**, *121*, 061801. [CrossRef] [PubMed]
16. Motta, T.F.; Guichon, P.A.M.; Thomas, A.W. Implications of neutron star properties for the existence of light dark matter. *arXiv* **2018**, arXiv:1802.08427.
17. Cline, J.M.; Cornell, J.M. Dark decay of the neutron. *J. High Energ. Phys.* **2018**, *2018*, 81. [CrossRef]
18. Demorest, P.; Pennucci, T.; Ransom, S.; Roberts, M.; Hessels, J. Shapiro delay measurement of a two solar mass neutron star. *Nature* **2010**, *467*, 1081. [CrossRef]
19. Ivanov, A.N.; Höllwieser, R.; Troitskaya, N.I.; Wellenzohn, M.; Berdnikov, Y.A. Electrodisintegration of deuteron into dark matter and proton close to threshold. *arXiv* **2018**, arXiv:807.04604.
20. Berezhiani, Z. Unusual Effects in $n - n'$ conversion, Talk at INT Workshop INT-17-69W, Seattle, 23–27 October 2017. Available online: http://www.int.washington.edu/talks/WorkShops/int_17_69W/People/Berezhiani_Z/Berezhiani3.pdf (accessed on 5 November 2021).
21. Berezhiani, Z. Neutron lifetime puzzle and neutron-mirror neutron oscillation. *Eur. Phys. J. C* **2019**, *79*, 484. [CrossRef]
22. Berezhiani, Z.; Frost, M.; Kamyshkov, Y.; Rybolt, B.; Varriano, L. Neutron disappearance and regeneration from mirror state. *Phys. Rev. D* **2017**, *96*, 035039. [CrossRef]
23. Berezhiani, Z.; Biondi, R.; Geltenbort, P.; Krasnoshchekova, I.A.; Varlamov, V.E.; Vassiljev, A.V.; Zhrebtsov, O.M. New experimental limits on neutron - mirror neutron oscillations in the presence of mirror magnetic field. *Eur. Phys. J. C* **2018**, *78*, 717. [CrossRef]
24. Berezhiani, Z. Neutron lifetime and dark decay of the neutron and hydrogen. *LHEP* **2019**, *2*, 118. [CrossRef]
25. Gamow, G.; Schönberg, M. Neutrino theory of stellar collapse. *Phys. Rev.* **1941**, *59*, 539. [CrossRef]
26. Friman, B.L.; Maxwell, O.V. Neutrino emissivities of neutron stars. *ApJ* **1979**, *232*, 541. [CrossRef]
27. Hänsel, P. Urca processes in dense matter and neutron star cooling. *Space Sci. Rev.* **1995**, *74*, 427. BF00751429. [CrossRef]
28. Märkisch, B.; Mest, H.; Saul, H.; Wang, X.; Abele, H.; Dubbers, D.; Klopff, M.; Petoukhov, A.; Roick, C.; Soldner, T.; Werder, D. Measurement of the weak axial-vector coupling constant in the decay of free neutrons using a pulsed cold neutron beam. *Phys. Rev. Lett.* **2019**, *122*, 242501. [CrossRef] [PubMed]
29. Czarnecki, A.; Marciano, W.J.; Sirlin, A. The neutron lifetime and axial coupling constant connection. *Phys. Rev. Lett.* **2018**, *120*, 202002. [CrossRef]
30. Ivanov, A.N.; Pitschmann, M.; Troitskaya, N.I. Neutron beta decay as a laboratory for testing the standard model. *Phys. Rev. D* **2013**, *88*, 073002. [CrossRef]
31. Fierz, M. Zur Fermischen Theorie des β -Zerfalls. *Z. Physik* **1937**, *104*, 553. [CrossRef]
32. Jackson, J.D.; Treiman, S.B.; Wyld, H.W., Jr. Possible tests of time reversal invariance in beta decay. *Phys. Rev.* **1957**, *106*, 517. [CrossRef]
33. Hardy, J.C.; Towner, I.S. Superallowed $0^+ \rightarrow 0^+$ nuclear beta decays: 2020 critical survey, with implications for V_{ud} and CKM unitarity. *Phys. Rev. C* **2020**, *102*, 045501. [CrossRef]
34. González-Alonso, M.; Naviliat-Cuncic, O.; Severijns, N. New physics searches in nuclear and neutron beta decay. *Prog. Part. Nucl. Phys.* **2019**, *104*, 165. [CrossRef]
35. Saul, H.; Roick, C.; Abele, H.; Mest, H.; Klopff, M.; Petukhov, A.; Soldner, T.; Wang, X.; Werder, D.; Märkisch, B. Limit on the Fierz interference term b from a measurement of the beta asymmetry in neutron decay. *Phys. Rev. Lett.* **2020**, *125*, 112501. [CrossRef] [PubMed]
36. Cirigliano, V.; Garcia, A.; Gazit, D.; Naviliat-Cuncic, O.; Savard, G.; Young, A. Precision beta decay as a probe of new physics. *arXiv* **2019**, arXiv:1907.02164.
37. Sun, X.; Adamek, E.; Allgeier, B.; Bagdasarova, Y.; Berguno, D.B.; Blatnik, M.; Bowles, T.J.; Broussard, L.J.; Brown, M.P.; Carr, R.; et al. Improved limits on Fierz interference using asymmetry measurements from the ultracold neutron asymmetry (UCNA) experiment. *Phys. Rev. C* **2020**, *101*, 035503. [CrossRef]
38. Ivanov, A.N.; Höllwieser, R.; Troitskaya, N.I.; Wellenzohn, M.; Berdnikov, Y.A. Precision analysis of pseudoscalar interactions in neutron beta decays. *Nucl. Phys. B* **2020**, *951*, 114891. [CrossRef]
39. Ivanov, A.N.; Höllwieser, R.; Troitskaya, N.I.; Wellenzohn, M.; Berdnikov, Y.A. Neutron dark matter decays and correlation coefficients of neutron beta decays. *Nucl. Phys. B* **2019**, *938*, 114. [CrossRef]
40. Ivanov, A.N.; Cargnelli, M.; Faber, M.; Fuhrmann, H.; Ivanova, V.A.; Marton, J.; Troitskaya, N.I.; Zmeskal, J. On kaonic deuterium: Quantum field theoretic and relativistic covariant approach. *Eur. Phys. J. A* **2005**, *23*, 79. [CrossRef]
41. Christmeier, S.; Griethammer, H.W. Pion-less effective field theory on low-energy deuteron electrodisintegration. *Phys. Rev. C* **2008**, *77*, 064001. [CrossRef]
42. Machleidt, R.; Holinde, K.; Elster, C. The Bonn meson exchange model for the nucleon nucleon interaction. *Phys. Rept.* **1987**, *149*, 1. [CrossRef]
43. Garcon, M.; Orden, J.W.V. The deuteron: Structure and form-factors. *Adv. Nucl. Phys.* **2001**, *26*, 293. X4 [CrossRef]
44. Ivanov, A.N.; Ivanova, V.A.; Oberhummer, H.; Troitskaya, N.I.; Faber, M. On the D wave state component of the deuteron in the Nambu-Jona-Lasinio model of light nuclei. *Eur. Phys. J. A* **2001**, *12*, 87. [CrossRef]

-
45. Gilman, R.A.; Gross, F. Electromagnetic structure of the deuteron. *J. Phys. G* **2002**, *28*, R37. [[CrossRef](#)]
 46. van der Leun, C.; Alderliesten, C. The deuteron binding energy. *Nucl. Phys. A* **1982**, *380*, 261. [[CrossRef](#)]
 47. Arenhövel, H. On deuteron break-up by electrons and the momentum distribution of nucleons on the deuteron. *Nucl. Phys. A* **1982**, *384*, 287. [[CrossRef](#)]
 48. Arenhövel, H.; Leidemann, W.; Tomusiak, E.L. General multipole expansion of polarization observables in deuteron electrodisintegration. *Eur. Phys. J. A* **2002**, *14*, 491. [[CrossRef](#)]
 49. Tamae, T.; Kawahara, H.; Tanaka, A.; Nomura, M.; Namai, K.; Sugawara, M. Out-of-plane measurement of the $D(e, e'p)$ coincidence cross section. *Phys. Rev. Lett.* **1987**, *59*, 2919. [[CrossRef](#)]
 50. Fabian, W.; Arenhövel, H. Electrodisintegration of deuteron including nucleon detection in coincidence. *Nucl. Phys. A* **1979**, *314*, 253. [[CrossRef](#)]
 51. von Neumann-Cosel, P.; Richter, A.; Schrieder, G.; Shevchenko, A.; Stiller, A.; Arenhövel, H. Deuteron breakup in the $^2\text{H}(e, e'p)$ reaction at low momentum transfer and close to threshold. *Phys. Rev. Lett.* **2002**, *88*, 202304.
 52. Ivanov, A.N.; Höllwieser, R.; Troitskaya, N.I.; Wellenzohn, M.; Berdnikov, Y.A. Theoretical description of the neutron beta decay in the standard model at the level of 10^{-5} . *Phys. Rev. D* **2021**, *104*, 033006. [[CrossRef](#)]
 53. Hernández-Monteagudo, C.; Ma, Y.; Kitaura, F.S.; Wang, W.; Génova-Santos, R.; Macías-Pérez, J.; Herranz, D. Evidence of the missing baryons from the kinematic Sunyaev–Zel’dovich effect in Planck data. *Phys. Rev. Lett.* **2015**, *115*, 191301. [[CrossRef](#)]
 54. Ejiri, H.; Vergados, J.D. Neutron disappearance inside the nucleus. *J. Phys. G Nucl. Part. Phys.* **2019**, *46*, 025104. [[CrossRef](#)]
 55. Karananas, G.K.; Kassiteridis, A. Small-scale structure from neutron dark decay. *JCAP* **2018**, *9*, 036. [[CrossRef](#)]
 56. McKeen, D.; Pospelov, M.; Raj, N. Cosmological and astrophysical probes of dark baryons. *Phys. Rev. D* **2021**, *103*, 115002. [[CrossRef](#)]