Solar Neutrino Detection Sensitivity in DARWIN via Electron Scattering

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Abstract We detail the sensitivity of the liquid xenon (LXe) DARWIN observatory to solar neutrinos via elastic electron scattering. We find that DARWIN will have the potential to measure the fluxes of five solar neutrino components: pp, 7Be, 13N, 13O and pep. The precision of the 13N, 13O and pep components is hindered by the double-beta decay of 136Xe and, thus, would benefit from a depleted target. A high-statistics observation of pp neutrinos would allow us to infer the values of the weak mixing angle, $\sin^2 \theta_W$, and the electron-type neutrino survival probability, $P_e$, in the electron recoil energy region from a few keV up to 200 keV for the first time, with relative precision of 5% and 4%, respectively, at an exposure of 300 ty. An observation of pp and 7Be neutrinos would constrain the neutrino-inferred solar luminosity down to 0.2%. A combination of all flux measurements would distinguish between the high (GS98) and low luminosity down to 0.2%. A combination of all flux measurements would allow us to infer the solar luminosity to better than 0.2% with an exposure of 300 ty.

Keywords Neutrino, Sun, Dark Matter, Direct Detection, Xenon

1 Introduction

Current and future LXe direct detection dark matter experiments, such as XENON1T, LZ [1], and DARWIN [2], will exhibit sensitivity to neutrinos at the ~MeV scale. Typically, neutrinos have been regarded as backgrounds in the search for dark matter (DM) [3, 4]; but, as signals, they present opportunities to characterize their sources and pursue physics beyond the Standard Model (SM) [5–10]. While DM remains the primary objective, detectors with multi-tonne (t) xenon targets will seek neutrino signals without the need for additional investments.

Solar neutrinos, in particular, are observable in dark matter detectors through two types of interactions: elastic electron scattering (ES) and coherent elastic neutrino-nucleus scattering (CEvNS) [11, 12]. In the SM, ES occurs with the exchange of a Z of W boson. The latter is only possible for $\nu_e$, which creates nearly an order of magnitude of difference.
between the interaction rates of $\nu_e$ and $\nu_{\mu,\tau}$. On the other hand, CEvNS occurs only through the exchange of a Z boson, with an interaction cross section that is strongly determined by the target’s neutron number. With their different sensitivity to the solar neutrino flux, these two channels provide complementarity over a wide range of energies.

Dedicated solar neutrino experiments have made numerous observations of ES with water, heavy water, and liquid scintillator targets. Borexino independently measured the fluxes of the lower-energy $pp$ [13], $^7$Be [14], and $pep$ [15] components. Subsequently, Borexino presented the first results from simultaneous spectroscopy of these three components above 0.19 MeV, yielding the most precise measurements to date as well as an upper limit on the combined carbon, nitrogen, and oxygen (CNO) flux that is ~4 times higher than predicted in the Standard Solar Model (SSM) [16, 17]. Five experiments, Borexino [18, 19], Super-K [20], KamLAND [21], SNO [22], and SNO+ [23], have measured the higher-energy $^8$B flux. COHERENT made the first observation of CEvNS [24], but astrophysical neutrinos have yet to be detected in this way.

After decades of investigation, important questions about our Sun persist. From an astrophysical perspective, the most salient issue lies in the solar abundance problem. The more recent low-metallicity (low-Z) AGSS09 SSM [25, 26] would seem to better represent the photosphere than its predecessor, the high-metallicity (high-Z) GS98 SSM [25, 27]. However, a comparison of individual flux measurements with theoretical predictions tends to favor the high-Z SSM, contradicting the common assumption that abundances in the radiative envelope are the same as those in the photosphere. This preference is further supported by helioseismic data that have long since disfavored a low-Z model [28]. As carbon, nitrogen, and oxygen constitute the majority of heavy elements in the Sun, their neutrino fluxes are the most sensitive to metallicity. A combined analysis of available measurements remains inconclusive, but a relative uncertainty of ~15% on a combined CNO flux measurement would begin to favor one model over the other [17, 29, 30]. While less sensitive to metallicity than CNO neutrinos, an improved measurement of the $^8$B flux would also help to distinguish them.

Measurements of electroweak parameters play an important role in our understanding of the SM and our search for new physics [31, 32]. Non-standard neutrino interactions (NSI) might modify the Large Mixing Angle (MSW-LMA) solution to the solar neutrino problem. Solar neutrinos serve as one probe to observe or set bounds on NSI. Two of these parameters, the weak mixing angle ($\sin^2 \theta_{\nu}$) and the $\nu_e$ survival probability ($P_{ee}$), may be measured with the ES process. On one hand, atomic parity violation in cesium at 2.4 MeV yields the lowest energy at which $\sin^2 \theta_{\nu}$ has been measured [33]. On the other, Borexino has provided the lowest-energy measurement of the $\nu_e$ survival probability extracted from the tail of the proton-proton distribution (>0.19 MeV) [17]. No experiment, thus far, has been able to access energies below these respective thresholds. DARWIN will measure $\sin^2 \theta_{\nu}$ and $P_{ee}$ for the first time in the energy region [1,200] keV.

In this manuscript, we highlight the efficacy with which DARWIN will shed light on solar and neutrino physics through elastic electron scattering. We first detail its sensitivity to each component of the solar neutrino flux. Then, we illustrate the precision with which DARWIN could reconstruct $\sin^2 \theta_{\nu}$ and $P_{ee}$ in the low energy range [1,200] keV. Lastly, we demonstrate how a combined analysis of neutrino flux measurements would resolve the solar abundance problem.

2 The DARWIN Experiment

The DARWIN observatory is a next-generation dark matter experiment that will operate with 50 t (40 t active) of xenon in a cylindrical, dual-phase time projection chamber (TPC) that is 2.6 m in both height and diameter [2]. The TPC will be placed underground in a double-walled cryostat vessel shielded by water Cherenkov and neutron vetoes that enable us to observe cosmic muons and their progeny. The TPC will be equipped to read out both light and charge signals.

A charged particle that interacts in liquid xenon (LXe) produces photons (scintillation) and electrons (ionization). The TPC promptly detects these photons as an “S1” scintillation signal with photosensors instrumented in arrays at the top and bottom of the target region. An applied electric field drifts the electrons upward and extracts them into the gas phase, where electroluminescence generates an amplified “S2” scintillation signal. The radial position of an interaction is reconstructed with the S2 light pattern in the top array, while its depth is inferred from the time delay between S1 and S2. Together, S1 and S2 reconstruct the energy of the event with excellent resolution. The ratio S2/S1 discriminates between scatters off electrons and those off nuclei. The combination of position, energy and discrimination allows for strong event selections to mitigate sources of background.

The most troublesome background for a solar neutrino search (ES) arises from the $^{222}$Rn emanated by detector components. More precisely, the $^{214}$Pb daughter decays directly to $^{214}$Bi with a branching ratio of 11%, emitting a lone $\beta$ with an energy up to $Q = 1.02$ MeV [34]. Otherwise, $^{214}$Pb decays to an excited state of $^{214}$Bi that emits a $\gamma$ coincident with the $\beta$ to create a sharp rise above the lone-$\beta$ continuum. There are several excited states that contribute, starting at 0.274 MeV, as illustrated in Figure 1. With a long half-life (3.8 d), $^{222}$Rn distributes itself homogeneously in the LXe volume, such that it is not reduced with the deliberate selection of an inner volume, known as fiducialization. The detector materials in DARWIN will be carefully selected for low radon emanation through a dedicated radioassay program, as
in XENON1T/nT [35]. DARWIN will deploy a radon distillation column to further reduce the radon level. Cryogenic distillation was successfully applied in XENON100 [36] and XENON1T [37] to reduce radon levels. For DARWIN, we assume a target $^{222}\text{Rn}$ activity of 0.1 μBq/kg.

A second background comes from intrinsic $^{85}\text{Kr}$, a β emitter ($Q = 0.687$ MeV; $T_{1/2} = 10.8$ y) that remains in the xenon volume after extraction from the atmosphere. As with $^{222}\text{Rn}$, $^{85}\text{Kr}$ homogeneously distributes itself in the LXe volume. XENON1T has already demonstrated a concentration \(n_{\text{Kr}}/\text{Xe} < 360 \text{ ppq} \) [38]. Krypton may be further reduced at any time via online distillation, as applied in XENON1T [37]. We assume a concentration of 2 ppq in this study, but find that it has a negligible effect even at its current level.

Long-lived radionuclides in detector materials constitute a third class of background events. The decay chains of $^{238}\text{U}$, $^{232}\text{Th}$ and $^{235}\text{U}$ generate various α and β particles as well as γ rays. The main contributors of γ rays from these three chains are $^{214}\text{Bi}$ (2.45 MeV) and $^{208}\text{Tl}$ (2.61 MeV), including the background induced by decays in the non-instrumented xenon volume around the TPC. Additional γ rays are emitted in the decays of $^{137}\text{Cs}$ (0.662 MeV), $^{40}\text{K}$ (1.46 MeV), and the daughters of $^{60}\text{Co}$ (1.17 and 1.33 MeV) and $^{44}\text{Ti}$ (2.66 MeV). The α and β particles do not travel far and thus are eliminated with fiducialization. The γ rays, however, penetrate the innermost region, where they experience photoabsorption or Compton scattering. The more notable contributors have historically been the stainless steel cryostat and photo-sensors [35]. We include a materials background component derived from the DARWIN simulation in [39], which considers a more radiopure titanium cryostat. The simulation is adapted to this case by incorporating position-dependent multiscatter resolution, 3-15 mm, and selecting events within a 30 t super-ellipsoidal fiducial volume that minimizes the contribution of these Compton scatters below 200 keV. With 10 live years of data, we would accrue 300 tonne-years (ty) of exposure, compared to the 200 ty goal for the dark matter search.

Finally, unstable xenon isotopes pose a potential background in the search for ES of solar neutrinos. The isotope $^{136}\text{Xe}$, which occurs naturally with an abundance of 8.9%, undergoes double-beta decay ($Q = 2.46$ MeV; $T_{1/2} = 2.17 \times 10^{21}$ y). The resultant spectrum circumscribes the entire signal region of interest. Furthermore, the muon-induced neutron capture process of $^{136}\text{Xe}$ creates $^{137}\text{Xe}$, which then beta decays ($Q = 4.16$ MeV; $T_{1/2} = 3.82$ min). The impact of $^{137}\text{Xe}$ proves to be negligible at the level of $10^{-3}$ per tonne-year per keV, three orders of magnitude lower than $^{136}\text{Xe}$ double-beta decay [39]. These $^{136}\text{Xe}$ background contributions are removable through isotopic depletion; however, depletion would diminish the prospects for a neutrinoless double-beta search with $^{136}\text{Xe}$ in DARWIN [39]. Lastly, $^{124}\text{Xe}$ decays via double electron capture ($T_{1/2} \approx 1.4 \times 10^{22}$ y) [40, 41], as first observed in XENON1T [42]. The subsequent cascade of Auger electrons and X-rays is observed as a single peak at 64.3 (36.7; 9.8) keV with a branching ratio of 0.75 (0.23; 0.017), following the fast atomic process and their sub-millimeter spread in liquid xenon. With an abundance of 0.1%, one expects a total of 228 double electron capture events per tonne-year.

### 3 Solar Neutrinos in DARWIN

DARWIN will be optimized for the detection of low-energy nuclear recoils. This fact also implies that DARWIN will be well equipped to detect ES with high efficiency and excellent energy resolution. In the following, we calculate the expected event rates for the individual solar components.

The spectral fluxes of $^{pp}$, $^{13}\text{N}$, and $^{15}\text{O}$ neutrinos are represented with the β form,

$$\frac{d\Phi_i}{dE_V} = \Phi_i A (x_i - E_V) [(x_i - E_V)^2 - m_i^2/2 E_V^2]^{1/2},$$

where $x_i \equiv Q_i/m_V$, $Q_i$, and $\Phi_i$ are the characteristic maximal energy and the flux scale of neutrino component $i$, respec-
We also apply the Gaussian energy resolution obtained with the coupling parameters

The flux scales, maximum neutrino energies and survival probability are given by the MSW-LMA solution at low energies in the vacuum-dominated regime. The differential cross section of elastic electron-neutrino scattering:

where \( P_{ej} \) is the oscillation probability of lepton flavor \( j \) to the electron neutrino, \( N_e \) is the number of target electrons per tonne of xenon, and \( E_r \) is the energy of the induced recoil. The flux scales, maximum neutrino energies and survival probabilities are listed in Table 1. The survival probabilities follow the MSW-LMA solution at low energies in the vacuum-dominated regime. The differential cross section is given by the MSW-LMA solution at low energies in the vacuum-dominated regime. The differential cross section of elastic electron-neutrino scattering:

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with the coupling parameters \( g_L = \sin^2 \theta _w - \frac{1}{2} \) and \( g_R = \sin^2 \theta _w \). For the \( \nu_e \), \( g_L \approx g_L + 1 \) to account for its charged current interactions. We assume \( \sin^2 \theta _w = 0.2387 \). We incorporate a step approximation according to the binding energies of electrons in the shells of a xenon atom, which leads to a small suppression of event rates below 35 keV. We also apply the Gaussian energy resolution obtained in XENON1T.

The \( \nu_{e} \) neutrinos constitute the most prominent component due to the low energy threshold achievable in LXe TPCs. Here, we assume a threshold at 1 keV, which yields an integrated rate of 365 events per tonne-year. This high rate presents an opportunity to probe \( \sin^2 \theta _w \) for the first time below \( \sim 200 \) keV, to improve upon the precision of existing measurements of \( P_e \) at low energies, and to further constrain the neutrino-inferred measurement of solar luminosity.

Table 1 The characteristic values of the flux scales [43], maximum neutrino energies and MSW-LMA \( \nu_e \) survival probability [44] used in this study.

| component | \( \Phi [\text{cm}^{-2}\text{s}^{-1}] \) | \( \sigma [\%] \) | \( Q [\text{keV}] \) | \( P_e \) |
|-----------|-----------------|----------|----------|------|
| pp        | \( 5.98 \times 10^{10} \) | 0.6      | 420      | 0.55 |
| \( ^{7}\text{Be} \) | \( 4.93 \times 10^{9} \) | 6        | 862, 384 | 0.52 |
| \( ^{13}\text{N} \) | \( 2.78 \times 10^{8} \) | 15       | 1200     | 0.52 |
| \( ^{15}\text{O} \) | \( 2.05 \times 10^{8} \) | 18       | 1732     | 0.50 |
| pep       | \( 1.44 \times 10^{8} \) | 1        | 1        | 0.50 |

The \( ^{7}\text{Be} \) neutrinos comprise the second most prominent component. The larger branch contributes 133 events per tonne-year, while the smaller one contributes 7.6 events. The \( ^{7}\text{Be} \) flux is more sensitive to solar metallicity and, as such, it may be combined with a high-precision measurement of the \( pp \) flux to make an initial assessment of different metallicity models.

The third most prominent components are those of \( ^{13}\text{N} \), \( ^{15}\text{O} \), and \( pep \), which induce 6.5, 7.1 and 7.6 events per tonne-year, respectively. Despite having the lowest rate, \( ^{13}\text{N} \) events fall within a narrower energy range than either \( ^{15}\text{O} \) or \( pep \), such that the \( ^{13}\text{N} \) spectrum rises above both below \( \sim 0.4 \) MeV. Consequently, it is possible for DARWIN to make the first statistically significant observation of CNO neutrinos by exploiting higher statistics at lower energies. As the most sensitive to metallicity, being 30% higher in the high-Z scenario, measurements of the \( ^{13}\text{N} \) and \( ^{15}\text{O} \) fluxes would greatly enhance the capability to distinguish between solar models. The rates of \( ^{13}\text{F} \), \( ^{8}\text{B} \) and \( pep \) neutrinos are negligible.

Finally, we consider neutrino capture on \( ^{131}\text{Xe} \) q-value \( = 0.355 \) MeV), the only isotope with a sufficiently low Q-value to exhibit sensitivity to solar neutrinos. The expected observable signature consists of two signals: a prompt electron and a combination of X-rays and Auger electrons that are emitted together in the subsequent electron capture (EC) decay of \( ^{131}\text{Cs}^+ \) (T1/2 = 9.69 days). The prompt electrons would create a spectrum that mirrors those of the spectral neutrino fluxes shifted to lower energies by the Q-value of this reaction \( (E_r = E_v - Q) \). The EC decay would appear as a Gaussian peak at 0.030 MeV. The long half-life of the EC process precludes delayed coincidence of these two signatures. The contribution of each solar component (including \( ^{8}\text{B} \)) follows from [49]. There are three distinct peaks visible in Figure 1. The two higher energy peaks come from capturing the monoenergetic \( ^{7}\text{Be} \) and \( pep \) neutrinos; while the peak below 50 keV is the combination of EC, the lower branch of \( ^{7}\text{Be} \), and the tail of the \( pp \) spectrum. With a \( ^{131}\text{Xe} \) abundance of 21.2%, we expect 1.23 neutrino capture events per tonne-year.

4 Flux and Luminosity

Having defined the signal and background models, we assess DARWIN’s sensitivity to each of the neutrino components. We employ a full spectral fit of all components up to 3 MeV. A set of maximum likelihood estimators is determined for the 5-dimensional set of flux scale parameters, \( \mathbf{f} = \{ pp, f_{\text{Be}}, f_{\text{Xe}}, f_{\text{O}}, f_{\text{pp}} \} \), and the neutrino capture rate, \( f_{\text{cap}} \), given the neutrino mixing parameters, \( \theta = \{ \sin^2 \theta _w, P_e \} \):

\[
P(\mathbf{f} | \mathbf{f}_{\text{cap}}) = \mathcal{L}(\mathbf{f}, f_{\text{cap}}) = \prod_{j=1}^{5} \frac{n_j^{f_j} e^{-f_j}}{f_j!}.
\]
These parameters predict the average number of events in the $j$th energy bin, $n_j$, while the observed number of events in that bin, $n_{ij}$, is randomly sampled. The background-only region ($>1.5$ MeV) is used to constrain the uncertainties in the normalization of the materials and $^{136}$Xe backgrounds at lower energies. All components are left free in the fitting routine.

We run toy experiments for each exposure in our range of interest, [1,1000] (ty), to ascertain the expected relative $1\sigma$ uncertainties, $\sigma_j$, for each neutrino component. These values are shown in Figure 2 normalized to their respective median high-Z values. The solid lines correspond to a natural target, while the dashed lines indicate a target depleted of $^{136}$Xe by two order of magnitude.

With 1 ty, DARWIN would quickly match the precision of the $pp$ flux (10%) currently set by Borexino. A subpercent measurement would follow with 20 ty, ultimately reaching 0.15% at 300 ty. Similarly, DARWIN would match Borexino’s $^7$Be measurement (2.7%) within 60 ty and then achieve 1% precision with 300 ty. The $^{13}$N and $^{15}$O neutrinos would also be attainable. The former (latter) would require 100 ty (200 ty) to reach $3\sigma$ detection with a natural xenon target. Finally, DARWIN could observe the $pep$ component and neutrino capture with 60 ty and 200 ty, respectively, using a necessarily depleted target.

The solar luminosity inferred from solar neutrino data, $L_{\odot}/L_{\odot} = 1.04^{+0.07}_{-0.08}$, agrees with the measured (photon-inferred) solar luminosity within $7\%$ [29]. The $pp$ reaction contributes most strongly to the total energy generation in the Sun. Thus, high-precision measurements of the $pp$ and $^7$Be components, which respectively comprise 92% and 7.4% of the solar luminosity, would reduce this uncertainty. With the precision levels shown here, DARWIN would achieve an uncertainty of $0.2\%$ on the neutrino-inferred solar luminosity.

### 5 Electroweak Parameters

Following a precise measurement of the $pp$ component, we may infer the values of the weak mixing angle and the $\nu_e$ survival probability, as they directly affect the shape of its observed recoil spectrum. We adopt a likelihood function in which the two electroweak parameters are free to vary:

$$P(n_j|\mu_j(\theta)) = \mathcal{L}(\theta).$$

\( \theta \)
The presence of $^7$Be neutrinos only slightly worsens the sensitivity to these parameters, while the other neutrino components have a negligible effect. The uncertainty in the $pp$ flux contributes negligibly to the total uncertainty of $\sin^2\theta_{w}$ and $P_e$.

We find the maximum likelihood estimators of $\sin^2\theta_{w}$ and $P_e$ in a series of toy experiments. From the resultant 2D distribution, we determine the 68% confidence regions as shown in Figure 3 (top) for four scenarios based on two exposures (30 and 300 ty) and two target compositions.

In the case of a natural target, DARWIN would reconstruct $\sin^2\theta_{w}$ and $P_e$ with uncertainties as small as 0.0122 (5.1%) and 0.022 (4.0%), respectively. Alternatively, with a depleted target, the uncertainties would shrink to 0.0099 (4.2%) and 0.017 (3.1%). A measurement of $\sin^2\theta_{w}$ would be the first in this energy range, albeit with an uncertainty roughly five times higher than those at higher energies. A measurement of $P_e$ would improve upon the existing one from Borexino by an order of magnitude. This projection is shown in Figure 3 (bottom) with solar neutrino measurements from Borexino [17, 19], KamLAND [21], and SNO [22].

6 Solar Abundance Problem

DARWIN may utilize a combination of neutrino flux measurements to probe the metallicity of the Sun. We repeat the sensitivity assessment of the flux measurements, $f$ described previously. In this instance, however, we allow the flux values derived from the high- and low-Z models to vary from their median values according to their respective theoretical uncertainties. We put these uncertainties, $\sigma_i$, into a multivariate (Gaussian) simulation characterized by a 5-dimensional matrix $\Sigma = [\rho_{ij}\sigma_i\sigma_j]$ that accounts for all correlations of the flux components, $\rho_{ij}$. The correlation values are based on [43]. For each trial at a given exposure, we use the randomly sampled $f$ to calculate its (squared) Mahalanobis distance $\delta^2 = (f - 1)^T \cdot \Sigma^{-1} \cdot (f - 1)$ [50], which quantifies the deviation from the true values. The simulation is repeated for both the high- and low-Z models. A p-value is calculated for each iteration of the high-Z simulation by integrating the low-Z distribution above the high-Z Mahalanobis value. We then take the median p-value from the final distribution.

Figure 4 displays the significance corresponding to these p-values as a function of exposure for the first pair of measurements, $pp$ and $^7$Be, and for each subsequent addition of the other components. The $^{13}$N component only modestly increases the exclusion potential due to the large uncertainties in both theory and experiment. The combination of both $^{13}$N and $^{15}$O, however, yields a significant gain above $\sim 10$ ty. The $pep$ component enhances the exclusion to $2.1\sigma$ (2.5$\sigma$) with a natural (depleted) target at an exposure of 300 ty.

DARWIN would remain limited by the $^{136}$Xe background with a natural target, but with depletion it would distinguish between the high- and low-Z SSMs up to the theoretical uncertainties. The significance illustrated in Figure 4 may be further improved either with a measurement of the solar $^8$B flux via CEvNS in DARWIN or with independent measurements from other experiments.

7 Outlook

The DARWIN observatory will feature sensitivity to five components of the solar flux via ES. A low energy threshold of 1 keV allows DARWIN to observe the majority of $pp$ neutrinos, which have (mostly) eluded contemporary neutrino observatories. With 300 ty, we would be able to achieve 0.15% precision in the $pp$ flux measurement, approximately two orders of magnitude better than the current precision from Borexino. DARWIN would improve upon existing measurements of the $^7$Be flux by a factor of 3. These measurements, in turn, would reduce the uncertainty on the neutrino-inferred solar luminosity to 0.2%. The $pep$ neutrinos may be observed with $3\sigma$ significance within the lifetime of the experiment, depending on the target composition. And, with only three years of data, DARWIN would make an observation of CNO neutrinos with $3\sigma$ significance.

Precise measurements of these solar components further extend the physics reach of DARWIN. The high-statistics $pp$ events would provide the means to measure both $\sin^2\theta_{w}$ and $P_e$ in an energy region that is yet to be probed. The better precision of $P_e$, in particular, would be up to one order of magnitude better than the current lowest-energy measurement from Borexino. All obtained measurements and limits on the fluxes would together provide information to distinguish between the high- and low-Z SSMs. These capabilities are dependent on the target composition. Only with a target depleted of $^{136}$Xe by approximately two orders of magnitude would DARWIN make such precise measurements via ES or...
exploit them to distinguish between solar models. DARWIN may further enhance its distinction power with a measurement of the $^{8}$B flux via CEvNS. The forecast for such a measurement is highly sensitive to the achieved energy threshold for nuclear recoils, and it is left for a future study. A powerful physics case exists for the pursuit of solar neutrinos in DARWIN, and it comes without the need for additional investment beyond the option of depletion.

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