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Ab initio calculation of the contact operator contribution in the standard mechanism for neutrinoless double beta decay

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Starting from chiral nuclear interactions, we evaluate the contribution of the leading-order contact transition operator to the nuclear matrix element (NME) of neutrinoless double-beta decay, assuming a light Majorana neutrino-exchange mechanism. The corresponding low-energy constant (LEC) is determined by fitting the transition amplitude of the $nn \to ppe^-e^-$ process to a recently proposed synthetic datum. We examine the dependence of the amplitude on similarity renormalization group (SRG) scale and chiral expansion order of the nuclear interaction, finding that both dependences can be compensated to a large extent by readjusting the LEC. We evaluate the contribution of both the leading-order contact operator and standard long-range operator to the neutrinoless double-beta decays in the light nuclei ^{6,8}He and the candidate nucleus ^{48}Ca. Our results provide the first clear demonstration that the contact term enhances the NME in calculations with commonly used chiral two- plus three-nucleon interactions. In the case of ^{48}Ca, for example, the NME obtained with the EM(1.8/2.0) interaction is enhanced from 0.61 to 0.87(4), where the uncertainty is propagated from the synthetic datum.

Introduction. The neutrinoless double-β ($0\nu\beta\beta$) decay is a hypothetical weak process that converts two neutrons into two protons, emitting two electrons but no corresponding antineutrinos. The observation of neutrino oscillations confirmed that neutrinos have nonzero masses, which has boosted interest in experimental searches for $0\nu\beta\beta$ decay. The observation of this decay would confirm the existence of a Majorana mass term for the neutrinos [1], shedding light on the mechanism of neutrino mass generation, and providing direct evidence of lepton number violation beyond the standard model—a key ingredient for generating the matter-antimatter asymmetry in the universe. Hence, there is a vast interest in this process, with multiple large-scale experiments either planned or underway.

An important ingredient for selecting suitable candidate nuclei for detectors and the interpretation of an observed lifetime is the nuclear matrix element (NME) $M^{0\nu}$, which encodes the impact of the structure of parent and daughter nuclei on the decay. A large variety of calculations of the NME for candidate nuclei have been reported in the literature[2–19], but results differ by up to a factor of 3. This difference amounts to an order of magnitude uncertainty in the lifetime, which is inversely proportional to the square of the NME [20].

A more reliable estimate requires a systematic calculation with quantified uncertainties. Such a calculation can be carried out in an *ab initio* framework, using chiral effective field theory (EFT) to derive the nuclear Hamiltonian and $0\nu\beta\beta$ transition operator in a consistent and systematically improvable manner. First milestone calculations have been performed for candidate nuclei from ^{48}Ca to ^{82}Se [21–23].

Recently, Cirgiliano *et al.* [24, 25] showed that a chiral EFT description of $0\nu\beta\beta$ decay based on the mechanism of light Majorana neutrino exchange requires a previously unknown leading-order contact contribution to the decay operator to ensure renormalizability. The strength of this contact term has to be determined by matching to a fundamental theory or experimental data. In the absence of experimental data, only the former is currently possible.

Cirigliano *et al.* [26, 27] proposed a way to estimate the size of the contact term by computing the $nn \to ppe^-e^-$ transition amplitude using the generalized forward Compton scattering amplitude. The underlying model assumes light Majorana neutrino exchange and incorporates input from elastic intermediate states in analogy to the Cottingham formula [28]. Since the strength of the contact term is scale and scheme dependent, they provide the value of the full transition amplitude at a given kinematic point. This amplitude is (in principle) observable, and can be used as a synthetic datum to constrain the contact term in other schemes.

In this work, we compute the $nn \to ppe^-e^-$ transition amplitude using chiral nucleon-nucleon (NN) interactions. We show that the renormalized transition amplitude is robust with respect to changes in the nuclear interaction, making it a reliable starting point for NME calculations in finite nuclei. In particular, we investigate the change of the contact contribution when the NN interaction undergoes a similarity renormalization group (SRG) transformation, as well as its dependence on the order of the chiral expansion. Finally, we show that the leading-order contact transition operator enhances the NME by 43(7) % in the lightest $0\nu\beta\beta$-decay candidate nucleus ^{48}Ca compared to the recent ab initio calculations based on the standard long-range transition operator alone [21]. This result conveys an important positive message for planning and interpreting future experiments.

The transition amplitude of $nn \to ppe^-e^-$ process. The central object of our investigation is the $0\nu\beta\beta$ transition operator in the standard light Majorana neutrino-exchange mechanism. Since the transition amplitude of the $nn \to ppe^-e^-$ process is computed in the $^1S_0$ channel, only the Fermi (F) and Gamow-Teller (GT) parts of the neutrino potentials contribute while the tensor part vanishes. At leading order, the neutrino potential is given by [25]

$$V_{\nu,L}^{^1S_0} = \Big[V_F(r) + V_{GT}(r)\Big]\tau^{(1)+}\tau^{(2)+} \tag{1}$$

with the radial functions

$$V_F(r) = -\frac{g_V^2}{4\pi r}, \tag{2}$$

$$V_{GT}(r) = -\frac{g_A^2}{4\pi r}\left[3 - e^{-m_\pi r}\left(1 + \frac{m_\pi r}{2}\right)\right]\tau^{(1)+}\tau^{(2)+}\,. \tag{3}$$

Here, r is the distance between the two decaying neutrons, and τ^+ is an isospin-raising operator with nonzero matrix element $\langle p|\tau^+|n\rangle = 1$. We use the axial coupling constant $g_A = 1.27$ and the average pion mass $m_\pi = 138.039\,\mathrm{MeV}$. According to Ref. [25], a leading-order contact transition operator must be introduced to ensure renormalizability. Choosing a separable non-local regulator, this contact operator has the following form:

$$V_{\nu,S}^{^1S_0} = -2g_\nu^{NN} V_S(r,r')\tau^{(1)+}\tau^{(2)+} \tag{4}$$

with

$$V_S(r,r') \equiv \left(\frac{m_N g_A^2}{4f_\pi^2}\right)^2 f_\Lambda^{n_{\rm exp}}(r) f_\Lambda^{n_{\rm exp}}(r') \tag{5}$$

and the pion decay constant $f_\pi = 92.2\,\mathrm{MeV}$. In coordinate space, the regulator reads

$$f_\Lambda^{n_{\rm exp}}(r) = \frac{1}{2\pi^2}\int_0^\infty \mathrm{d}q\, q^2 \exp\left[-\left(\frac{q}{\Lambda}\right)^{2n_{\rm exp}}\right] j_0(qr). \tag{6}$$

The momentum cutoff Λ and $n_{\rm exp}$ are parameters whose values should be chosen to be consistent with chiral nuclear interactions. We choose the prefactor similar to Ref. [25], such that the LEC g_ν^{NN} multiplying the contact term becomes dimensionless and of natural size.

In accordance with Refs. [26, 27], we define the nuclear part of the $nn \to ppe^-e^-$ transition amplitude as

$$\mathcal{A}(p,p') = 4\pi\,\langle ^1S_0(p')|V_{\nu,L}^{^1S_0} + V_{\nu,S}^{^1S_0}|^1S_0(p)\rangle\,. \tag{7}$$

The wavefunctions $|^1S_0(p)\rangle$ and $|^1S_0(p')\rangle$ are scattering solutions for neutrons and protons in the $^1S_0$ channel at incoming and outgoing momenta p and p', respectively.

Scattering wavefunctions. We compute scattering wavefunctions using the R-matrix formalism [29] with the channel radius set to $a = 15\,\mathrm{fm}$, well beyond the range of the nuclear potential. The wavefunctions are normalized such that the asymptotic form of the radial wavefunction in the $^1S_0$ channel is

$$u_p(r) = rR(r) \to \tfrac{1}{p}\sin[pr + \delta(p)], \tag{8}$$

This normalization recovers the free solution $R(r) = j_0(r)$, hence the full plane wave is normalized as $\phi_{\vec{p}}(\vec{r}) = \exp(i\vec{p}\cdot\vec{r})$. For consistency with Refs. [26, 27], we omit the Coulomb interaction from all two-body calculations.

Using the scattering wavefunctions, we compute the long- and short-range parts of the amplitude,

$$\mathcal{A}_L(p,p') = 4\pi\int_0^\infty \mathrm{d}r\, u_{p'}(r)[V_F(r) + V_{GT}(r)]u_p(r) \tag{9}$$

$$\mathcal{A}_S(p,p') = 4\pi\int_0^\infty \mathrm{d}r' r' \int_0^\infty \mathrm{d}r\, r u_{p'}(r')V_S(r,r')u_p(r), \tag{10}$$

such that

$$\mathcal{A}(p,p') = \mathcal{A}_L(p,p') - 2g_\nu^{NN}\mathcal{A}_S(p,p'). \tag{11}$$

We obtain the LEC g_ν^{NN} by requiring that the total amplitude matches the synthetic datum

$$\mathcal{A}(p = 25\,\mathrm{MeV}/c, p' = 30\,\mathrm{MeV}/c) = -0.0195(5)\,\mathrm{MeV}^{-2} \tag{12}$$

given by Refs. [26, 27]. We have validated our amplitude calculations and the extraction of the LEC against the results in Ref. [27] — see the supplemental material [30] for details.

Nucleon-nucleon interactions. In the present study, we employ three different interactions, all derived from chiral EFT. First, we investigate the effect of an SRG transformation on the transition amplitude, employing the N^{3}LO interaction by Entem and Machleidt [31], which we denote by "EM". Next, we perform an analysis of the convergence behavior of the amplitude with respect to the chiral order of the interaction. For this, we use the family of interactions from Entem *et al.* [32], called "EMN" in the following, which provides interactions from LO to N^{4}LO. Finally, we consider the ΔN^{2}LO$_{\rm GO}$(394) [33] Hamiltonian, a low-cutoff NN+3N interaction that accounts for Δ isobars and whose parameters are constrained by $A \leq 4$ few-body data and nuclear matter properties. With these interactions, we make the connection to the *ab initio* calculations of the $0\nu\beta\beta$ NME in light nuclei [34] and the candidate ^{48}Ca [21, 22].

SRG scale dependence. In order to accelerate the convergence of many-body calculations, the nuclear Hamiltonian is usually preprocessed via similarity renormalization group transformations that reduce the coupling between low and high momenta [35]. The continuous unitary SRG transformation introduces a scale λ that controls the Hamiltonian's bandwidth in momentum space. The transformation preserves the eigenvalues of H but changes its eigenstates, hence observables should be transformed consistently.

RG arguments suggest that the evolution of an operator generates a series of short-range counter terms (see, e.g., Refs. [36–38]). Since the $0\nu\beta\beta$ operator is primarily of intermediate- to long-range character, we expect it to evolve only weakly under the SRG, and we attempt to absorb this effect by readjusting the contact LEC. To this end, we calculate the long and short-range amplitudes at the kinematic point using wavefunctions of the Entem and Machleidt interaction at different SRG scales.[1]

The results are shown in fig. 1(a). The long-range part of the amplitude (with or without higher-order corrections, labeled $\mathcal{A}_L$ and $\tilde{\mathcal{A}}_L$, respectively) shows a very mild dependence on the SRG scale while the short-range part initially changes by 18 % before settling into a weak scale dependence as well.

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[1] As discussed above, we use $n_{\rm exp} = 3$ when regularizing the contact, consistent with the regulator for the EM interaction.

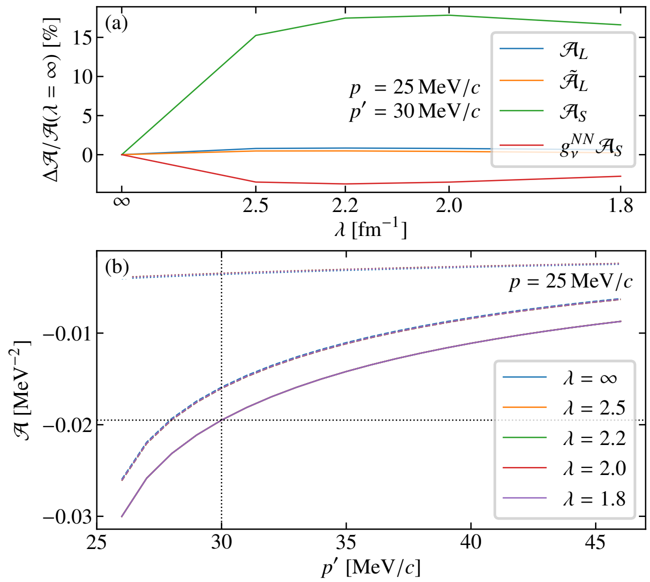

FIG. 1. (a) Dependence of the short- and long-range parts of the amplitude on the SRG scale λ at the kinematic point p = 25 MeV/c, p' = 30 MeV/c for the EM potential. Shown are the changes relative to the unevolved potential. Note that the λ-dependence of $\mathcal{A}_S$ is partially compensated by the LEC g_ν^{NN} in the short-range contribution to the amplitude, which depends on $g_\nu^{NN}\mathcal{A}_S$. (b) Momentum dependence of the short- and LO long-range parts, as well as the total amplitude for the EM potential at different SRG scales λ. Shown are the scaled short-range part $-2g_\nu^{NN}\mathcal{A}_S$ (dotted lines), the long-range part $\mathcal{A}_L$ (dashed lines), and the total amplitude $\mathcal{A}_L - 2g_\nu^{NN}\mathcal{A}_S$ (solid lines). The dotted black lines mark the synthetic datum. The variation of the total amplitude with respect to λ over the momentum range shown is less than 0.1 %.

This confirms the intuition that the SRG mainly affects short-range operators. The total amplitudes adjusted to the synthetic datum change by less than a percent over the range of flow parameters shown. Overall, the short-range operator enhances the transition amplitude by approximately 22 % at the kinematic point. The similar momentum dependence, shown in fig. 1(b), implies that the short-range amplitude just acquires a scale-dependent factor $Z(\lambda)$ during the SRG evolution, $\mathcal{A}_S(\lambda) = Z(\lambda)\mathcal{A}_S(\lambda=\infty)$. This scaling factor can indeed be compensated by a change in the LEC as suggested above, resulting in a total amplitude that is virtually independent of the SRG scale once the LEC has been fixed to the synthetic datum.

Convergence of the chiral expansion. Next, we consider the dependence of the $0\nu\beta\beta$ amplitude on the order of the chiral expansion. To this end we use the EMN family of interactions from LO up to N^{4}LO [32].

Figure 2 shows the total amplitude as a function of incoming and outgoing relative momenta. For incoming momenta up to 375 MeV/c, the range up to which the potentials are fitted, we notice a sizable dependence on the chiral order, which is evident in fig. 2(a). The LO amplitude is more than 60 % smaller than the N^{4}LO amplitude, but systematically converges to the N^{4}LO result with increasing order. The variation in the low-momentum region [cf. fig. 2(b)] is smaller than 1 % and convergence is rapid.

TABLE I. Value of the $0\nu\beta\beta$ contact LECs for the interactions used in this paper. The contact term is regularized using Λ = 500 MeV/c and n_{exp} = 3 [Λ = 394 MeV/c and n_{exp} = 4 for ΔN^{2}LO$_{\mathrm{GO}}$(394)]. Amplitudes are shown in units of MeV^{-2} at the kinematic point p = 25 MeV/c, p' = 30 MeV/c. The quantities with a tilde incorporate beyond-LO effects in the operator. The quoted uncertainties Δg_ν^{NN} are propagated from the uncertainty of the synthetic datum and are identical for g_ν^{NN} and $\tilde{g}_\nu^{NN}$. See supplemental material [30] for recommended values at other SRG scales and chiral orders.

Interaction	λ	$10^3\tilde{\mathcal{A}}_L$	$10^3\mathcal{A}_L$	$10^3\mathcal{A}_S$	$\tilde{g}_\nu^{NN}$	g_ν^{NN}	Δg_ν^{NN}
EM	∞	−15.847	−15.898	3.0152	0.606	0.597	0.083
	2.50	−15.921	−16.024	3.0635	0.584	0.567	0.082
	2.24	−15.923	−16.033	3.0451	0.587	0.569	0.082
	2.20	−15.923	−16.033	3.0408	0.588	0.570	0.082
	2.00	−15.912	−16.025	3.0061	0.597	0.578	0.083
	1.88	−15.898	−16.011	2.9733	0.606	0.587	0.084
	1.80	−15.885	−15.998	2.9446	0.614	0.595	0.085
EMN N^{3}LO	∞	−15.857	−15.903	2.3816	0.765	0.755	0.105
	2.00	−15.934	−16.043	2.9031	0.614	0.595	0.086
ΔN^{2}LO$_{\mathrm{GO}}$ (394)	∞	−15.846	−15.968	3.1225	0.585	0.566	0.080
	2.00	−15.776	−15.892	2.9610	0.629	0.609	0.084

To investigate the effect of beyond-LO terms in the $0\nu\beta\beta$ operator, we compute the amplitude $\tilde{\mathcal{A}}(p,p')$ and determine the LEC $\tilde{g}_\nu^{NN}$ using the neutrino potentials

$$\tilde{V}_{\nu,L}^{^1S_0} \equiv \left[\tilde{V}_F(r) + \tilde{V}_{GT}(r)\right]\tau^{(1)+}\tau^{(2)+}, \tag{13}$$

$$\tilde{V}_{\nu,S}^{^1S_0} \equiv -2\tilde{g}_\nu^{NN} V_S(r,r')\tau^{(1)+}\tau^{(2)+}\,. \tag{14}$$

The radial functions

$$\tilde{V}_i(r) = \frac{1}{2\pi^2}\int_0^\infty \mathrm{d}q\, q^2 h_i(q)\, j_0(qr), \tag{15}$$

are Fourier transforms of the neutrino potentials $h_i(q)$ in momentum space [34]

$$h_F(q) = -\frac{g_V^2(q)}{q^2} \tag{16}$$

$$h_{GT}(q) = -3\frac{g_A^2(q)}{q^2} - \frac{q^2 g_P^2(q)}{4m_N^2} - \frac{g_A(q)g_P(q)}{m_N} - \frac{g_M^2(q)}{2m_N^2}. \tag{17}$$

The dipole form factors $g_i(q)$ can be found in Ref. [34] and the supplemental material [30].

The phenomenological corrections only modify the neutrino potentials at short distances, hence they are virtually indistinguishable from the LO ones at distances r > 1.5 fm . Since we use NN interactions with relatively low cutoffs, the total amplitudes are fairly insensitive to the short-range modifications. The relative difference between them is below 0.5 % for momenta within an NN interactions' range of applicability. For the LO NN interaction the difference may reach 3 % at

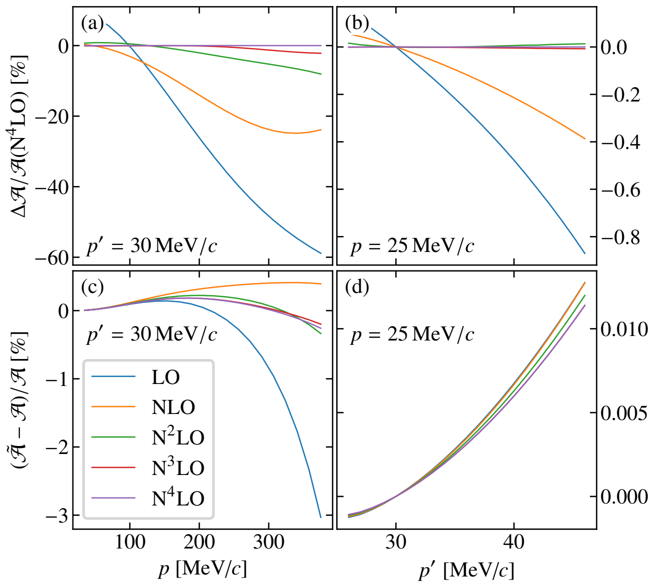

FIG. 2. (a-b) Ratio of total amplitudes (relative to the N^{4}LO result) for different orders of the chiral expansion as a function of incoming and outgoing momentum, respectively. (c-d) Relative difference between the amplitudes using the LO operator and the operator containing beyond-LO corrections as a function of incoming and outgoing momentum, respectively.

incoming momenta exceeding $300\,\mathrm{MeV}/c$ [cf. fig. 2(c)]. The difference between both amplitudes at low momenta, shown in fig. 2(d), is negligible. Table I summarizes the long-range amplitudes and LECs $\mathcal{A}$, g_ν^{NN} and $\tilde{\mathcal{A}}$, $\tilde{g}_\nu^{NN}$ associated with the LO long-range transition operator and its extension, respectively.

Application to finite nuclei. Previous calculations of the NME in finite nuclei only considered the transition operator's long-range part. With the LEC of the operator's short-range part adjusted to the synthetic datum, we can now calculate its effect and provide a first result that is renormalized to leading order. Here, we revisit our benchmark calculations for light nuclei [34], as well as the candidate pair ^{48}Ca and ^{48}Ti [21]. In these studies, we used the so-called EM1.8/2.0 interaction [39], which consists of the EM interaction SRG-evolved to a scale $\lambda = 1.8\,\mathrm{fm}^{-1}$ augmented by an unevolved N^{2}LO three-nucleon interaction. To estimate the dependence of the NME on SRG scale and chiral order, we additionally consider the EM interaction with a local-nonlocal 3N force [40], called "LNL" here, the EMN N^{3}LO with an N^{2}LO 3N interaction [41] (designated there as N^{3}LO'), and the ΔN^{2}LO$_{\mathrm{GO}}$(394) NN+3N Hamiltonian. The LECs $\tilde{g}_\nu^{NN}$ for each NN interaction are taken from table I.

The (dimensionless) NME is defined as

$$M^{0\nu} = \frac{4\pi R}{g_A^2}\,\langle {}^{\mathrm{A}}(\mathrm{Z}+2)|\tilde{V}_{\nu,L} + \tilde{V}_{\nu,S}|{}^{\mathrm{A}}\mathrm{Z}\rangle\,, \tag{18}$$

where $|{}^{\mathrm{A}}\mathrm{Z}\rangle$ and $|{}^{\mathrm{A}}\mathrm{Z}+2\rangle$ are the ground-state wave functions of the initial and final nuclei, respectively, and $R \equiv A^{1/3}{\cdot}1.2\,\mathrm{fm}$ is the empirical nuclear radius. The long-range operator $\tilde{V}_{\nu,L}$ for finite nuclei also contains the tensor part — detailed expressions can be found in Ref. [34] and the supplemental material [30].

First, we investigate the NME in the pairs of light nuclei ^{6}He–^{6}Be and ^{8}He–^{8}Be as examples of $\Delta T = 0$ and $\Delta T = 2$ transitions with the importance-truncated no-core shell model (IT-NCSM) [42]. The results are summarized in fig. 3. We note that the contact operator increases the NME by a factor ranging from 11 % to 17 % for the $\Delta T = 0$ transition in ^{6}He. Transitions with $\Delta T = 2$ have a node in the transition density that causes a cancellation between short- and long-distance contributions to the NME. This effect is greater for the long-range part than for the contact term, leading to small overall NMEs and larger relative contributions from the contact term: It increases the $\Delta T = 2$ transition in ^{8}He by 92 % to 172 %. Overall, the NMEs obtained with different Hamiltonians and SRG scales barely differ. The EM1.8/2.0 interaction systematically produces smaller NMEs than the other interactions, although it uses the same NN interaction and a similar SRG scale as LNL. The EMN + N^{3}LO' Hamiltonian yields a smaller NME in ^{6}He than LNL, while the ^{8}He NME is larger. Both differences are due to the long-range part, the short-range contribution is of similar size compared to the LNL Hamiltonian. This shows that there is still some uncertainty stemming from the Hamiltonian, in particular the 3N interaction, which needs to be quantified further.

For the $0\nu\beta\beta$-decay candidate nucleus ^{48}Ca, the short-range operator increases the NME by 43(7) %. With this contribution, the value of $M^{0\nu}$ is 0.875(40) for ^{48}Ca from the in-medium generator coordinate method (IM-GCM) [21] calculation. Here, we only state the uncertainty due to the LEC $\tilde{g}_\nu^{NN}$ of the short-range transition operator.

Conclusions and outlook. In this work, we present a determination of the LEC of a contact term that enters the $0\nu\beta\beta$ operator at leading order for a set of chiral interactions which are used in *ab initio* calculations of nuclei. We fix the LEC by reproducing the synthetic datum provided by Cirigliano *et al.* [26, 27], which assumes a light Majorana-neutrino exchange. We investigate the dependence of the $nn \to ppe^-e^-$ amplitude on the SRG scale λ and chiral order of the interaction. We find that a change in λ can be compensated by readjusting the LEC, so that only small changes in the total amplitude remain. At low chiral order, there are significant differences in the amplitude at momenta near or beyond the interaction's range of applicability, but beyond N^{2}LO, the total amplitude converges quickly over the entire momentum range to which the potential is fitted. This robustness of the amplitude shows that the two-body system is under control and any changes in the momentum dependence will come from subleading terms in the operator. Moreover, any such changes will likely be small, because beyond-LO effects in the long-range part barely affected our results, apart from a modification of the LEC.

The contact operator significantly increases the NME of isospin-changing transitions in finite nuclei. For the light-

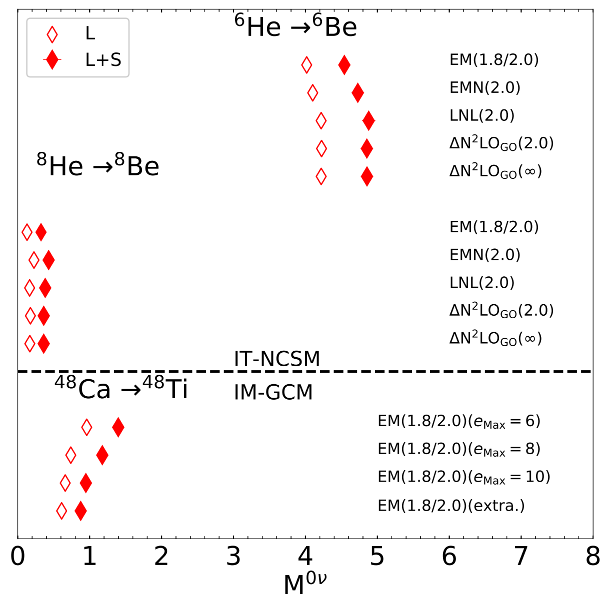

FIG. 3. The NMEs $M^{0\nu}$ of isospin-conserving ($\Delta T = 0$) transition ^{6}He → ^{6}Be, and isospin-nonconserving ($\Delta T = 2$) transitions ^{8}He → ^{8}Be and ^{48}Ca → ^{48}Ti, calculated with different chiral nuclear forces and with both long- and short-range transition operators.

est candidate nucleus ^{48}Ca, the NME we obtained for the EM1.8/2.0 interaction is enhanced from 0.61 to 0.87(4) [21], where the uncertainty is propagated from the synthetic datum and does not account for many-body approximations or the choice of different chiral potentials. An enhancement is also found in *ab initio* calculations for the light nuclei ^{6,8}He, using three families of chiral interactions with low resolution scales. This indicates that the contact operator will generally enhance the NMEs predicted by *ab initio* many-body calculations using these interactions, and this effect should be taken into account in future studies. The robustness of this enhancement under changes of the SRG resolution, EFT orders and regulators, to the extent tested here through the use of different interactions, suggests that it will persist in a fully consistent treatment of the interaction and transition operator. The extension of the present work to the NMEs of heavier $0\nu\beta\beta$-decay candidate nuclei is highly interesting.

We note that our study relies on the synthetic datum, whose uncertainty is dominated by neglected inelastic contributions. Hopefully, this uncertainty will be reduced in a future lattice QCD calculation [43]. Nevertheless, apart from the total NMEs all the findings presented here are independent of the actual value of the synthetic datum. The availability of a more precise datum will merely cause a shift of the total amplitudes, and we provide separate short- and long-range parts to enable matching to an updated value.

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