

Probing New Hadronic Forces with Heavy Exotic Atoms

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We explore the potential of precision spectroscopy of heavy exotic atoms where electrons are substituted by negative hadrons to detect new force carriers with hadronic couplings. The selected transitions are unaffected by nuclear contact terms, thus enabling highly accurate calculations using bound-state QED, provided that the nuclear polarization is under control. Alternatively, we demonstrate that the dipole polarizability, a fundamental property of nuclei, can be extracted from the spectroscopy of exotic atoms in a novel way by combining two transitions while maintaining high sensitivity to new physics. Based on existing data, we extracted world-leading bounds on mediator masses ranging from 0.1 to 10 MeV for two benchmark models and show that forthcoming experiments could enhance the sensitivity to new physics by 2 orders of magnitude.

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Introduction—High-precision atomic spectroscopy plays a key role in fundamental physics. Two applications are determining fundamental constants [1,2] and searching for physics beyond the standard model (BSM), e.g., [3–6]. Such new physics (NP) is well motivated by experimental evidence and strong theoretical arguments and can be associated with low-mass states well below the GeV scale; see, e.g., Ref. [7]. NP searches in atomic spectra can be broadly categorized into two types. The first category involves scenarios where (approximated) symmetries and/or factorization properties significantly amplify the NP signal compared to the standard model (SM) (see, e.g., Refs. [8–15]). The second category involves identifying the NP signal by a meticulous comparison between the SM predictions and measurements as in [3,4,16,17]. This Letter falls into the second category.

We consider the effect of a new spin-independent interaction coupled to hadrons on the spectra of exotic atoms, where the electrons are replaced by a single $\bar{p}$, π^- , or a K^- , and derive novel bounds and projections for future measurements. These atomic systems present several advantages over electronic or muonic atoms: (i) They allow the study of purely hadronic interactions, unaffected by

electronic and muonic couplings; (ii) they enable probing of shorter distances than those in molecules or electronic atoms, enhancing the sensitivity to the detection of new force mediators with higher masses, ~ 10 MeV compared to ~ 4 keV (we use natural units: $\hbar = c = 1$); and (iii) they facilitate straightforward theoretical comparisons, as electrons are absent or their influence is greatly reduced [18], making these simple and highly charged systems amenable to precise QED calculations [19–23]. However, these searches face theoretical and experimental challenges.

The transition energies are proportional to $\alpha^2 Z^2 m_H$ (Z is the atomic number, α the fine-structure constant, and m_H the hadron mass), placing them primarily in the x-ray range. Measuring these energies with high accuracy is challenging due to the low resolving power of solid-state detectors [24] and the narrow band and low efficiency of high-resolution wavelength measurement techniques [25]. These difficulties are compounded with the limited rates at which exotic particle beams are available. Nevertheless, high-resolution measurements of the x-ray energies of exotic atoms have been made using crystal spectrometers [26–49]. Moreover, precision x-ray spectroscopy of exotic atoms is currently undergoing a paradigm shift due to the introduction of cryogenic microcalorimeter detectors [50–56], which offer high quantum efficiency and exceptional resolution [57,58].

On the theory side, it has been difficult to extend NP searches with atomic spectroscopy to high NP mediator masses. Here, factors such as nuclear structure (size, shape, deformation, etc.) and, in certain systems, strong interaction effects [33,39,41,42,45,51,59,60], become significant while being poorly estimated due to the nonperturbative nature of QCD at low energies. However, circular states, that is, states of a high principal quantum number n and a

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maximal angular momentum $l = n - 1$, are not sensitive to the short-distance nuclear effects [20,59]; thus, they are amenable to state-of-the-art QED calculations, e.g., [20].

For these states, the least known nuclear effect is the long-range part of the nuclear polarization (NPol) [21,61], which depends on a fundamental nuclear property: static electric dipole polarizability α_E^N . As a single measurement cannot distinguish NPol from NP, we demonstrate how the use of two transitions enables extracting both with minimal loss in sensitivity. Measurements of α_E^N are interesting on their own for nuclear structure studies [62], as well as for determining the contribution of the SM to nonlinearities of King plots [63], which limits the sensitivity to new “fifth forces” [64]. Simultaneous measurements of two transitions also benefit from the broadband capabilities of microcalorimeter detectors.

Below, we extract new bounds on the BSM hadronic interactions from existing data in $\bar{p}\text{Ne}$ [39], $\bar{p}\text{Pb}$ [65,66], and $\pi^{-14}\text{N}$ [47] and derive projections to $\bar{p}^{20}\text{Ne}$, $\bar{p}^{132}\text{Xe}$, and $K^{-20}\text{Ne}$, which are targets of ongoing measurements [56,67–71]. In particular, we show that these can be the leading probes of certain models, where the bounds from rare kaon decay are insignificant [72]. Although there are bounds existing from hadronic atom spectroscopy (e.g., $\bar{p}^4\text{He}$ [73,74]), we analyze atoms that probe higher mediator masses ($\gtrsim 100$ keV) of the new boson, corresponding to a shorter interaction range.

Contributions of nuclear polarization and new physics— We consider transitions between circular states in nuclei bound to negatively charged hadrons. To increase NP sensitivity, n is chosen to be as small as possible but large enough so that the effects of QCD are negligible at the relevant accuracy level, given in Table I; see also Refs. [20,59].

Consequently, we parametrize the theoretical prediction of the n level as

$$E_n^{\text{th}} = \underbrace{E_n^{\text{SM-NPol}} + E_n^{\text{NPol}}}_{E_n^{\text{SM}}} + E_n^X, \quad (1)$$

where $E_n^{\text{SM-NPol}}$ is the contribution of the SM excluding the NPol, E_n^{NPol} is the sum of the contributions of the polarizations of the nucleus and the orbiting hadron, and E_n^X is the contribution of NP due to the exchange of an X boson. Hereafter, wherever n is written alone, the angular momentum number is implied to be $l = n - 1$.

Because of the separation of the NPol effect, we assume that the uncertainty in $E_n^{\text{SM-NPol}}$ is either already negligible compared to the precision goals of ongoing experiments [20] or that it would be reduced hand in hand with the experimental improvements [56].

For the states considered, the orbiting particle velocity is roughly $Z\alpha/n \ll 1$, so the leading-order contribution to the energy levels, given in Table I, is of the Coulomb type $E_n^{\text{SM,LO}} = -(Z\alpha/n)^2\mu/2$, where μ is the reduced mass. In the static (Born-Oppenheimer) approximation, the energy shift associated with the dipole contribution of the electric polarizability is [21,61]

$$E_n^{\text{NPol}} = -\frac{1}{2}\alpha(\alpha_E^N + Z^2\alpha_E^H)\langle r^{-4} \rangle_n \equiv \alpha_E^{\text{tot}} h_n^{\text{NPol}}, \quad (2)$$

where $\alpha_E^{\text{tot}} \equiv \alpha_E^N + Z^2\alpha_E^H$ is the total polarizability, comprising that of the nucleus α_E^N and the orbiting hadron α_E^H . For $H = \{\bar{p}, \pi^-, K^-\}$, $\alpha_E^H = (12.0 \pm 0.5, 2.0 \pm 0.9, < 200) \times 10^{-4} \text{ fm}^3$ [75–77], respectively. $\langle r^{-4} \rangle_n$ is the expectation value of r^{-4} for a state with principal quantum number n . For circular states, it returns $h_n^{\text{NPol}} = -8\mu^4 Z^4 \alpha^5 (2n-4)!/(n^4(2n)!)$.

To assess the order of magnitude of α_E^N , we adopt the results of a recent global analysis of photoabsorption cross-section measurements, which returns [78]

$$\alpha_E^N \approx 8 \frac{\left(\frac{A}{132}\right)^2}{\left(\frac{A}{132}\right)^{1/3} - 0.31} \text{ fm}^3, \quad (3)$$

where A is the mass number of the nucleus. Equations (2) and (3) allow us to approximate the NPol corrections listed

TABLE I. The transitions considered in this Letter along with the leading-order standard model prediction $E_{n,n-1}^{\text{SM,LO}}$, the measured (or projected) values of $\Delta_{n,n-1}/E_{n,n-1}^{\text{SM,LO}}$ given with (or without) references, the inverse decoupling radius $r_{n_f}^{-1}$ of the lower level in the transition, and an estimation of the relative nuclear polarization contribution.

Bound state	(n_i, l_i)	(n_f, l_f)	$E_{n,n-1}^{\text{SM,LO}}$ [keV]	$\Delta_{n,n-1}/E_{n,n-1}^{\text{SM,LO}}$ [ppm]	$1/r_{n_f}$ [MeV]	$E_{n,n-1}^{\text{NPol}}/E_{n,n-1}^{\text{SM,LO}}$ [ppm]
$\pi^{-14}\text{N}$	(5,4)	(4,3)	4.05	3.9 ± 1.7 [47]	0.44	0.005
$K^{-20}\text{Ne}$	(6,5)	(5,4)	15.6	± 1	1.4	< 0.5
$\bar{p}^4\text{He}$	(32,31)	(31,30)	5.11×10^{-3}	$(2.2 \pm 2.3) \times 10^{-3}$ [73]	0.011	10^{-8}
$\bar{p}^{20}\text{Ne}$	(13,12)	(12,11)	2.44	14 ± 23 [39]	0.45	0.005
$\bar{p}\text{Pb}$	(12,11)	(11,10)	221	109 ± 77 [65,66]	4.6	20
$\bar{p}\text{Pb}$	(11,10)	(10,9)	290	114 ± 72 [65,66]	5.5	40
$\bar{p}^{20}\text{Ne}$	(6,5)	(5,4)	29.0	± 1	2.6	1
$\bar{p}^{132}\text{Xe}$	(11,10)	(10,9)	125	± 1	3.7	8
$\bar{p}^{132}\text{Xe}$	(10,9)	(9,8)	170	± 1	4.5	20

in Table I, revealing that they are not negligible at the accuracy goals of the upcoming experiments and that the contribution of α_E^N outweighs that of $Z^2\alpha_E^H$.

The uncertainties associated with these medium-mass and heavy nuclei are projected to be considerable [62,78–81]; thus, NPol could become a bottleneck to NP searches in these systems. Below, we show that, by using two transitions, one can probe NP without having to calculate NPol, thus bypassing this difficulty.

The spin-independent component of new interactions manifests as an effective Yukawa potential [82]

$$V_X(\mathbf{r}) = (-1)^s \frac{g_N^X g_H^X}{4\pi} \frac{e^{-m_X r}}{r}, \quad (4)$$

where X denotes the new boson with spin s . $g_H^X(g_N^X)$ represents the coupling to the hadron(nucleus). In a non-relativistic approximation, the first-order perturbation of this potential to the energies of circular states is

$$E_n^X = (-1)^s \frac{g_H^X g_N^X}{4\pi} \frac{1}{r_n} \frac{1}{\left(1 + \frac{m_X r_n}{2n}\right)^{2n}} \equiv g_H^X g_N^X h_n^X, \quad (5)$$

where $r_n \equiv n^2/(Z\alpha\mu)$ represents the decoupling radius the distance beyond which the sensitivity to NP decreases. Note that r_n^2 corresponds to $\langle r^2 \rangle_n$ when $n \gg 1$. Table I lists inverse decoupling radii of the lower levels in the transitions considered here. The transitions span a range of 11 keV for a Rydberg transition in $\bar{p}^4\text{He}$, which laser technology can access, up to 5.5 MeV for the $10 \rightarrow 9$ transition in $\bar{p}\text{Pb}$, situated in the x-ray regime. This highlights the importance of x-ray spectroscopy in investigating short-range interactions.

Probing new physics—The strongest radiative transitions in the cascade of the exotic particle are those between two subsequent circular states [24], so that the transition energies are $E_{n,n-1}^{\text{exp}}$, where for any quantity Y we define $Y_{n,n-1} \equiv Y_n - Y_{n-1}$.

When the NPol uncertainty $\sigma_{E_{n,n-1}^{\text{NPol}}}$ is negligible compared to the experimental uncertainty $\sigma_{E_{n,n-1}^{\text{exp}}}$, we can use a single transition, preferably to the lowest n not affected by hadronic interactions, to probe NP. Assuming an agreement between the experiment and the prediction of SM, the upper bound of the projected 95% confidence level is

$$|E_{n,n-1}^X| = |E_{n,n-1}^{\text{exp}} - E_{n,n-1}^{\text{SM}}| < 2\sigma_{E_{n,n-1}^{\text{exp}}}. \quad (6)$$

Combining Eqs. (5) and (6) returns

$$[g_H^X g_N^X]_{1\text{ T}} < \frac{2\sigma_{E_{n,n-1}^{\text{exp}}}}{|h_{n,n-1}^X| m_X r_n \rightarrow 0} \longrightarrow 4\pi Z\alpha R_\sigma, \quad (7)$$

where $R_\sigma \equiv \sigma_{E_{n,n-1}^{\text{exp}}}/E_{n,n-1}^{\text{exp}}$. From Eq. (7), we learn that the sensitivity is flat up to the mass of $m_X \sim 1/r_n$ and then

quickly decouples as m_X^{2n} . We denote this case as *single transition* (1 T).

The second case is when $\sigma_{E_{n,n-1}^{\text{exp}}} < \sigma_{E_{n,n-1}^{\text{NPol}}}$. As the uncertainty in α_E^N is expected to be much larger than the magnitude of the corrections to Eq. (2), we can simultaneously determine α_E^N and probe NP by considering two transitions measured for the same system. We combine Eqs. (1), (2), and (5) and obtain

$$\begin{aligned} \Delta_{n,n-1} &\equiv E_{n,n-1}^{\text{exp}} - E_{n,n-1}^{\text{SM-NPol}} \\ &= g_H^X g_N^X h_{n,n-1}^X + \alpha_E^{\text{tot}} h_{n,n-1}^{\text{NPol}}, \end{aligned} \quad (8)$$

where $g_H^X g_N^X$ and α_E^{tot} are the two unknowns. Next, assuming that $\Delta_{n,n-1}$ and $\Delta_{n',n'-1}$ were measured, we can solve for $g_H^X g_N^X$ and α_E^{tot} and get

$$[g_H^X g_N^X]_{2\text{T}} = \frac{\Delta_{n,n-1} h_{n',n'-1}^{\text{NPol}} - \Delta_{n',n'-1} h_{n,n-1}^{\text{NPol}}}{h_{n,n-1}^X h_{n',n'-1}^{\text{NPol}} - h_{n',n'-1}^X h_{n,n-1}^{\text{NPol}}}, \quad (9)$$

$$[\alpha_E^{\text{tot}}]_{2\text{T}} = \frac{\Delta_{n',n'-1} h_{n,n-1}^X - \Delta_{n,n-1} h_{n',n'-1}^X}{h_{n,n-1}^X h_{n',n'-1}^{\text{NPol}} - h_{n',n'-1}^X h_{n,n-1}^{\text{NPol}}}. \quad (10)$$

Thus, by measuring two transitions and combining with theory, we can determine both NPol and NP. For every pair of transitions, there is a specific m_X for which $h_{n',n'-1}^X h_{n,n-1}^{\text{NPol}} = h_{n,n-1}^X h_{n',n'-1}^{\text{NPol}}$, and the sensitivity is lost. The sensitivity to $g_H^X g_N^X$ is estimated using error propagation of Eq. (9). For simplicity, we assume that the uncertainties on $\Delta_{n,n-1}$ and $\Delta_{n',n'-1}$ are not correlated and are of the same fraction of the energies. This case is denoted as *dual transition* (2 T).

For heavy nuclei, a non-negligible contribution from the quadrupole electric polarizability is possible [61]. Its contribution to the potential scales as r^{-6} , and the relative effect compared to the dipole polarizability is $(r_A/r_n)^2$, where $r_A \approx 1.2A^{1/3}$ fm is the rms nuclear charge radius [61]. It is expected to be small for our chosen transitions and nuclei but can still be systematically fitted from the data using additional transitions. Moreover, different isotopes could be probed to better understand this effect.

In Fig. 1, we illustrate the use of 1 T Eq. (7) and 2 T Eq. (9) by plotting the projection for $\bar{p}^{132}\text{Xe}$ assuming the experimental accuracy of $R_\sigma = 1$ ppm. Three cases are considered: (i) 1 T: $10 \rightarrow 9$ neglecting the error on the nuclear polarizability; (ii) 1 T: $10 \rightarrow 9$ with 50% error on the nuclear polarizability; and (iii) 2 T: $11 \rightarrow 10$ and $10 \rightarrow 9$ which is free of NPol. Case (i) is best only when NPol is controlled to at least 11% of its value, which is beyond current knowledge for a heavy nucleus such as ^{132}Xe . However, case (iii) is the most sensitive when a realistic uncertainty is assumed, as in case (ii).

Current data and bounds—We consider the available data and ongoing experiments in hadronic atoms and derive

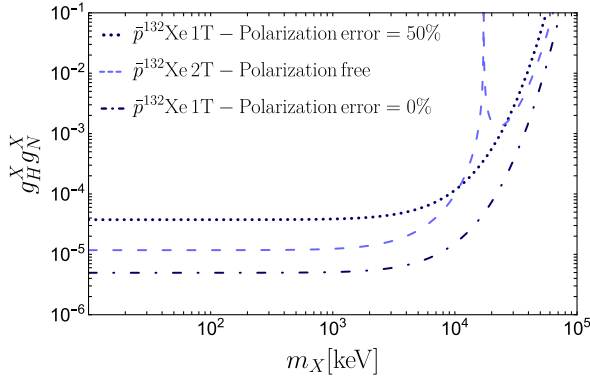


FIG. 1. $\bar{p}^{132}\text{Xe}$ projections with $R_\sigma = 10^{-6}$. The projected bound in dotted (dot-dashed) blue is for the $(10, 9) \rightarrow (9, 8)$ transition with (without) 50% polarizability error that constitutes a 10 ppm uncertainty to the NP contribution. In dashed light blue, we show the bound for combining two transitions: $(11, 10) \rightarrow (10, 9)$ and $(10, 9) \rightarrow (9, 8)$ to reduce the sensitivity to NP.

novel bounds and future projections on NP; see Fig. 2. They are given in the $m_X - g_H^X g_N^X$ plane and can be matched to specific models as shown for two examples below.

We begin with an analysis of mesonic atoms, which have so far been used to extract meson masses [46–48,75,83,84] and measure strong interaction effects [33,41,45,51,59]. To utilize them for NP searches, we adopt the pion mass $[m_\pi]_{\text{kin}} = 139.57021(14)$ MeV, accurate to 1.0 ppm, from kinematic measurements [83–85]. The most precise single transition measurement in pionic atoms is of the $5 \rightarrow 4$ line in $\pi^{-14}\text{N}$ and returns $[m_\pi]_{5 \rightarrow 4} = 139.57077(18)$ MeV [47], accurate to 1.3 ppm. Because the transition energy is proportional to m_π at the percent level, we deduce $\Delta_{5,4}/E_{5,4}^{\text{SM,LO}} = 3.9 \pm 1.7$ ppm. Other high-precision measurements in pionic and kaonic atoms produce weaker bounds [75] or are affected by residual electrons [23,48,86] or by QCD [33,41,45,51,87,88].

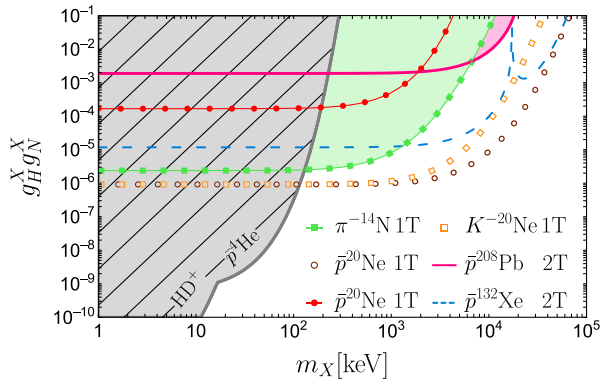


FIG. 2. New bounds (shaded solid lines) and projections (dashed lines) from this Letter compared to existing bounds from $\bar{p}^4\text{He}$ and HD^+ (shaded gray area).

The SIDDHARTA-2 experiment at the DAΦNE collider recently demonstrated high-resolution spectroscopy of circular transitions in $K^-\text{Ne}$ [69], of which the one with the highest energy is $6 \rightarrow 5$. For a future projection of the sensitivity of this transition, we consider a 1 ppm accuracy and also assume that the kaon mass is measured independently, e.g., by laser spectroscopy [89].

Next, we consider transitions in antiprotonic atoms. In Ref. [39], the strong interaction shift of the $2p$ manifold in $\bar{p}\text{D}$ was measured in two ways: (i) comparing with the known $K\alpha_1$ x-ray fluorescence line in atomic sulfur and (ii) comparing with the $\bar{p}^{20}\text{Ne } 13 \rightarrow 12$ line whose energy was calculated assuming that there is no NP. As both methods return the same $\bar{p}\text{D}$ strong interaction shift, they can be reinterpreted as a measurement of $\bar{p}^{20}\text{Ne } 13 \rightarrow 12$ energy calibrated by the sulfur line. From the information given in Table 9 in Ref. [39], we deduce $\Delta_{13,12}/E_{13,12}^{\text{SM,LO}} = 14 \pm 23$ ppm given in Table I.

To probe higher new boson masses, we consider the transitions measured in $\bar{p}\text{Pb}$ [65], where a natural abundance sample was used. Since the lines for different isotopes were not experimentally resolved, the NP may be treated as an average over them. A calculation of the corresponding energies is given in [66]. However, it does not include the effect of nuclear polarization. A rough estimation for $^{208}\text{Pb}(11, 10) \rightarrow (10, 9)$ using Eq. (2) returns ~ 40 ppm. As this is of similar magnitude as the experimental error, we remove it employing the 2T method to search for NP, considering the two lowest-lying measured intervals $11 \rightarrow 10$ and $10 \rightarrow 9$. An agreement is found between experiment [65] and theory [66], resulting in the bound plotted in Fig. 2. Although the accuracy is not as high as in lighter systems, the compact nature of this system allows one to competitively probe a new boson mass of $1/r_n \approx 6$ MeV. Other high-precision measurements in antiprotonic atoms either produce weaker bounds (Ref. [43] and Table IX in [90]) or are affected by QCD [18,42,60,90–92].

Having established that x-ray spectroscopy in hadronic atoms is sensitive to the 0.1–10 MeV NP scale, we consider the up-and-coming PAX experiment at the CERN antiproton decelerator [56,68,70,71]. Suitable transitions, where QCD contact terms and finite-size effects are negligible, were identified in Ref. [20] in the context of the probing of high-field QED. Considering the existing bounds discussed above, an accuracy better than 100 ppm would already probe a new parameter space. To show the full potential of these measurements, we consider an accuracy of 1 ppm for two representative cases: (i) 1 T for the $6 \rightarrow 5$ line in $\bar{p}^{20}\text{Ne}$ —since $E_{6,5}^{\text{NP}} \approx 1$ ppm, it is not expected to be the bottleneck; and (ii) 2 T combining $12 \rightarrow 11$ and $11 \rightarrow 10$ in $\bar{p}^{132}\text{Xe}$, as $E_{11,10}^{\text{NP}} \approx 20$ ppm, it can potentially limit the sensitivity of a single-transition measurement.

The existing strongest bound from exotic atoms is from $\bar{p}^4\text{He}$ [73,74], which decouples at 20 keV, as shown in

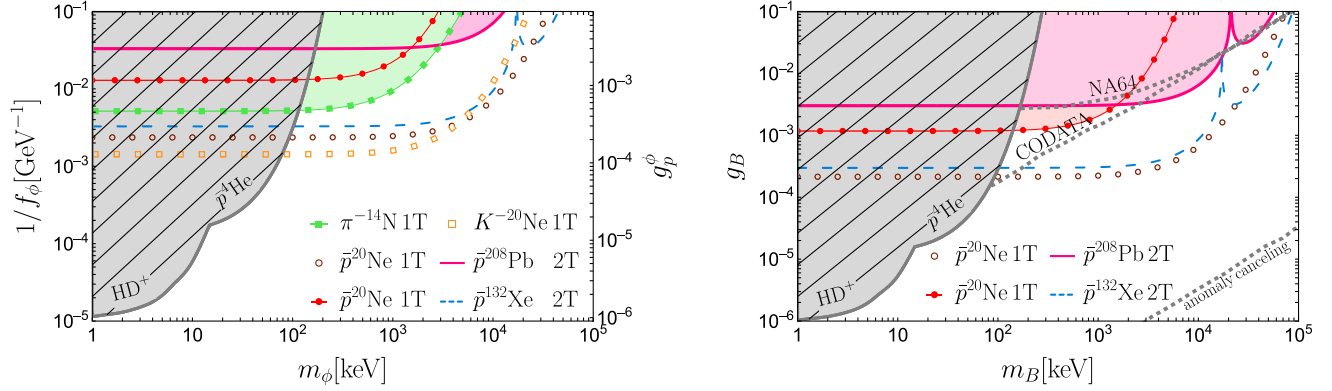


FIG. 3. The same as Fig. 2 with (left) the uds -scalar model and (right) the B -boson model with additional bounds from NA64, CODATA, and new anomaly-canceling fermions (see the main text for details).

Fig. 2. Other probes of new hadronic forces are from molecular spectroscopy ($m_X \lesssim 10$ keV) [93,94] and neutron scattering ($m_X \lesssim 100$ keV) [95]. There are stringent stellar cooling limits [96,97] that decouple at 100 keV and from supernova 1987A bounds [98] that reach higher masses and relevant to smaller couplings. However, these are model dependent and subject to different systematics; see, e.g., Refs. [99–105]. Our updated bounds and projections reach a greater mass than previous probes, up to ~ 10 MeV.

Application to benchmark models—The above bounds can be cast into specific BSM models; here are the results for two benchmark models. The first is the uds scalar from Ref. [72], and the second is the B model (where B stands for a gauged baryon number) assuming predominantly invisible decays. In the following, we show that exotic atoms can be the leading probes of these models for a mediator mass in the 100 keV to 10 MeV range. Note that the Higgs-mixing model is severely constrained by $K^+ \rightarrow \pi^+ + \text{inv}$ [106,107].

In the uds -scalar model, a new CP -even scalar ϕ , with mass m_ϕ , exclusively interacts with the u , d , and s quarks and decays invisibly. The couplings are proportional to the quark masses and are suppressed by the cutoff scale f_ϕ . As shown in Ref. [72], the stringent bounds from $K \rightarrow \pi\phi$ [106,108] are evaded to leading order in the chiral expansion and, thus, relaxed, unlike in the case of scalar Higgs mixing. The effective ϕ -quark interaction is given by

$$\mathcal{L}_\phi^{\text{int}} = \frac{\phi}{f_\phi} \sum_{q=u,d,s} m_q \bar{q}q, \quad (11)$$

without coupling to other SM particles. Following, e.g., [109,110], we match $\mathcal{L}_\phi^{\text{int}}$ to the hadron level

$$\begin{aligned} \mathcal{L}_\phi^{\text{int,had}} \subset & \phi(g_p^\phi \bar{p}p + g_n^\phi \bar{n}n \\ & + 2m_\pi g_\pi^\phi \pi^+ \pi^- + 2m_K g_K^\phi K^+ K^{s-}), \end{aligned} \quad (12)$$

with $g_{\pi(K)}^\phi = -[m_{\pi(K)}/2f_\phi]$, $g_{p(n)}^\phi = [m_{p(n)}/f_\phi] \sum_q f_q^{p(n)}$, $f_u^{p(n)} = 0.018(0.016)$, $f_d^{p(n)} = 0.034(0.038)$, and $f_s^{p(n)} = 0.044(0.044)$ [109]. The interaction with nuclei is given by $g_N^X \approx (A-Z)g_n^X + Zg_p^X$.

The bounds on the uds model are plotted in the left panel in Fig. 3 in the $m_\phi - f_\phi^{-1}(g_p^\phi)$ plane, where we projected the bounds of Fig. 2. The approximated next-to-leading-order bounds from rare kaon decay are $1/f_\phi \lesssim 0.8/\text{GeV}$ [72] and are not shown. We note that the probed range of parameter space is mildly fine-tuned, since, for a TeV cutoff, the one-loop correction to m_π is $\delta m_\pi^2 \sim \text{TeV}^2(m_s/f_\phi)^2/16\pi^2$. We learn that heavy exotic atoms already set the strongest bounds on the uds model for $0.1 \lesssim m_\phi \lesssim 10$ MeV with the potential to improve by at least an order of magnitude.

The B -boson model introduces a new massive spin-1 gauge boson B with universal vectorlike couplings to the quarks. The SM charged leptons are coupled via one-loop kinetic mixing, and we assume $\text{BR}(B \rightarrow \text{inv}) \approx 1$. This model was analyzed in several places, e.g., [111,112]. The interactions with the SM fermions are given by

$$\mathcal{L}_B^{\text{int}} = \frac{g_B}{3} B^\mu \sum_q \bar{q} \gamma_\mu q - \frac{g_B e^2}{48\pi^2} B^\mu \sum_\ell \bar{\ell} \gamma_\mu \ell, \quad (13)$$

where $q(\ell)$ is the SM quarks (charged leptons). The $\mathcal{L}_B^{\text{int}}$ can be mapped to the hadron interactions

$$\mathcal{L}_B^{\text{int,had}} = g_B B_\mu (\bar{p} \gamma^\mu p + \bar{n} \gamma^\mu n). \quad (14)$$

The baryon number is an anomalous symmetry and, thus, requires additional degrees of freedom. Such considerations lead to strong bounds from rare bottom and kaon decays [113–115]. However, a similar model that is anomaly-free can be built by mixing the SM fermions with heavy vectorlike fermions as in, e.g., [116,117].

We plot our new $\bar{p}\text{Ne}$ and $\bar{p}\text{Pb}$ bounds and the projections for the B model in the right panel in Fig. 3.

We compare our result to the existing bounds from $\bar{p}^4\text{He}$ and NA64 [118] and to rescaling of the $B - L$ bound from [17], denoted as CODATA. The last two are based on a loop-induced B -electron coupling that depends on the model's UV details and can be adjusted accordingly. We learn that $\bar{p}\text{Ne}$ and $\bar{p}\text{Pb}$ are already the robust leading probes of this model and that future measurements have the potential to increase sensitivity by an order of magnitude.

Conclusions—We explored the potential of precision spectroscopy of heavy exotic atoms in which electrons are replaced by $\bar{p}$, π^- , or K^- , to probe new force carriers with hadronic couplings. We have considered transitions that are clean from short-range hadronic effects; thus, the SM contribution can be predicted to high accuracy. However, nuclear polarizability can still have sizable effects on these transition lines. Therefore, we propose to use two lines and simultaneously solve for new-physics and polarizability effects. Based on the available data in $\bar{p}\text{Ne}$, $\bar{p}\text{Pb}$, and $\pi^- \text{N}$, we extract new world-leading bounds on two benchmark models and derive projections for future measurement for several representative systems. For mediator masses of up to 10 MeV, future experiments have the potential to improve the sensitivity by up to 2 orders of magnitude. In addition, while this Letter considered only spin-independent interactions, spin-dependent interactions can be probed in a future work.

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Data availability—The data that support the findings of this article are openly available [119].

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