

Identification of a universal three-body *s*-wave resonance in ^{10}He

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)
Referee report for the paper

First identification of a universal three-body *s*-wave resonance in ^{10}He

by Y.L. Sun et al

The new highly accurate data on ^{10}He populated in the proton knockout reaction from ^{11}Li halo nucleus is reported in this work. The Authors report on the low-energy enhancement in the invariant mass spectrum of ^{10}He , which was not identified in the previous studies due to insufficient resolution or/and statistics. These data are interpreted as providing evidence to existence of *s*-wave resonance in ^{10}He , built on three attractive *s*-wave pairwise interactions. Such a resonance is discussed as representative of the "universal" long-range dynamics of Efimov type. The search for these class of phenomenon was so far unsuccessful in nuclear systems, therefore such a discovery could be a real "gem" in the studies of exotic phenomena near the nuclear driplines.

In my analysis of situation I fully rely on the reliability of the data. These are provided by one of leading groups in the field with broad expertise in analogous studies. So, in the following analysis of the proposed interpretation complete reliability of the data is implied.

There are important questions about interpretation of the data. It can be found in the literature that alternative interpretations are possible. These interpretations are for a long time "on the market" and should not be neglected without significant explanation. It should be noted that alternative interpretations are also not trivial and are related to questionable types of the long-range dynamics in nuclear systems, which are also of significant interest.

I find the experimental observations of this paper and various types of associated physical phenomena sufficiently interesting to be published in Nature. However, major revision of the manuscript in aspects concerning the data interpretation is due (see the discussion below). I would strongly recommend this paper for publication in Nature if my criticism concerning interpretation is fully taken into account.

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Point 1. Scattering length in the $9\text{He}=8\text{He}+n$.

Broad theoretical exploratory studies of the 10He spectra sensitivity to the s-wave $8\text{He}-n$ interaction have been performed in Ref. [18] by Grigorenko and Zhukov.

Since further we rely on the results of Refs. [18, 19], it is necessary to comment to their description in this work:

"Currently, the most advanced theoretical work on 10He is given in Refs. [18, 19]. On the one hand, it has been discussed that the 10He ground state could be at ~ 2 MeV, as observed by the $2n$ transfer reaction, and has a $[0p_{1/2}]^2_{0+}$ structure, while the initial state effects due to the halo nature of 11Li or 14Be may lower the energy of 10He to ~ 1.5 MeV as observed in knockout reactions. Calculations with such effects qualitatively agree with the 10He invariant-mass spectrum from $11\text{Li}(-p)$ [19] but cannot explain the spectrum from $14\text{Be}(-2p2n)$ [20]."

(1) The low energy strength in the 10He spectrum has mixed character $[0s_{1/2}]^2_{0+} + [0p_{1/2}]^2_{0+}$ with around 50% mixing. Important special attention was paid in [18] to evolution of these components in various conditions.

(2) The statement that the results of [19] "cannot explain the spectrum from $14\text{Be}(-2p2n)$ " is not relevant, since the calculations in [19] were about alpha knockout, while there were no clear identification of the reaction channel in [20] and " $14\text{Be}(-2p2n)$ " (not alpha removal!) is just one of reasonable assumptions of this work.

Let's have a look in Fig. 5f of this work. The solid curve shows the spectrum which is very consistent with the new experimental data. In Fig. 6c the decomposition of exactly this spectrum is shown demonstrating energy split between $[s^2]_0$ and $[p^2]_0$ components at about 1 MeV, which is, again, very consistent with theoretical results shown in Fig. 1 of this work. The complete three-body correlations for this case also can be found in Fig. 13c of Ref. [18]. These are calculated not exactly for the excitation energy range, used in Fig. 2 of the Refereed paper, but they look very similar to the recent data. So, the agreement of this specific theoretical prediction with the data seem to be very good. However, this specific calculation corresponds to quite a different scattering length 2.9 fm in the $8\text{He}+n$, which is not ATTRACTIVE, but REPULSIVE. This is not in accord about the basic message of this work about universal Efimov-type phenomenon.

Let's have a look on the situation in a different way. The energy of the $p_{1/2}$ resonant state used in the calculations of this work is mentioned to be 0.76 MeV. The results for such $p_{1/2}$ position can be found in Fig. 5d of [18]. They should be between dotted and dash-dotted curve, producing peak between 30 and 200 keV. So, there seem to be strong contradiction between theoretical approaches of this work and of Ref. [18]. According to [18] the universal s-wave structure built on the s-wave attractions in all three subsystems should have been seen as extreme low-energy (100 keV? 200 keV?) structure in this reaction.

I would mention one qualitatively suspicious moment in the provided theoretical calculations. Based on the energy of $p_{1/2}$ state 0.76 MeV, the trivial independent particle approximation should provide the energy ~ 1.5 MeV for the $[p_{1/2}]^2_0$ configuration. The peak energy for this configuration in Fig. 1 of this work is ~ 1.9 MeV. This means that the pairing interaction is effectively repulsive for the $[p_{1/2}]^2_0$ configuration. This is quite unexpected result, which I see as strange for the three-body model and which it is not within the systematics of effective pairing energies for the $p_{1/2}$ subshell, which can be traced for the other members of $N=8$ isotone. In Ref. [18] these effective pairing energies vary from 0.5 to 1.8 MeV,

which is smaller than the typical values in the $p_{3/2}$ subshell, but not negative at least.

The strong theoretical controversy is quite intriguing, considering the nice agreement between the three-body calculations of this group [33] and [Grigorenko et al. PRC 102, 014611 (2020)] for another quite complicated peripheral phenomenon: soft dipole excitation in the continuum of ^6He system.

It is not impossible that quite old calculations of Ref. [18] are deficient in some way. However, unless this deficiency is demonstrated they can not be just disregarded: these are published and well documented results, while for the calculations of this work not much details are available. The Authors should either find out what is wrong with calculations of [18] or rely on them as alternative interpretation of the data.

Some separate note concerning the $^8\text{He}+n$ scattering length issue.

I would like to pay attention of the Authors to results of paper

[Khirk et al., Phys. Rev. C 111, L051601 (2025)].

In this work the data of Uberseder et al. [39] were reinterpreted with more advanced treatment of isospin symmetry. The scattering length in the $^8\text{He}+n$ channel deduced in this work was weakly attractive as -2.7 fm, with no need for $s_{1/2}$ resonance. This is quite close to the deduced in this work value -3.45 fm. However, the $p_{1/2}$ state should be at about 2.3 MeV (original analysis of Uberseder et al. do not allow any resonances with $l>0$ and $E<3$ MeV at all).

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Point 2. Reaction mechanism issue.

The structures promoted in this paper as "two low-lying 0^+ states of ^{10}He at ~ 1 MeV and ~ 2 MeV above its two-neutron decay threshold" according to calculations of [18] are strongly sensitive to the reaction mechanism. Let's compare solid curves Fig. 5 c and f in [18]. One is well consistent with the data of the refereed work the other is shifted to higher energy to more than 1 MeV. The same if we compare Fig. 6 b and c in [18]. For one the $[s^2]_0$ and $[p^2]_0$ components are well energy split (as in the calculations of this work), but for the other they more or less overlaps, so we can hardly speculate about separate $[s^2]_0$ and $[p^2]_0$ states.

The results of the refereed work are based on some realistic reaction model where the ^{11}Li WF is present. So, all these effects should be there, they are just not discussed. These could be easily checked if I am right by the Authors of this work in two reasonably simple ways:

(1) By performing calculations without ^{10}He FSI - just plane waves.

Typically people try to check, whether the signal they see is not provided just by a plane wave, without any dynamics.

(2) By changing the reaction mechanism by using not a halo nucleus ^{11}Li , but a compact system. For example $^{14}\text{C}(-4p)$. Not very realistic reaction for practical realization, but theoretically we may play games. If the strength function is strongly qualitatively sensitive to the reaction mechanism, then you can hardly speculate about resonance states. Resonant states is something independent on reaction mechanism by definition.

Also, if your population cross section strongly depends on the reaction mechanism then what is your "universality" about? This is not about that the story is not interesting and important, but about carefully choosing terms for the discussion.

I am a bit amused that this topic is total missing in the manuscript, since the Authors has recently studies soft dipole excitation in ^6He [33], where they do not attempt to interpret the E1 strength function in terms

of resonance position and width.

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Point 3. Possibility of 1- state population.

The excitations of ^{10}He with $J>0$ are only briefly discussed in this work as possibly contributing the high-energy part of the strength function. This is not substantiated with any calculations. However, it was shown in [19] that due to extreme halo extent of the ^{11}Li WF the specific mechanism of proton knockout may lead to population of 1- as the lowest energy component of the ^{10}He spectrum. It should be noted that mechanism of such a knockout is not just s-wave removal and do not lead to typical s-wave momentum distributions of the spectator in the outgoing channel (see Fig. 2 of [19]).

The population of the 1- configuration was predicted on the level up to 25% to the $0+$ population rate. However, the low-energy region, where a specific enhancement was observed in the $^{11}\text{Li}(p)$ reaction, the 1- may provide dominating contribution.

Please check the following:

Text:

"As shown in Fig.4, the distributions can be well reproduced by the quasi free knockout calculations that assume a p-wave proton removal from ^{11}Li ."

Caption Fig.4:

"s-wave (red solid line) or p-wave (blue solid line)"

There is agreement with the red solid line in the figure, which is in contradiction with the text.

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Minor things

I find the presentation of data of [Korshennikov et al] misleading in Fig. 1. The original paper contains the data on CD_2 and C targets, which are not in full agreement. The conclusions of [Korshennikov et al] are based on subtracted spectrum which has large error bars, while the authors of this work arbitrarily have chosen one of initial spectra with comfortably small error bars.

I sincerely believe that considering all the problematic issues discussed above the deduced scattering length precision " $-3.45(20)$ fm" is a strong overestimation of the achievable precision. Something like " ~ -3.5 fm" will be more realistic, since criterion of the error determination is unclear.

The Authors use two Figures (2 and 3) to show the complete three-body correlation patterns and their projections. I think it could be more instructive to demonstrate evolution of the correlation patterns with energy. According to the theoretical interpretation there are energy ranges where the $[s^2]_0$ component is totally dominant and where the $[p^2]_0$ contribution is important. It is a bit strange not to try to observe the difference in the correlations.

The same is somehow true about Fig. 4. When gated on the excitations of ^{10}He these spectra may (or may not) demonstrate some differences related to peculiarities of reaction mechanisms populating $[s^2]_0$ and $[p^2]_0$ configurations (if there are any).

I find the topic "Deduction of the effective angular momentum for a three-body system". On one hand, the relevance of this derivation to the topic of the paper is doubtful. On the other hand, this derivation is valid within the specific adiabatic framework. The conclusion of this derivation is trivial: between "no s-wave interaction" and "Efimov case" there will be a continuum

of effective interactions as the pairwise scattering lengths (all together simultaneously or in some separate manner) tend from zero to minus infinity. Do not think this deserve publication in the Nature.

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To finalize the discussion. All the theoretical points above are quite complicated. I doubt that within the limited volume this particular publication the mentioned controversies could be well resolved. However, these theoretical discussions also do not devaluate the potential importance of the current experimental observation and its interest to a broad scientific community.

My proposal is to reformulate the paper from modality "solidly understood in a unique way" (which I doubt the Authors can actually prove) to "there are different possible intriguing interpretations of the data". Possible alternative interpretations should be clearly discussed in the paper. They are also not trivial and may be of significant scientific interest by themselves as ideas existing in parallel with ideology of Efimov-type phenomena. The title of the paper should be also changed to a broader context and statements about "resonant states" replaced everywhere with something neutral like "peaks in the population cross section".

Reviewer #2

(Remarks to the Author)

Report on "First identification of a universal three-body s-wave resonance in ^{10}He "

The subject of this paper is the experimental identification of an Efimov state (resonance) in the ^{10}He system.

Although Efimov states were first observed in cold atom systems and have long been discussed in the context of atomic He_3 , they were originally predicted within the realm of nuclear physics by Efimov. I believe it is extremely important to identify nuclear systems that can be described by this universal model, further highlighting the universality of Efimov physics. For this reason, I think the present paper, especially given its experimental nature, deserves publication.

I have only a few remarks, which do not pertain to the experimental techniques that are well explained.

1. A simple remark is on line 6, where the emergence of an infinite tower of three-body states is related, strictly speaking, to an infinite (and not just a sufficiently large) scattering length.
2. The explanation of the resonance is mostly based on the shell model interpretation of the state. It would be useful for a reader from another community (thanks to the universality of Efimov physics) to at least provide a sketch of what is happening and why the state appears as a double-intruder nucleus (lines 45-..., 90-..., and 122).
3. The explanation of the state rests heavily on the shell model. However, there are other ways to view it that rely on both the scattering length, which has been extracted (as mentioned again in line 199), and on the effective range (Kievsky A., Gattobigio M., Girlanda L., Viviani M., *Efimov Physics and Connections to Nuclear Physics.*, Annu. Rev. Nucl. Part. Sci **71**, 465, 2021). It would be important to try to extract the effective range to allow for other interpretations of the same state.
4. The grand-angular momentum K is discussed in the Methods section, but I'm not sure that the introduction of K in line 171 without a previous explanation is correct.

To summarize, the paper deserves publication as it sheds a nuclear light on Efimov physics, which originates from Nuclear Physics.

Reviewer #3

(Remarks to the Author)

Summary

The manuscript describes measurements of ^{10}He produced through $(p, 2p)$ reactions of a ~ 250 MeV/u ^{11}Li beam with a liquid hydrogen target. Analysis of the three-body relative energy and Jacobi correlation spectra utilized a coupled-channel three-body model of ^{11}Li combined with the quasi-free knockout reaction model, and complex-scaled solutions of the Lippmann-Schwinger equation were used to compute final states in ^{10}He . The low-energy structure in the three-body relative energy spectrum is explained by two 0^+ states with ^8He cores, one with a $[1s1/2]^2$ neutron component and another with a $[0p1/2]^2$ neutron component. By tuning the ^8He -n interaction to fit the ^{10}He spectrum below 2 MeV, the authors extracted an s-wave scattering length between ^8He and the neutron. The Jacobi-T normalized relative energy and Jacobi-Y angle ^8He -n-n correlations gated on relative energies < 1 MeV show enhancements that are qualitatively reproduced by the three-body calculations. The authors conclude that the observation of the two 0^+ states resolves the long-standing difference between ^{10}He ground state energies measured from knockout and $2n$ transfer. Furthermore, the ^{10}He ground state is a three-body s-wave resonance that exemplifies a novel class of universal three-body bound states.

Revisions

The paper is well-constructed, concise, and it provides new information suggesting a resolution to a long-standing question about the structure of ^{10}He . The following revisions would strengthen the paper and should be satisfactorily addressed:

1. How is the 1-sigma energy resolution dependence as a function of relative energy determined? Does this come from a previous measurement? A Monte Carlo simulation of the setup? A brief explanation or reference in Section 2 is necessary to support the stated relationship. An addition to the top panel in Fig. 1 to show the resolution alongside the efficiency or an illustration and accompanying explanation in the methods section would help further convince the reader of the setup's sensitivity.
2. Including additional information in the Methods section about the cross-talk rejection procedures would benefit the reader. For example, reference [31] includes empirically derived values for the same-wall cross-talk rejection filters based on the $^7\text{Li}(p,n)^7\text{Be}$ test case. Are similar values used here?
3. Some clarification of the analysis procedure is needed to help the reader understand the comparison between data and calculation shown in Fig. 1.
 - a. How does the output from the three-body ^{11}Li model + quasi-free knockout model inform the calculation of the final ^{10}He states? Do the reaction calculations provide cross-sections that scale the contributions of the ^{10}He states in the relative energy spectrum?
 - b. What parameters for the ^8He -n interaction are varied and how? Including an additional figure in the Methods section that shows how these parameters impact the agreement with data would help reinforce the assertion from lines 131 – 133: “the spectrum’s shape is highly sensitive to the ^8He -n interaction, and the observed low-energy structure is reproduced only with a weakly attractive ^8He -n s-wave interaction.”
4. The legend and caption for Fig. 1 should be revised to clarify what is indicated by the green dashed curve labeled ‘others.’ It’s not clear if this is referring to the discussion in lines 124 – 131 regarding higher-lying states.
5. Does the Argonne v8’ force include/account for the large neutron-neutron s-wave scattering length $a_{nn} \sim 19$ fm referenced in line 174?
6. Is it possible to extract cross-sections for populating the two 0^+ states? Or a ratio of these cross-sections? This could be useful for comparing to previous predictions e.g. reference [22].
7. The $[2s1/2]^2$ should be $[1s1/2]^2$ to be consistent with notation elsewhere (e.g. the legend of Fig. 1 and line 196).
8. In lines 173-174 and in the Methods section, the ^{10}He ground state is shown to have an effective angular momentum $K=1/2$ which should be associated with a repulsive effective three-body potential indicated by the black curve in Fig. 5. The next line seems contradictory: “This is physically due to that a neutron occupying the halo virtual state can mediate an attractive interaction between the other neutron and the ^8He core up to large distance ...” And line 180 emphasizes again the ^{10}He system shows long-range repulsion. The explanation of how the attractive interaction arises needs to be clarified.
9. In the methods subsection “deduction of the effective angular momentum for a three-body system,” additional context is needed around line 304 to explain or justify why the right hand side of Eq.(6) is $O(1)$ so that the leading order term of the left-hand side must vanish.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)

Report on “First identification of a universal three-body s-wave resonance in ^{10}He ”

The authors have addressed most of my concerns. However, their response

regarding the effective range, which I had previously inquired about, remains unconvincing.

The paper they cite solves the Schrödinger equation only for cases where both the scattering length and the effective range are negative. This constraint (a negative effective range) is mandatory in their scheme, which involves summing to all orders.

In contrast, the spirit of the article by Kievsky et al. (Annu. Rev. Nucl. Part. Sci 71, 465, 2021) is different. It has been shown that a positive effective range can also be handled. Moreover, the effective range is not a correction to the infinite scattering-length result, nor is it presented as such in the paper cited by the authors.

I understand that extracting the effective range can be subject to large errors; still, I believe providing it would be very important. Its sign, in particular, could be of great significance.

This remains my main concern. I can understand if the authors are not interested in analyzing their results further to provide this estimation, perhaps because they believe their result is solid regardless of the effective range. However, they rely on only one type of EFT, where the effective range is either treated as a perturbation or is required to be negative.

Despite my concerns, the paper deserves publication as it brings the physics of universal states back into the focus of Nuclear Physics.

Reviewer #3

(Remarks to the Author)

The manuscript describes measurements of ^{10}He produced through $(p, 2p)$ reactions of a ~ 250 MeV/u ^{11}Li beam with a liquid hydrogen target. Analysis of the three-body relative energy and Jacobi correlation spectra utilized a coupled-channel three-body model of ^{11}Li combined with the quasi-free knockout reaction model, and complex-scaled solutions of the Lippmann-Schwinger equation were used to compute final states in ^{10}He . The low-energy structure in the three-body relative energy spectrum is explained by two 0^+ states with ^8He cores, one with a $[1s1/2]^2$ neutron component and another with a $[0p1/2]^2$ neutron component. By tuning the ^8He -n interaction to fit the ^{10}He spectrum below 2 MeV, the authors extracted an s-wave scattering length between ^8He and the neutron. The Jacobi-T normalized relative energy and Jacobi-Y angle ^8He -n-n correlations gated on relative energies < 1 MeV show enhancements that are qualitatively reproduced by the three-body calculations. The authors conclude that the observation of the two 0^+ states resolves the long-standing difference between ^{10}He ground state energies measured from knockout and $2n$ transfer. Furthermore, the ^{10}He ground state is a three-body s-wave resonance that exemplifies a novel class of universal three-body bound states.

This reviewer's comments have been sufficiently addressed by the author's revision, and publication is recommended. Many thanks to the authors for their thoughtful and thorough responses to this reviewer's comments.

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Reply to comments of Reviewer #1

The new highly accurate data on ^{10}He populated in the proton knockout reaction from ^{11}Li halo nucleus is reported in this work. The Authors report on the low-energy enhancement in the invariant mass spectrum of ^{10}He , which was not identified in the previous studies due to insufficient resolution or/and statistics. These data are interpreted as providing evidence to existence of s-wave resonance in ^{10}He , built on three attractive s-wave pairwise interactions. Such a resonance is discussed as representative of the "universal" long-range dynamics of Efimov type. The search for these class of phenomenon was so far unsuccessful in nuclear systems, therefore such a discovery could be a real "gem" in the studies of exotic phenomena near the nuclear driplines.

In my analysis of situation I fully rely on the reliability of the data. These are provided by one of leading groups in the field with broad expertise in analogous studies. So, in the following analysis of the proposed interpretation complete reliability of the data is implied.

There are important questions about interpretation of the data. It can be found in the literature that alternative interpretations are possible. These interpretations are for a long time "on the market" and should not be neglected without significant explanation. It should be noted that alternative interpretations are also not trivial and are related to questionable types of the long-range dynamics in nuclear systems, which are also of significant interest.

I find the experimental observations of this paper and various types of associated physical phenomena sufficiently interesting to be published in Nature. However, major revision of the manuscript in aspects concerning the data interpretation is due (see the discussion below). I would strongly recommend this paper for publication in Nature if my criticism concerning interpretation is fully taken into account.

Reply: Thank you to the reviewer for the comments, especially for directing us deeper to the pioneer theoretical work of Ref. [18] regarding the interpretation of the experimental data. Firstly, we would like to clarify the differences between Ref. [18] and the theoretical framework of the present work. One of the differences is in the treatment of the Pauli blocking in the ^8He - n interaction. The treatment of the Pauli blocking can affect both the ^{10}He structure and the initial-state ^{11}Li wavefunction. Ref. [18] employs a local repulsive potential to take the effect of occupied $0s_{1/2}$ orbit into account. In our model, the Pauli forbidden states are excluded by using the so-called Pauli projection method with pseudopotential. A comparison between different methods for the three-body states could be found in Ref. [I.J. Thompson *et al.*, Phys. Rev. C 61 (2000) 024318]. The differences are small for bound and resonant states, but larger for continuum states. Larger differences are expected for halo nuclei where the s-wave channel plays a significant role, such as ^{11}Li .

The other difference is the s - and p -wave potentials between the neutron and the ^8He core. Ref. [18] adopts Gaussian potentials for different partial waves for the ^8He - n subsystem. The evolution of s -wave and p -wave components were checked by tuning the strengths of the s -wave and p -wave Gaussian potentials separately. In our theoretical model, we take the folding potential for the ^8He - n subsystem. This does not allow us to tune the s -wave and p -wave interactions separately. However, we have indeed checked the evolution of the s & p components by tuning the potential depth of the folding potential. Considering the uncertainty of the ^8He - n interaction, this is the only parameter we have tuned to reproduce the experimental data.

Secondly, we would like to emphasize that our main conclusion that the observed ^{10}He ground state is a universal 3-body s -wave resonance related to the prediction by Hongo and Son (Ref. [10]) doesn't change depending on the details of nuclear-structure interpretation or the sign of neutron-core scattering length. Since the Hongo-Son state only requires a small "absolute value" of the core-neutron scattering length, even if the neutron-core scattering length is slightly positive, the ^{10}He resonance can still be interpreted as an unbound analogue of the universal Hongo-son state; The sign of the scattering length only plays a very minor role as shown in Ref [10]. Furthermore, in Ref. [18], it is also stated that **"The state with the $[s_{1/2}]^2$ structure should be characterized by domination of the component with the lowest possible value of the generalized angular momentum $K = 0$. However, the centrifugal barrier $L(L + 1)/2M\rho^2$ is not zero even in the channel with $K = 0$, as it depends on the "effective angular momentum" $L = K + 3/2$. This means that the low-energy three-body virtual state may exist in the form of a real resonance peak, not a threshold peculiarity as the two-body virtual state."** Our claim on the universal properties of the 3-body s -wave state is consistent with the above statement in Ref. [18]. We note that the definition of "effective angular momentum" in Ref. [18] based on the hyperspherical harmonics model is slightly different to our definition based on the Faddeev approach. We take the induced long-range interaction into account. In our definition, the effective angular momentum for the three-body s -wave state is reduced from non-interacting value $3/2$ (lowest value given in Ref. [18]) to $1/2$ due to the mediated attraction originating from the hyper-angular motion.

Point 1. Scattering length in the $^9\text{He}=^8\text{He}+n$.

Broad theoretical exploratory studies of the ^{10}He spectra sensitivity to the s -wave ^8He - n interaction have been performed in Ref. [18] by Grigorenko and Zhukov.

Since further we rely on the results of Refs. [18, 19], it is necessary to comment to their description in this work:

"Currently, the most advanced theoretical work on ^{10}He is given in Refs. [18, 19]. On the one hand, it has been discussed that the ^{10}He ground state could be at ~ 2 MeV, as observed by the

2n transfer reaction, and has a $[0p_{1/2}]^2_{0+}$ structure, while the initial state effects due to the halo nature of ^{11}Li or ^{14}Be may lower the energy of ^{10}He to ~ 1.5 MeV as observed in knockout reactions. Calculations with such effects qualitatively agree with the ^{10}He invariant-mass spectrum from $^{11}\text{Li}(-p)$ [19] but cannot explain the spectrum from $^{14}\text{Be}(-2p2n)$ [20]."

(1) The low energy strength in the ^{10}He spectrum has mixed character $[0s_{1/2}]^2_{0+} + [0p_{1/2}]^2_{0+}$ with around 50% mixing. Important special attention was paid in [18] to evolution of these components in various conditions.

Reply: We agree with the reviewer that the low-energy region of the ^{10}He spectrum has mixed character $[1s_{1/2}]^2 + [0p_{1/2}]^2$. But in our case, it is not 50% mixing. As shown in Fig. 1 of our manuscript, the percentages of the $[1s_{1/2}]^2$ and $[0p_{1/2}]^2$ components are 72% and 26%, respectively, which in our calculations mainly depend on the initial state wave function of ^{11}Li , the final ^{10}He wave function (governed by the $^8\text{He}-n$ and $n-n$ interactions), and also the phase space of the final ^{10}He states as a function of the excitation energy. As mentioned before, in our theoretical model, we take the folding potential for the $^8\text{He}-n$ subsystem. This does not allow us to tune the s -wave and p -wave interactions separately as done in Ref. [18]. However, we have indeed checked the evolution of the s & p components by tuning the potential depth of the folding potential. Considering the uncertainty of the $^8\text{He}-n$ interaction, this is the only parameter we have tuned to reproduce the experimental data.

(2) The statement that the results if [19] "cannot explain the spectrum from $^{14}\text{Be}(-2p2n)$ " is not relevant, since the calculations in [19] were about alpha knockout, while there were no clear identification of the reaction channel in [20] and " $^{14}\text{Be}(-2p2n)$ " (not alpha removal!) is just one of reasonable assumptions of this work.

Reply: We agree with the reviewer that the calculations in Ref. [19] assumed a direct α removal from ^{14}Be , while ^{10}He data in Ref. [20] could be populated by either $2p2n$ removal or α removal from ^{14}Be . Nevertheless, we think the discussions in Ref. [19] and Ref. [20] show an important step to understand the ^{10}He spectrum from ^{14}Be . We would like to keep this sentence and modify it accordingly as below:

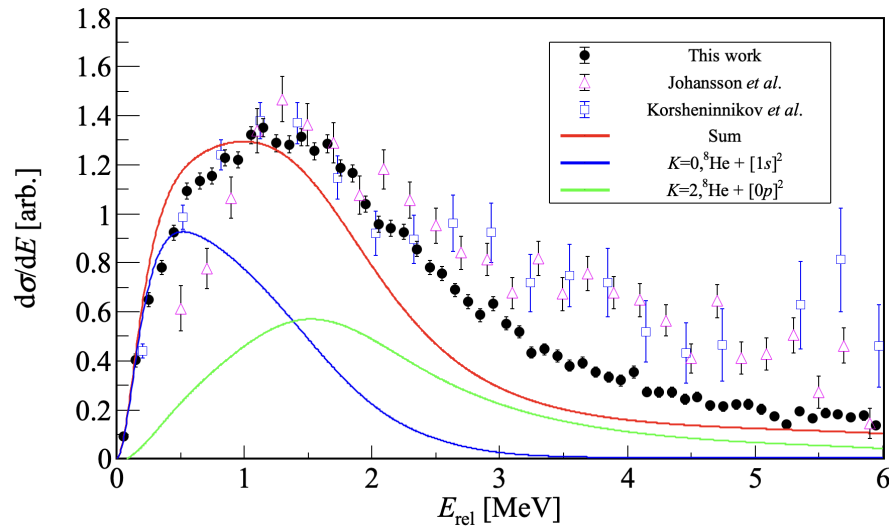
"Calculations with such effects qualitatively agree with the ^{10}He invariant-mass spectrum from $^{11}\text{Li}(-p)$ [19] but similar calculations assuming a direct α -particle removal from ^{14}Be cannot explain the spectrum from $^{14}\text{Be}(-\alpha \text{ or } -2p2n)$ [20]."

Let's have a look in Fig. 5f of this work. The solid curve shows the spectrum which is very consistent with the new experimental data. In Fig. 6c the decomposition of exactly this spectrum is shown demonstrating energy split between $[s^2]_0$ and $[p^2]_0$ components at about 1 MeV, which is, again, very consistent with theoretical results shown in Fig. 1 of this work. The complete three-body correlations for this case also can be found in Fig. 13c of Ref. [18]. These

are calculated not exactly for the excitation energy range, used in Fig. 2 of the Refereed paper, but they look very similar to the recent data. So, the agreement of this specific theoretical prediction with the data seem to be very good. However, this specific calculation corresponds to quite a different scattering length 2.9 fm in the $^8\text{He}+n$, which is not ATTRACTIVE, but REPULSIVE. This is not in accord about the basic message of this work about universal Efimov-type phenomenon.

Let's have a look on the situation in a different way. The energy of the $p_{1/2}$ resonant state used in the calculations of this work is mentioned to be 0.76 MeV. The results for such $p_{1/2}$ position can be found in Fig. 5d of [18]. They should be between dotted and dash-dotted curve, producing peak between 30 and 200 keV. So, there seem to be strong contradiction between theoretical approaches of this work and of Ref. [18]. According to [18] the universal s-wave structure built on the s-wave attractions in all three subsystems should have been seen as extreme low-energy (100 keV? 200 keV?) structure in this reaction.

Reply: Since the reviewer thinks of the solid curve in Fig. 5f or Fig. 6c in Ref. [18] looks very consistent with the experimental data, we have compared this curve with the data. The results are shown in the figure below. Note that we have convoluted the curve with our experimental resolution, and to be consistent with our analysis, the amplitude of the curve has been tuned to better reproduce the data below 2 MeV. We found that this calculation reproduces the shape of the data reasonably well, although the distribution below 1 MeV is slightly overestimated compared to our theoretical calculations. This calculation corresponds to a $^8\text{He}-n$ s-wave scattering length of +2.9 fm and a p -wave resonance of ^9He at 2 MeV.



We would like to note that a different scattering length of +2.9 fm does not change the basic message of the current work. Although the position of the p -wave resonance of ^9He is different with ours, it is consistent with our interpretation that the distribution below 1 MeV is dominated by the configuration of two neutrons in the s -wave state. 1) In the Faddeev approach, this state, with a positive peak position and a finite width, could exist due to the universal repulsive hyper-radial potential in the three-body system. Small positive scattering length does not change

this conclusion. 2) Since the Hongo-Son state only requires a small absolute value of the core-neutron scattering length, this state is still an unbound analogue of the universal Hongo-Son state. We have added this information in “Theoretical calculations of the ^{10}He energy spectra” in the Method section.

“We note that previous theoretical calculations of Ref. [18], as shown in Fig. 6(c) of Ref. [18], which utilized ^8He - n Gaussian potentials tuned to induce a p -wave resonance of ^9He around 2 MeV and an a_{cn} around +2.9 fm, also reproduce the observed low-energy structure in the ^{10}He spectrum reasonably well. In this case, the partial decomposition in Ref. [18] leads to a consistent conclusion with us that the ^{10}He spectrum below 1 MeV is dominated by the configuration of two neutrons in the s -wave state. We also note that the universal halo states predicted by Hongo and Son [10] only require a small absolute value of the core-neutron scattering length. Even if a_{cn} is slightly positive, the ^{10}He resonance can still be interpreted as an unbound analogue of the universal Hongo-Son state.”

On the other hand, according to Ref. [18], Fig. 5d corresponds to a p -wave resonance of ^9He around 0.74 MeV (indeed close to our value of 0.76 MeV.), and various s -wave scattering lengths of -10/-5/-1.4/1.8/2.9 fm (-5 fm is close to our value of ~ 3.5 fm). All curves in Fig. 5d shows narrow peaks below 1 MeV that apparently cannot reproduce the experimental data. This is indeed in contradiction with our calculation results. It is indeed valuable to investigate the reasons between the calculations of Ref. [18] and ours. We have tried our best to investigate the reasons based on the information given in Ref. [18].

1) We found that the initial state wave function of ^{11}Li (details given in N.B. Shulgina *et al.*, Nuclear Physics A 852 (2009) 175-199) adopted in Ref. [18] and ours are rather consistent. Both wave functions consider a large mixture of the s -wave and the p -wave configurations, and reproduce the charge-radius, matter radius of ^{11}Li and ^9Li .

2) As mentioned in the previous reply, one reason may be related to the different ^8He - n potential used in our model and in Ref. [18]. Ref. [18] adopted Gaussian form potentials. In our model, we employ a folding potential with the ^8He core density for the ^8He - n interaction. The explicit form of the potential is given in Ref. [S. Aoyama *et al.*, Phys. Rev. C 55, 393 2379–2384 (1997).]. We have added this information in “Theoretical calculations of the ^{10}He energy spectra” in the Method section.

3) Another reason may be related to the treatment of the Pauli blocking for the ^8He - n interaction. This will result in differences in the internal part of the ^8He - n - n three-body wave functions. Ref. [18] includes a Pauli repulsive core in the ^8He - n interaction. In our model, for the final scattering states, we use the complex-scaled solutions of the Lippmann-Schwinger equation (CSLS) with the $^8\text{He} + n + n$ orthogonality condition model (OCM). The Pauli forbidden states are excluded by using the so-called Pauli projection method with pseudopotential. A comparison between different Pauli blocking methods for the three-body states could be found in Ref. [I.J. Thompson

et al., Phys. Rev. C 61 (2000) 024318]. The differences between “Pauli repulsive core method” and “Pauli projection method” are small for bound and resonant states, but larger for continuum states. Larger differences are expected for halo nuclei where the s -wave channel plays a significant role, such as ^{11}Li . As far as we know, Pauli repulsive core method is an approximate method to exclude the Pauli forbidden states from the inter-cluster motion but cannot correctly describe nodal behaviors of the inter-cluster motion, while the OCM is a semimicroscopic approach in which the Pauli forbidden states are excluded accurately by using the projection operator. We have added this information in “Theoretical calculations of the ^{10}He energy spectra” in the Method section.

“We would like to comment on the different treatment of the Pauli principle between our work and that presented in Ref. [18]. In the $^8\text{He} + n + n$ OCM, the Pauli blocking in the $^8\text{He}-n$ subsystem is taken into account by using the projection operator, the so-called pseudo potential, which excludes the Pauli forbidden states (occupied states by neutrons in the ^8He core) from the $^8\text{He}-n$ relative motion microscopically. This treatment of the Pauli blocking is important to investigate the knockout reaction, especially for the s -waves in the $^8\text{He}-n$ subsystems, because the internal wave function is crucial to determine the distribution function W quantitatively. The analysis in Ref. [18] has been performed using the core repulsion potential to exclude the Pauli forbidden states, resulting in a different internal wave function of ^{10}He from the microscopic calculations as shown in Ref. [55]. The Pauli repulsive core method is an approximate method to exclude the Pauli forbidden states from inter-cluster motions but cannot correctly describe nodal behaviors of inter-cluster motions. By contrast, the OCM is a semimicroscopic approach in which the Pauli forbidden states are excluded accurately via projection operators.”

I would mention one qualitatively suspicious moment in the provided theoretical calculations. Based on the energy of $p_{1/2}$ state 0.76 MeV, the trivial independent particle approximation should provide the energy ~ 1.5 MeV for the $[p_{1/2}^2]_0$ configuration. The peak energy for this configuration in Fig. 1 of this work is ~ 1.9 MeV. This means that the pairing interaction is effectively repulsive for the $[p_{1/2}^2]_0$ configuration. This is quite unexpected result, which I see as strange for the three-body model and which it is not within the systematics of effective pairing energies for the $p_{1/2}$ subshell, which can be traced for the other members of $N=8$ isotope. In Ref. [18] these effective pairing energies vary from 0.5 to 1.8 MeV, which is smaller than the typical values in the $p_{3/2}$ subshell, but not negative at least.

The strong theoretical controversy is quite intriguing, considering the nice agreement between the three-body calculations of this group [33] and [Grigorenko et al. PRC 102, 014611 (2020)] for another quite complicated peripheral phenomenon: soft dipole excitation in the continuum of ^6He system.

Reply: In the present calculation, the energy of the $p_{1/2}$ state of ^9He is 0.76 MeV with a decay width of 0.95 MeV, and the 0_2^+ resonance of ^{10}He is located at 1.4 MeV in the complex-energy plane, with its decay width of 1.0 MeV. Since the $[0p_{1/2}]^2$ decay channel has a small phase space in the low-energy region, the cross section decaying into this channel is suppressed in the

low-energy region, and then the peak is shifted to slightly higher energy (~ 1.9 MeV in Fig. 1) than the expected one. We also note that the 0_2^+ resonance has a small s -wave mixing and such an s -wave component also decays into the $[1s_{1/2}]^2$ channel shown as the red dashed line in Fig. 1.

It is not impossible that quite old calculations of Ref. [18] are deficient in some way. However, unless this deficiency is demonstrated they can not be just disregarded: these are published and well documented results, while for the calculations of this work not much details are available. The Authors should either find out what is wrong with calculations of [18] or rely on them as alternative interpretation of the data.

Reply: In Ref. [18], the detailed analysis has been performed and, we think, the calculations are quite accurate within the model the authors employed. However, they use the Pauli repulsion core for the $^8\text{He}-n$ potential, and the wave function obtained with the repulsion core is much different from that obtained in the microscopic calculations, such as RGM and OCM, especially in the internal region. To discuss the initial state effect, namely the effect of the “ ^{11}Li source”, quantitatively, an accurate description of the internal wave function would be crucial. We think that the analysis in Ref. [18] is thought-provoking and is correct in a qualitative way, but it is not sufficient in a quantitative way. In the Method section of the revised manuscript, we have explained this point in detail. We think more detailed investigations, such as performing calculations with the same treatment of Pauli blocking, will be beyond the scope of the current work. As an alternative interpretation of the data, it is now explicitly mentioned in the Method section that the calculations of Ref. [18] with a scattering length of $+2.9$ fm reproduce the data reasonably well. However, this does not change the main conclusion of this work.

Some separate note concerning the $^8\text{He}+n$ scattering length issue. I would like to pay attention of the Authors to results of paper [Khirk et al., Phys. Rev. C 111, L051601 (2025)].

In this work the data of Uberseder et al. [39] were reinterpreted with more advanced treatment of isospin symmetry. The scattering length in the $^8\text{He}+n$ channel deduced in this work was weakly attractive as -2.7 fm, with no need for $s_{1/2}$ resonance. This is quite close to the deduced in this work value -3.45 fm. However, the $p_{1/2}$ state should be at about 2.3 MeV (original analysis of Uberseder et al. do not allow any resonances with $l>0$ and $E<3$ MeV at all).

Reply: We thank the reviewer for pointing out the recent work by Khirk *et al.* But after going through the paper [Khirk *et al.*, Phys. Rev. C 111, L051601 (2025)], we do not find the value of -2.7 fm mentioned by the reviewer. We have modified our manuscript to include the conclusion of this work on the $^8\text{He}-n$ s -wave interaction.

“The calculation results for the $^8\text{He}-n$ subsystem, with the tuned $^8\text{He}-n$ interaction to fit the current ^{10}He spectrum below 2 MeV, produced an s -wave scattering length between ^8He and neutron (a_{cn}) of $-3.45(20) \sim -3.5$ fm, in reasonable agreement with the results from some knockout reactions ($-3.17(66)$ fm [14], -3 fm $< a_{cn} < 0$ fm [37], $-2.1(6)$ fm or $-6.8(14)$ fm [38]) and the weak $^8\text{He}-n$ s -wave attraction from the (p, p) resonance elastic scattering [39], but not with the

strong one ($a_{cn} \leq -10$ fm) reported in Ref. [40] and Ref. [41]. A recent analysis of the (p, p) resonance elastic scattering data with more advanced treatment of the isospin symmetry also suggests a small negative a_{cn} [Khirk *et al.*...]. ...”

Point 2. Reaction mechanism issue.

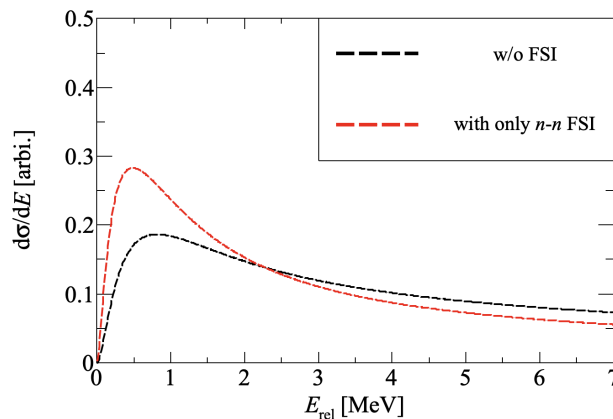
The structures promoted in this paper as "two low-lying 0^+ states of ^{10}He at ~ 1 MeV and ~ 2 MeV above its two-neutron decay threshold" according to calculations of [18] are strongly sensitive to the reaction mechanism. Let's compare solid curves Fig. 5 c and f in [18]. One is well consistent with the data of the refereed work the other is shifted to higher energy to more than 1 MeV. The same if we compare Fig. 6 b and c in [18]. For one the $[s^2]_0$ and $[p^2]_0$ components are well energy split (as in the calculations of this work), but for the other they more or less overlaps, so we can hardly speculate about separate $[s^2]_0$ and $[p^2]_0$ states.

The results of the refereed work are based on some realistic reaction model where the ^{11}Li WF is present. So, all these effects should be there, they are just not discussed. These could be easily checked if I am right by the Authors of this work in two reasonably simple ways:

(1) By performing calculations without ^{10}He FSI - just plane waves.

Typically people try to check, whether the signal they see is not provided just by a plane wave, without any dynamics.

Reply: We have indeed performed calculations without any FSI and with only the n - n FSI. As shown in the figure below, deactivating the FSI results in a shift of the excitation strength towards higher energies, consistent with the disappearance of the $[0p_{1/2}]^2$ resonance and a broadening of the peak from the $[1s_{1/2}]^2$ neutrons. Calculations without any FSI or with only the n - n FSI produce a bump below 1 MeV, and cannot reproduce the experimental E_{rel} distribution. We therefore conclude that it is important to include the ^8He - n FSI for the observed ^{10}He structure. We have also added this information in “Theoretical calculations of the ^{10}He energy spectra” in the Methods section.



(2) By changing the reaction mechanism by using not a halo nucleus ^{11}Li , but a compact system. For example $^{14}\text{C}(-4p)$. Not very realistic reaction for practical realization, but theoretically we may play games. If the strength function is strongly qualitatively sensitive to the reaction mechanism, then you can hardly speculate about resonance states. Resonant states is something independent on reaction mechanism by definition.

Also, if your population cross section strongly depends on the reaction mechanism then what is your "universality" about? This is not about that the story is not interesting and important, but about carefully choosing terms for the discussion.

I am a bit amused that this topic is total missing in the manuscript, since the Authors has recently studies soft dipole excitation in ^6He [33], where they do not attempt to interpret the E1 strength function in terms of resonance position and width.

Reply: We are not sure about the terminology of “reaction mechanism” mentioned by the reviewer. It seems to us it means the “initial-state effect”. If so, in our opinion, the population cross section is always strongly dependent on the reaction mechanism. Regarding the position and width of a resonance, they might also depend on the reaction mechanism. For a narrow resonance, its position and width should be independent of the reaction mechanism. On the other hand, for a broad resonance, the position and width may show dependence on the initial state, as demonstrated by the solid curves in Fig. 5 c and f in Ref. [18].

In the present analysis, we assume that the proton knockout does not disturb the configuration of the valence neutrons, so that the decaying neutrons are spectators through the reaction. Under this assumption, the "sources" of $[1s_{1/2}]^2$ and $[0p_{1/2}]^2$ configurations are generated by the equal amount to each other just after the knockout process. We also note that the source effect in the present calculation has a smaller contribution than that discussed in Ref. [18]. Details of our calculations have been added in the Method section.

The “universality” in our work does not refer to the energy position and width of the ^{10}He states is universal, instead it refers to that we found the ^{10}He ground state populated from $^{11}\text{Li}(p, 2p)$ reaction has a universal property, *i.e.* it is a three-body s -wave state governed by a universal repulsion. Considering the small absolute value of the core-neutron scattering length, we propose that this state is an unbound analogue of the universal Hong-Son halo state. We note again that the above two aspects (universal repulsion; candidates of universal halo) only require the absolute value of ^8He - n scattering length is small, and the sign of the ^8He - n scattering length does not matter.

We think discussion of the population of ^{10}He from other reaction channels like $^{14}\text{C}(-4p)$ is beyond the scope of the current work. To the best of our knowledge, no reliable theoretical framework currently exists that can treat four-proton removal. But it is indeed interesting to

perform such an experiment to see whether the same ^{10}He states (or similar peak structure) could be populated.

Finally, the soft dipole excitation of ^6He [33] is another story. In Ref. [33], ^6He is populated via Coulomb breakup. It has been reported for a long time that the Coulomb breakup reaction of halo nuclei populates continuum states instead of resonances. Indeed, the soft dipole excitation of ^6He from the Pb target was found to be dominated by the 1- continuum state. Therefore, there are no discussions in Ref. [33] about resonance and its position/width.

Point 3. Possibility of 1- state population.

The excitations of ^{10}He with $J>0$ are only briefly discussed in this work as possibly contributing the high-energy part of the strength function. This is not substantiated with any calculations. However, it was shown in [19] that due to extreme halo extent of the ^{11}Li WF the specific mechanism of proton knockout may lead to population of 1- as the lowest energy component of the ^{10}He spectrum. It should be noted that mechanism of such a knockout is not just s-wave removal and do not lead to typical s-wave momentum distributions of the spectator in the outgoing channel (see Fig. 2 of [19]).

The population of the 1- configuration was predicted on the level up to 25% to the 0+ population rate. However, the low-energy region, where a specific enhancement was observed in the $^{11}\text{Li}(-p)$ reaction, the 1- may provide dominating contribution.

Reply: In our calculations, in the same manner as Ref. [19], we assume a $p_{3/2}$ -orbital proton is removed from the ^9Li core populating a ^8He core in the ground state. The neutrons of ^{11}Li thus remain as spectators, *i.e.* two neutrons always stay in the same orbitals and are coupled to 0^+ states. Therefore, the populated ^{10}He final state from ^{11}Li could be only in positive parity states. The population of ^{10}He depends on the initial state configuration. In Ref. [19], the 1- state are dominated by two components of hyperspherical decomposition: $K = 1$ (one neutron in p wave and one neutron in s wave) and $K = 3$ (one neutron in p wave and one neutron in d wave.). Our initial state wave function of ^{11}Li does not have such configurations, therefore, no 1- state is populated in our calculations.

Please check the following:

Text: "As shown in Fig.4, the distributions can be well reproduced by the quasi free knockout calculations that assume a p-wave proton removal from ^{11}Li ." Caption Fig.4: "s-wave (red solid line) or p-wave (blue solid line)"

There is agreement with the red solid line in the figure, which is in contradiction with the text.

Reply: Thank you to the reviewer for pointing out the typo in the text. We have modified the caption of Fig. 4 to "s-wave (~~red~~-blue solid line) or p-wave (~~blue~~-red solid line)"

Minor things

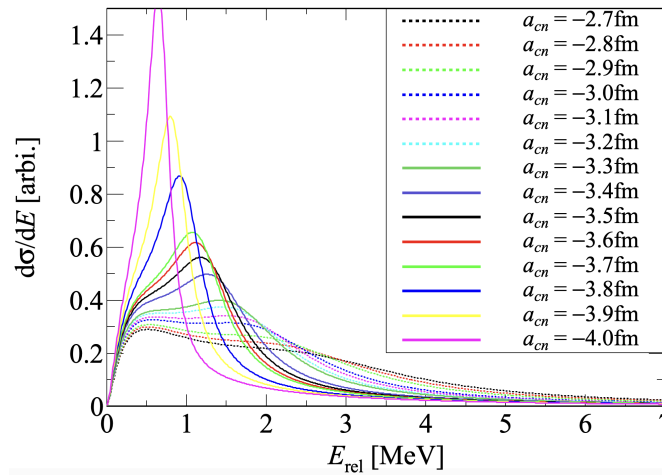
I find the presentation of data of [Korshennikov et al] misleading in Fig. 1. The original paper contains the data on CD_2 and C targets, which are not in full agreement. The conclusions of [Korshennikov et al] are based on subtracted, spectrum which has large error bars, while the authors of this work arbitrarily have chosen one of initial spectra with comfortably small error bars.

Reply: We did not arbitrarily choose the initial spectra of Korshennikov *et al.* We actually followed the previous work of [H. Johansson *et al.* Nuclear Physics A 354 842, 15 – 32 (2010).], which also compared the GSI data with the data on CD2 target.

Indeed, in the paper of Korshennikov *et al.*, both the CD2 target data and deuteron target data are shown. It is mentioned explicitly in [Korshennikov *et al.*] that the peak position from CD2 target, C target and deuteron target are the same. We therefore do not think showing the data on CD2 target is problematic.

I sincerely believe that considering all the problematic issues discussed above the deduced scattering length precision " $-3.45(20)$ fm" is a strong overestimation of the achievable precision. Something like " ~ -3.5 fm" will be more realistic, since criterion of the error determination is unclear.

Reply: The scattering length value of $-3.45(20)$ fm was obtained by chi2 minimization for the experimental spectrum below 2 MeV with tuning of the ^8He - n interaction strength that produces different s -wave scattering length in our calculation (See also "Theoretical calculations of the ^{10}He energy spectra" in the updated Methods section). As shown in the figure below (all distributions with area normalized to unity), the distributions become flatter when the absolute values of ^8He - n scattering length become smaller. The ^{10}He spectrum below 2 MeV is well reproduced with an a_{cn} value around -3.45 fm. Considering that $-3.45(20)$ is a model dependent value and the model in Ref. [18] with a slightly positive scattering length $+2.9$ fm also reproduces the data reasonably well, we agree with the reviewer to use a value of ~ -3.5 fm throughout the text.



The Authors use two Figures (2 and 3) to show the complete three-body correlation patterns and their projections. I think it could be more instructive to demonstrate the evolution of the correlation patterns with energy. According to the theoretical interpretation there are energy ranges where the $[s^2]_0$ component is totally dominant and where the $[p^2]_0$ contribution is important. It is a bit strange not to try to observe the difference in the correlations.

The same is somehow true about Fig. 4. When gated on the excitations of ^{10}He these spectra may (or may not) demonstrate some differences related to peculiarities of reaction mechanisms populating $[s^2]_0$ and $[p^2]_0$ configurations (if there are any).

Reply: It is indeed very interesting to investigate the evolution of the correlation patterns and the momentum distributions with the excitation energy of ^{10}He . In the current work, we see that the momentum distributions do not show significant dependence on the excitation energy, while the correlation patterns indeed show some dependencies. However, since the current work focuses on the three-body s -wave state below 1 MeV, and the current calculations do not reproduce the E_{rel} distribution above 2 MeV, such investigations will be done in the future.

I find the topic "Deduction of the effective angular momentum for a three-body system". On one hand, the relevance of this derivation to the topic of the paper is doubtful. On the other hand, this derivation is valid within the specific adiabatic framework. The conclusion of this derivation is trivial: between "no s -wave interaction" and "Efimov case" there will be a continuum of effective interactions as the pairwise scattering lengths (all together simultaneously or in some separate manner) tend from zero to minus infinity. Do not think this deserve publication in the Nature.

Reply: We respectfully disagree with the reviewer's opinion. Our experimental data has clearly demonstrated the existence of the s -wave three-body resonance peak, and therefore it is necessary to explain at least qualitatively why an s -wave resonant state can emerge; Textbooks on quantum mechanics often emphasize that higher angular-momentum two-body states can exhibit resonant behavior, while s -wave state does not show resonant state but rather becomes a virtual state due to the absence of centrifugal repulsion. In contrast, our data reveals an s -wave resonance, which makes it essential to explain its physical origin. The effective angular momentum discussion, although qualitative, offers a transparent physical picture: the s -wave three-body resonance arises from the interplay between a short-range attraction and long-range universal repulsion. Regarding the adiabatic approximation, which the reviewer has expressed doubts about, we would like to emphasize that it remains a well-established and reliable approximation as long as the condition $|a_{nn}| \gg R \gg |a_{\text{He-n}}|$ is satisfied (see Braaten Hammer Phys. Rep. 428, 259 (2006) or Naidon SciPost Phys. 15, 123 (2023)). We acknowledge that the three-body resonant state may also be interpreted in an alternative framework (*e.g.*, conventional nuclear structure theories). However, it is equally important to recognize recent advances in universal halo three-body studies, such as the work of Hongo and Son *Phys. Rev. Lett.* 2022. For this reason, we believe it is scientifically fair to retain the effective angular momentum argument

and its connection to the Hongo–Son’s work, while also revising the manuscript to reflect the reviewer’s valid point that other interpretations deserve to be mentioned [see revisions made in response to the reviewer’s other comments].

We have added a short sentence to clarify the validity of the adiabatic approximation in the present work:

“Under the adiabatic approximation [2], which is valid for the current $^8\text{He}-n-n$ three-body system in the region of $a_{nn} \gg R \gg a_{cn}$, the hyperradial functions $F_n(R)$ in Eq. (5) are the solutions of the hyperradial equation.”

To finalize the discussion. All the theoretical points above are quite complicated. I doubt that within the limited volume this particular publication the mentioned controversies could be well resolved. However, these theoretical discussions also do not devalue the potential importance of the current experimental observation and its interest to a broad scientific community.

My proposal is to reformulate the paper from modality "solidly understood in a unique way" (which I doubt the Authors can actually prove) to "there are different possible intriguing interpretations of the data". Possible alternative interpretations should be clearly discussed in the paper. They are also not trivial and may be of significant scientific interest by themselves as ideas existing in parallel with ideology of Efimov-type phenomena. The title of the paper should be also changed to a broader context and statements about "resonant states" replaced everywhere with something neutral like "peaks in the population cross section".

Reply: We thank the reviewer again for the valuable comments. There are indeed differences between our calculations and that in Ref. [18]. In the revised version of the manuscript, we have added details of our calculations and also explain the reasons that may result in these differences. We think more detailed investigations, such as performing calculations with the same potentials and/or with the same treatment of Pauli blocking, will be beyond the scope of the current work. Although there exist differences between our calculations and that in Ref. [18], we do not think these differences will change the main conclusion of present work, *i.e.* the low-energy state below 1 MeV of ^{10}He is a three-body s -wave state and it could be an unbound analogue of the universal halo state predicted recently by Hong and Son. The three-body s -wave state appears in the experimental spectrum as a real resonance peak distinct from the two-body s -wave virtual state. We therefore respectfully disagree with the reviewer’s opinion to change the title of the paper.

Reply to comments of Reviewer #2

1) Comment:

The subject of this paper is the experimental identification of an Efimov state (resonance) in the ^{10}He system.

Although Efimov states were first observed in cold atom systems and have long been discussed in the context of atomic He_3 , they were originally predicted within the realm of nuclear physics by Efimov. I believe it is extremely important to identify nuclear systems that can be described by this universal model, further highlighting the universality of Efimov physics. For this reason, I think the present paper, especially given its experimental nature, deserves publication.

I have only a few remarks, which do not pertain to the experimental techniques that are well explained.

1. A simple remark is on line 6, where the emergence of an infinite tower of three-body states is related, strictly speaking, to an infinite (and not just a sufficiently large) scattering length.

Reply: We have modified the text to “...energy and spatial structures when the inter-particle scattering length a_s is ~~sufficiently~~ infinitely large.”

2. The explanation of the resonance is mostly based on the shell model interpretation of the state. It would be useful for a reader from another community (thanks to the universality of Efimov physics) to at least provide a sketch of what is happening and why the state appears as a double-intruder nucleus (lines 45-..., 90-..., and 122).

Reply: We have modified the text to explain the reason.

“The ^{10}He , which is traditionally considered as a doubly magic nucleus, thus appears as a “double-intruder” nucleus with the last two neutrons in the $1s_{1/2}$ shell, in line with the intruder s-wave dominated ground state of ^9He . The intruder dominant configuration could be understood in the shell-model framework due to the melting of the $N = 8$ shell closure for the neutron-rich isotopes below $Z = 4$.”

3. The explanation of the state rests heavily on the shell model. However, there are other ways to view it that rely on both the scattering length, which has been extracted (as mentioned again in line 199), and on the effective range (Kievsky A., Gattobigio M., Girlanda L., Viviani M., *Efimov Physics and Connections to Nuclear Physics.*, Annu. Rev. Nucl. Part. Sci **71**, 465, 2021). It would be important to try to extract the effective range to allow for other interpretations of the same state.

Reply: We have tried to extract the effective range, but compared to the scattering length, the experimental E_{rel} distribution is not sensitive to the effective range, and the extracted value has large uncertainties. On the other hand, our explanation of the state as a candidate of the universal

Hongo-Son state will not be changed by the correction of the effective range. This is shown by a recent work [<https://arxiv.org/abs/2507.19171>] that including effective range correction does not significantly change the universal property of the Hongo-Son state.

4. The grand-angular momentum K is discussed in the Methods section, but I'm not sure that the introduction of K in line 171 without a previous explanation is correct.

Reply: The effective angular momentum K , which characterizes the long-range behaviour the three-body potential, comes naturally when the low-energy 3-body problem is treated using the hyper-spherical formalism. We have added an explanation of the grand-angular momentum K .

“Such an s -wave resonance peak appears only in systems with ≥ 3 particles and can be attributed to a non-zero value of the effective angular momentum K , which characterizes the long-range behaviour of the three-body potential [2, 11, 18] (see Methods for the definition of K).”

To summarize, the paper deserves publication as it sheds a nuclear light on Efimov physics, which originates from Nuclear Physics.

Reply to comments of Reviewer #3

Summary

The manuscript describes measurements of ^{10}He produced through (p, 2p) reactions of a ~ 250 MeV/u ^{11}Li beam with a liquid hydrogen target. Analysis of the three-body relative energy and Jacobi correlation spectra utilized a coupled-channel three-body model of ^{11}Li combined with the quasi-free knockout reaction model, and complex-scaled solutions of the Lippmann-Schwinger equation were used to compute final states in ^{10}He . The low-energy structure in the three-body relative energy spectrum is explained by two 0^+ states with ^8He cores, one with a $[1s1/2]^2$ neutron component and another with a $[0p1/2]^2$ neutron component. By tuning the ^8He -n interaction to fit the ^{10}He spectrum below 2 MeV, the authors extracted an s-wave scattering length between ^8He and the neutron. The Jacobi-T normalized relative energy and Jacobi-Y angle ^8He -n-n correlations gated on relative energies < 1 MeV show enhancements that are qualitatively reproduced by the three-body calculations. The authors conclude that the observation of the two 0^+ states resolves the long-standing difference between ^{10}He ground state energies measured from knockout and $2n$ transfer. Furthermore, the ^{10}He ground state is a three-body s-wave resonance that exemplifies a novel class of universal three-body bound states.

Revisions

The paper is well-constructed, concise, and it provides new information suggesting a resolution to a long-standing question about the structure of ^{10}He . The following revisions would strengthen the paper and should be satisfactorily addressed:

1. How is the 1-sigma energy resolution dependence as a function of relative energy determined? Does this come from a previous measurement? A Monte Carlo simulation of the setup? A brief explanation or reference in Section 2 is necessary to support the stated relationship. An addition to the top panel in Fig. 1 to show the resolution alongside the efficiency or an illustration and accompanying explanation in the methods section would help further convince the reader of the setup's sensitivity.

Reply: The energy resolution was obtained based on Monte Carlo simulation of the setup. As suggested by the reviewer, we have added additional information in the Methods section about the energy resolution:

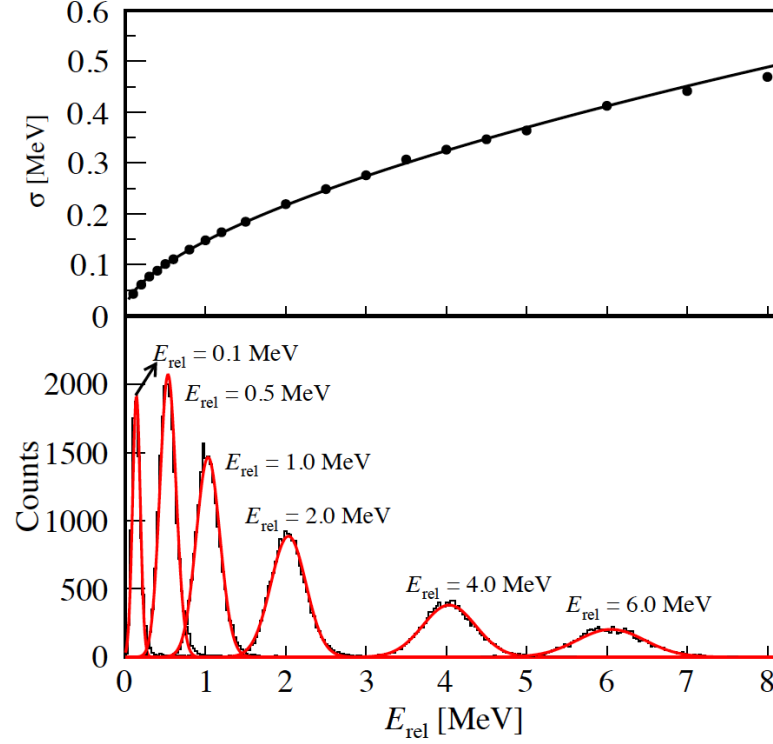


Fig. 4 (Color online) The upper panel shows the energy resolution of the experimental setup as a function of the ^8He - n - n three-body relative energy. Each black point corresponds to the resolution for one fixed relative energy in the simulation, and the black solid line is the fit result which has been given in the main text. The lower panel shows the simulated relative energy distributions for fixed relative energies of 0.1 MeV, 0.5 MeV, 1.0 MeV, 2.0 MeV, 4.0 MeV and 6.0 MeV, respectively. The red solid lines are the fit results using Gaussian functions.

“The relative-energy resolutions have been obtained from GEANT4 simulations considering the realistic experimental setup and the resolutions of the detectors. The upper panel of Fig. 4 shows the resolutions as a function of the ^8He - n - n three-body relative energy. The energy resolution (1σ) can be well approximated by $\sigma(E_{\text{rel}}) = 0.0131 + 0.133 E_{\text{rel}}^{0.611}$ MeV. Some typical relative energy distributions fitted with symmetric Gaussian functions for fixed relative energies are shown in the lower panel of Fig. 4. The distributions are slightly asymmetric below $E_{\text{rel}} = 0.5$ MeV, which has been taken into account in the convolution of the theoretical distributions shown in Fig. 1, although the effect is minor.”

2. Including additional information in the Methods section about the cross-talk rejection procedures would benefit the reader. For example, reference [31] includes empirically derived values for the same-wall cross-talk rejection filters based on the $^7\text{Li}(p,n)^7\text{Be}$ test case. Are similar values used here?

Reply: Yes, similar values have been used here for the same-wall cross-talk rejection filters. The cross talk rejection procedure of current work is similar to the rejection condition described in Ref. [31]. We have now included “cross-talk rejection” in the Methods section regarding the detailed parameters used in the cross-talk rejection filters:

“Cross-talk rejection. Neutrons are electrically neutral particles and are capable of generating multiple detection hits within the neutron detector array mainly caused by neutron scattering. In the present work, to measure the energy and momentum of two neutrons, rejection of such cross-talk background in the neutron detector array NEBULA is required. In the data analysis, we applied 6 MeVee energy threshold to the measured hits to reduce the γ background and applied the cross-talk rejection procedures following the previous work presented in Ref. [31]. The parameters for the cross-talk rejection conditions were obtained using the single-neutron events taken from the experimental $^{11}\text{Li}(p, pn)^9\text{Li} + n$ reaction.

For the events of two neutrons detected in the same wall of NEBULA, the cross talks due to a secondary recoil proton are identified using the following condition

$$\sqrt{\left(\frac{dr - dr_0}{R}\right)^2 + \left(\frac{dt - dt_0}{T}\right)^2} < 1, \quad (4)$$

where dr and dt are the distance and time difference between two hits, and parameters of $dr_0 = 15.8$ cm, $R = 15.0$ cm and $dt_0 = 0.32$ ns and $T = 1.8$ ns were adopted. In addition, the cross talks due to γ and scattered neutrons in larger dr and dt are rejected through a two-dimensional selection applied to Q_2 and β_{01}/β_{12} , where Q_2 is the energy deposit (unit in MeVee) of the secondary hit, β_{01} is the velocity (unit in speed of light) between the reaction position and the primary hit, β_{12} is the velocity between the primary and the secondary hits. The selection could be parameterized as $Q_2 < 108 \times |\beta_{01}/\beta_{12}| - 60$ and $Q_2 < -12 \times |\beta_{01}/\beta_{12}| + 80$. For the events of two neutrons detected in the different wall of NEBULA, the cross talks are mainly due to neutron scattering from the upstream wall to the downstream one. Since the neutron's velocity is reduced after the scattering, most of these cross talks could be identified by a simple condition of $|\beta_{01}/\beta_{12}| > 1$. In the current analysis, we require that $Q_1 < 250 \times |\beta_{01}/\beta_{12}| - 200$, taking into account that Q_1 , the energy deposit of the primary hit, becomes larger when $|\beta_{12}|$ is smaller in the neutron scattering. Finally, some remaining γ cross talks are rejected by the condition of $1/\beta_{12} \sim 1$. After applying the above procedures, we found that 96.9% of the cross talk is eliminated in the data, while 98.7% is eliminated in the simulation. We also confirmed that varying the cross-talk rejection conditions reasonably yields consistent relative-energy spectra, as long as the cross-talk rejection procedures are consistently incorporated into the estimation of the $2n$ detection efficiency. This further demonstrates that the above cross-talk rejection procedures are valid.”

3. Some clarification of the analysis procedure is needed to help the reader understand the comparison between data and calculation shown in Fig. 1.

a. How does the output from the three-body ^{11}Li model + quasi-free knockout model inform the calculation of the final ^{10}He states? Do the reaction calculations provide cross-sections that scale the contributions of the ^{10}He states in the relative energy spectrum?

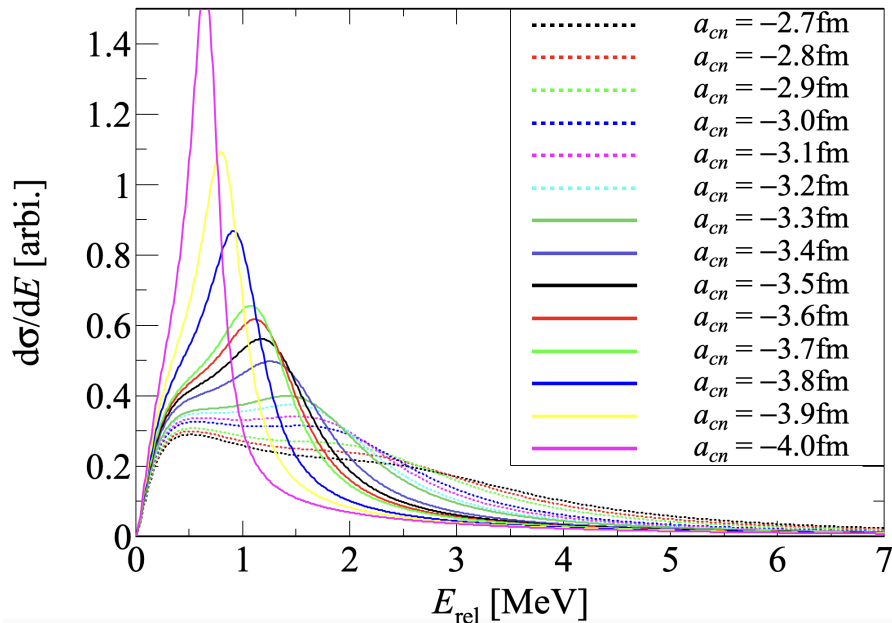
Reply: The initial wave function (^{11}Li - p w.f.) was computed from the three-body ^{11}Li model + quasi-free knockout of a p -wave proton. The final ^{10}He wave function (^{10}He w.f.) was computed

with the complex-scaled solutions of the Lippmann-Schwinger equation (CSLS) method. The cross section for the population of the three-body continuum can be obtained by calculating the T matrix from the initial state ($^{11}\text{Li}-p$ w.f.) to the final state (^{10}He w.f.).

In our calculations, the ^{10}He final state wave function is expressed using three-body Jacobi coordinates. The three-body relative energy can be easily deduced using the Jacobi momenta. The cross section is thus computed naturally as a function of the relative energy. We have added additional context about the details of the calculations in the Methods section to make the explanation clearer. See “Theoretical calculations of the ^{10}He energy spectra” in the Method section.

b. What parameters for the $^8\text{He}-n$ interaction are varied and how? Including an additional figure in the Methods section that shows how these parameters impact the agreement with data would help reinforce the assertion from lines 131 – 133: “the spectrum’s shape is highly sensitive to the $^8\text{He}-n$ interaction, and the observed low-energy structure is reproduced only with a weakly attractive $^8\text{He}-n$ s-wave interaction.”

Reply: In our calculation of the ^{10}He wave function, we adopted the ^8He -neutron folding potential given in Aoyama *et al.*, PRC 55, 2379 (1997). Considering the uncertainty of the ^8He -neutron interaction, the depth of the potential is varied to better reproduce the experimental data. This results in different ^8He -neutrons scattering lengths. The figure below shows how the three-body relative energy distributions (area normalized to unity) change when we tune potential depths corresponding to various s -wave scattering lengths. The distributions become flatter when the absolute values of the $^8\text{He}-n$ scattering length become smaller. The low-energy structure in the experimental ^{10}He spectrum is reproduced only with a slightly negative a_{cn} around -3.5 fm. We have added this information in “Theoretical calculations of the ^{10}He energy spectra” in the Method section.



4. The legend and caption for Fig. 1 should be revised to clarify what is indicated by the green dashed curve labeled ‘others.’ It’s not clear if this is referring to the discussion in lines 124 – 131 regarding higher-lying states.

Reply: ‘others’ means two neutrons in partial waves other than $1s_{1/2}$ and $0p_{1/2}$, such as d wave etc. We have clarified the label ‘others’ in the caption of Fig. 1.

“.....that is decomposed to three components: ${}^8\text{He}_{\text{g.s.}} + [1s_{1/2}]^2$ (red dashed line), ${}^8\text{He}_{\text{g.s.}} + [0p_{1/2}]^2$ (blue dashed line) and others (two neutrons in partial waves other than $1s_{1/2}$ and $0p_{1/2}$, green dashed line).”

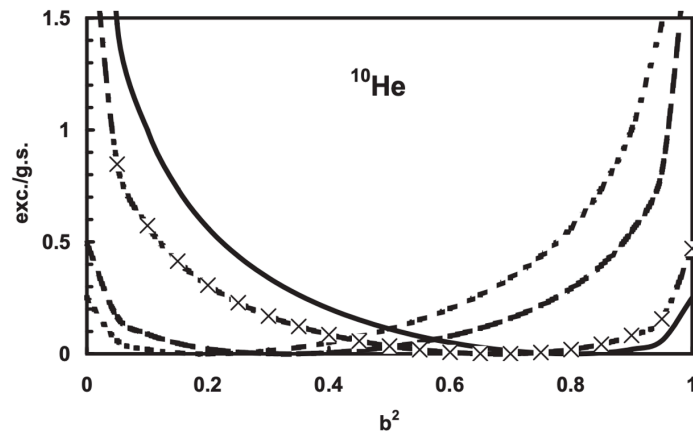
5. Does the Argonne v8’ force include/account for the large neutron-neutron s-wave scattering length ann ~ 19 fm referenced in line 174?

Reply: Yes, Argonne v8’ force accounts for the large neutron-neutron s -wave scattering length. Argonne v8’ force [B. S. Pudliner *et al.*, Phys. Rev. C 56, 1720–1750 (1997)] have been determined by fitting to NN scattering data in the range of 0-350 MeV. It was also fit to nn scattering length measured in experiments [$-18.7(6)$ fm from O. Schori *et al.*, Phys. Rev. C 35, 2252-2257 (1987)] and the deuteron binding energy.

6. Is it possible to extract cross-sections for populating the two 0^+ states? Or a ratio of these cross-sections? This could be useful for comparing to previous predictions e.g. reference [22].

Reply: Extraction of the absolute cross-sections needs further corrections on the acceptance of the two outgoing protons in the data analysis. Since the two-proton acceptance of the two 0^+ states should be the same, we have extracted the ratio and compared it to the predictions in Ref. [22]. From Fig. 1, we extracted the percentages of the $[1s_{1/2}]^2$ and $[0p_{1/2}]^2$ components, which are 72% and 26%, respectively. Therefore, the ratio for populating the excited 0^+ state relative to the ground state is $0.26/0.72 = 0.36$.

In Ref. [22], the 0^+ states of ${}^{10}\text{He}$ are described as a linear combination of the $[p]^2$ and $[sd]^2$ basis states. The cross-section ratio for the excited 0^+ state relative to the ground state (exc./g.s.) is estimated as a function of the assumed fraction of the $[sd]^2$ component in ${}^{10}\text{He}$ ground state, as shown in the figure below by the long-dashed line.



In our theoretical calculations, the mixing between the $[p]^2$ and $[s]^2$ basis states have been fully taken into account. We found the mixture in the 0^+ states is not so strong, which probably comes from the unbound nature of ^{10}He , and the ground state of ^{10}He has a nearly pure $[s]^2$ component, which means $b^2 \sim 100\%$ in the definition of Ref. [22]. According to the long-dash line in the above figure, the (exc./g.s.) ratio will be larger than 1.5. This is in contrast to our value of 0.36. However, no details or references are given in Ref. [22] about the adopted ‘simple direct-reaction model’. We are not able to track the reason why the predicted ratio is different from ours. Nevertheless, we have added this information in the main text:

“This finding resolves the long-standing puzzle about the different ^{10}He ground-state energies obtained from knockout and $2n$ transfer reactions. Our work suggests that the ground state of ^{10}He has a nearly pure $[s]^2$ configuration. The ^{10}He , which is traditionally considered as a doubly magic nucleus, thus appears as a “double-intruder” nucleus with the last two neutrons mainly in the $1s_{1/2}$ shell, in line with the intruder s - wave dominated ground state of ^9He . The intruder dominant configuration could be understood in the shell-model framework due to the melting of the $N = 8$ shell closure for the neutron-rich isotopes below $Z = 4$. In addition, the cross-section ratio for populating the excited 0^+ state relative to the ground state was extracted to be about 0.36. This value is in contrast to the estimation of a simple direct-reaction model presented in Ref. [22], where a pure $[sd]^2$ -dominant configuration in the ground state of ^{10}He was expected to yield a ratio greater than 1.5. ”

7. The $[2s_{1/2}]^2$ should be $[1s_{1/2}]^2$ to be consistent with notation elsewhere (e.g. the legend of Fig. 1 and line 196).

Reply: The $[2s_{1/2}]^2$ in line 115 has been corrected to $[1s_{1/2}]^2$. We have also double-checked the main text to make sure all the notations are consistent.

8. In lines 173-174 and in the Methods section, the ^{10}He ground state is shown to have an effective angular momentum $K=1/2$ which should be associated with a repulsive effective three-body potential indicated by the black curve in Fig. 5. The next line seems contradictory: “This is physically due to that a neutron occupying the halo virtual state can mediate an attractive interaction between the other neutron and the ^8He core up to large distance ...” And line 180 emphasizes again the ^{10}He system shows long-range repulsion. The explanation of how the attractive interaction arises needs to be clarified.

Reply: The repulsive hyper-radial potential is reduced due to the induced three-body attraction, but the hyper-radial potential still remains repulsive in the current ^8He - n - n system. To make the explanation cleaner, we have modified the text to:

“Indeed, even for a non-interacting three-body system, the hyper-radial (*i.e.* three-body effective) potential is repulsive with $K = 3/2$. More precisely, in our system, a large neutron-neutron s -wave scattering length of $|a_{nn}| \approx 18.6$ fm [45] reduces the effective angular momentum to $K = 1/2$ (see Methods for a deduction of the effective angular momentum based on the Faddeev approach). This is physically due to that a neutron occupying the halo virtual state can mediate an attractive interaction between the other neutron and the ^8He core up to large distance of $\sim |a_{nn}|$, thereby effectively reducing the strength of the repulsive hyper-radial potential. Nevertheless, the hyper-radial potential retains its repulsive character in the $^8\text{He}-n-n$ three-body system. This mechanism is similar to the emergence of long range three-body attraction in the Efimov effect [3, 7].”

9. In the methods subsection “deduction of the effective angular momentum for a three-body system,” additional context is needed around line 304 to explain or justify why the right hand side of Eq.(6) is $O(1)$ so that the leading order term of the left-hand side must vanish.

Reply: It is easy for the reader to check that the right-hand side of Eq. (6) (Eq. (10) in the revised

manuscript) could be rewritten to $2 \left[\frac{2\gamma'}{\sin(2\gamma')} \right]^2 \left[\frac{\sin(s_n \gamma')}{s_n \gamma'} \right]^2$. Since $0 < \gamma' < \pi/4$ and $s_n \neq 0$, the right-hand side of Eq. (6) is basically $[\sin(x)/x]^2$, if we take $x = s_n \gamma'$. Since $\sin(x)/x$ is $O(1)$, so does the right-hand side of Eq. (6). We have modified the main text as below:

“Since the right-hand side of Eq. (10) is of the order unity (recall that $0 < \gamma' < \pi/4$ and $s_n \neq 0$), to satisfy Eq. (10), we need the leading order term of the left-hand side vanish, *i.e.*:”

Reply to comments of Reviewer #2

Reviewer #2 (Remarks to the Author):

Report on "First identification of a universal three-body s-wave resonance in ^{10}He "

The authors have addressed most of my concerns. However, their response regarding the effective range, which I had previously inquired about, remains unconvincing.

The paper they cite solves the Schrödinger equation only for cases where both the scattering length and the effective range are negative. This constraint (a negative effective range) is mandatory in their scheme, which involves summing to all orders.

In contrast, the spirit of the article by Kievsky et al. (Annu. Rev. Nucl. Part. Sci 71, 465, 2021) is different. It has been shown that a positive effective range can also be handled. Moreover, the effective range is not a correction to the infinite scattering-length result, nor is it presented as such in the paper cited by the authors.

I understand that extracting the effective range can be subject to large errors; still, I believe providing it would be very important. Its sign, in particular, could be of great significance.

This remains my main concern. I can understand if the authors are not interested in analyzing their results further to provide this estimation, perhaps because they believe their result is solid regardless of the effective range. However, they rely on only one type of EFT, where the effective range is either treated as a perturbation or is required to be negative.

Despite my concerns, the paper deserves publication as it brings the physics of universal states back into the focus of Nuclear Physics.

Reply: We appreciate further comments of reviewer #2 regarding the ^8He -neutron effective range. As detailed in the Method section, in our analysis, we have taken the folding potential as the ^8He - n interaction. The depth of the potential has been tuned to reproduce the experimental E_{rel} distribution of ^{10}He . From the folding potential with depth fitted to the experimental data, the ^8He -neutron effective range is estimated as about 2 fm. Since both the ^8He - n scattering length and ^8He - n effective range are much smaller than the neutron-neutron scattering length, we expect that the leading order halo EFT (Hongo and Son, Phys. Rev. Lett 128, 212501 (2022)) should be valid for the ^8He - n - n system. We have added the estimated effective range value in the Method section.

The modified Method section now reads:

“.....Furthermore, the spectrum’s shape is highly sensitive to the ^8He - n interaction. In Fig. 6, the calculated distributions, which correspond to ^8He - n scattering lengths of $-3.9 \text{ fm} \leq a_{\text{cn}} \leq -2.7 \text{ fm}$, are also shown. The distributions become flatter when the absolute value of a_{cn} becomes smaller. The low-energy structure in the experimental ^{10}He spectrum is reproduced only with a slightly negative a_{cn} around -3.5 fm . Besides, from the folding potential with depth fitted to the experimental data, the ^8He - n effective range is estimated as about 2 fm.”

Reply to comments of Reviewer #3

Reviewer #3 (Remarks to the Author):

The manuscript describes measurements of ^{10}He produced through $(p, 2p)$ reactions of a ~ 250 MeV/u ^{11}Li beam with a liquid hydrogen target. Analysis of the three-body relative energy and Jacobi correlation spectra utilized a coupled-channel three-body model of ^{11}Li combined with the quasi-free knockout reaction model, and complex-scaled solutions of the Lippmann-Schwinger equation were used to compute final states in ^{10}He . The low-energy structure in the three-body relative energy spectrum is explained by two 0^+ states with ^8He cores, one with a $[1s1/2]^2$ neutron component and another with a $[0p1/2]^2$ neutron component. By tuning the ^8He -n interaction to fit the ^{10}He spectrum below 2 MeV, the authors extracted an s-wave scattering length between ^8He and the neutron. The Jacobi-T normalized relative energy and Jacobi-Y angle ^8He -n-n correlations gated on relative energies < 1 MeV show enhancements that are qualitatively reproduced by the three-body calculations. The authors conclude that the observation of the two 0^+ states resolves the long-standing difference between ^{10}He ground state energies measured from knockout and $2n$ transfer. Furthermore, the ^{10}He ground state is a three-body s-wave resonance that exemplifies a novel class of universal three-body bound states.

This reviewer's comments have been sufficiently addressed by the author's revision, and publication is recommended. Many thanks to the authors for their thoughtful and thorough responses to this reviewer's comments.

Reply: We sincerely thank the reviewer for evaluating our manuscript and recommending its publication.