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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Clarification Letter on “Probing the excited halo in ^{10}Be through halo-to-halo transfer reaction”

April 15, 2023

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Requested shifts: [12] shifts, (split into [1] runs over [1] years)
Installation: [MINIBALL + CD-only]

In the original proposal, we proposed a new experimental method to study the existence of the halo structure in the 2^- excited state of ^{10}Be. The basic idea is to perform a halo-to-halo transfer reaction at low energy, so the cross sections should be significantly enhanced if there is a halo structure in the final state. This has been confirmed by Adiabatic Distorted Wave Approximation (ADWA) calculations of the reaction using a halo-EFT description of the nuclei. In that description, the structure of the final 2^- excited state of ^{10}Be is viewed as a ^{9}Be core and a loosely bound neutron. If successful, this method could be generalized to study other possible excited halo states. We had initially planned to perform the experiment at two different beam energies: 0.61 and 1.22 MeV/u. The former corresponds to the largest integrated transfer cross section, and the second one would have enabled us to test the beam-energy dependence of the reaction.

Since the TAC review shows that the originally requested energies are not available, we will perform the reaction at 1.55 MeV/u as suggested. The cross section at the other possible beam energy (0.3 MeV/u) is actually too low for practical purposes. Accordingly, we will focus on the measurement of the absolute cross sections at one beam energy. The elastic-scattering events will be employed to normalize the cross sections. We have received the following questions and prepared this clarification letter accordingly.

From INTC: *The proposal aims to study the possible one-neutron halo structure of the excited* 2^- *state in* ^{10}Be *via a challenging halo-to-halo transfer reaction,* $^9Be(^{11}Be,^{10}Be)^{10}Be^*(2^-)$. *The authors assume that the cross section will be largely enhanced if the* 2^- *state exhibits a neutron halo. The proposal is well motivated, and the physics case is very interesting. However, the proposed experiment and its interpretation are challenging and the INTC will need to get clarifications on several issues before accepting the proposal. In particular, the following should be addressed in a letter of clarification:*

Question 1: *A complete analysis of the consequences of performing the measurement at a single (higher) energy as was the outcome of the TAC review. The cross section is*

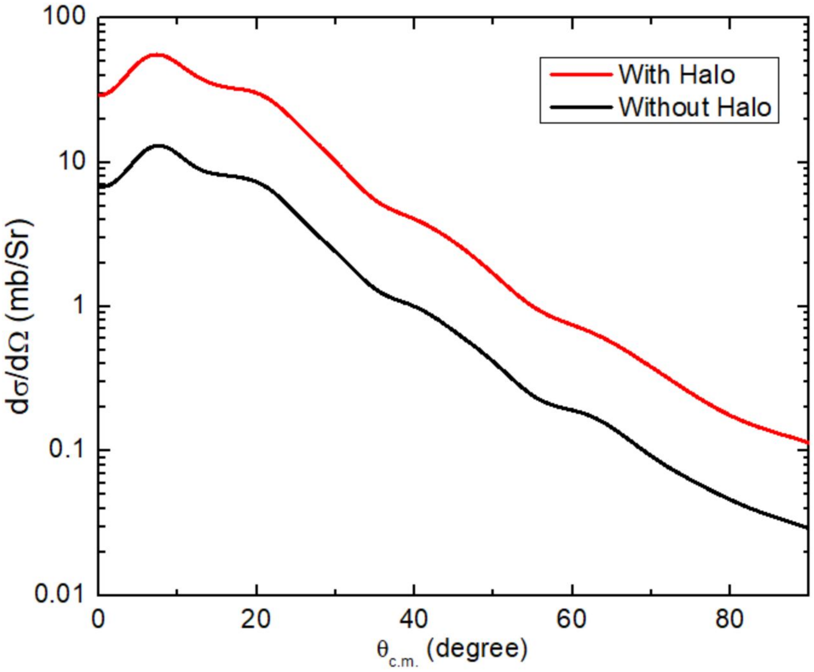

Figure 1: Transfer cross sections as a function of the center-of-mass angle for $E_{\mathrm{c.m.}}$ =7.7 MeV. Results obtained with NLO Gaussian ^{10}Be*(2^-) with 2.0 fm. The potentials were fitted to reproduce the values $r_{\mathrm{h}}^{\mathrm{rms}}$ (With halo, red solid line) and $r_{\mathrm{nh}}^{\mathrm{rms}}$ (Without halo, black solid lines).

smaller, and important information that could have been obtained from the energy dependence is lost.

Response: We appreciate the recognition of the physics case by the INTC, and we answer the questions as follows.

The major goal of the proposal is to confirm the existence of a halo structure in the 2^- state of ^{10}Be. To achieve this goal, the absolute differential cross sections will be measured, which will be compared to the results of calculations using the Adiabatic Distorted Wave Approximation (ADWA). The beam-intensity normalization method will be described in the reply to Question 3, see below.

In our original proposal, the aim was to use two different beam energies so we could better study the beam-energy dependence of our results and take the most advantage of the experimental setup. However, as explained in our answer to Question 2, from a theoretical point of view, our predictions will be in agreement with the experimental measurement only if ^{10}Be*(2^-) has a clear core + neutron structure. If the structure of the ^{10}Be*(2^-) nucleus does not exhibit a halo, e.g., if it is better described by a 4-cluster model (2α and 2n), the experimental cross section will not have the same shape as the theoretical one and, more clearly, not the same magnitude. Accordingly, if only one beam energy is available, we will still be able to confirm the existence of the halo structure in the 2^- state. A second energy would have provided additional information about the energy dependence, but is not a cornerstone of the proposed measurement. The 1.55 MeV/u beam energy corresponds to 7.7 MeV in the c.m. Although the cross section at this energy is a little lower than at the 6.0 MeV in c.m. requested in the original proposal, the higher beam energy allows for a thicker target to be used, which will improve our statistics. In the following, we will show that the measurement is still feasible at 1.55 MeV/u.

Figure 1 shows the cross sections at $E_{\mathrm{c.m.}} = 7.7$ MeV, corresponding to a ^{11}Be beam at 1.55 MeV/u. We found that the difference in the magnitude of the cross sections for halo (solid red line) and non-halo (solid black line) states is the quotient of the assymptotic normalization coefficients (ANCs) squared. In this case, the ratio is almost equal to 4.0. In our model, the magnitude of the cross section clearly shows whether ^{10}Be*(2^-) is a halo nucleus. Moreover, as detailed in our answer to Question 2, we also expect a significant change in the angular dependence of the cross section if the final-state exhibits an 2α-2n structure.

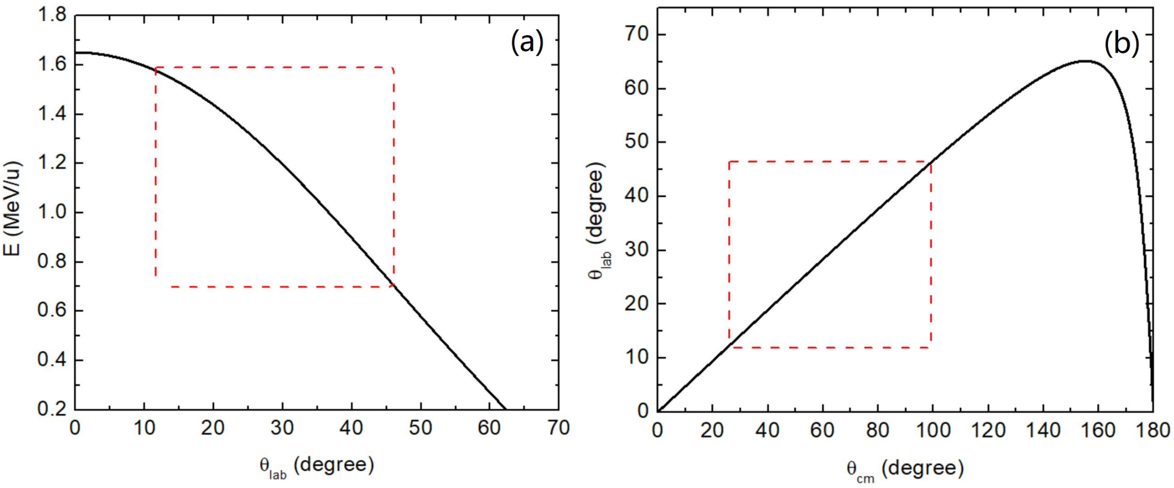

Figure 2: (a) The kinematics of the ^{9}Be(^{11}Be,^{10}Be)^{10}Be*(2^-) transfer reaction at 1.55 MeV/u ($E_{\mathrm{c.m.}}$=7.7 MeV). (b) The relationship of ^{10}Be energies (E) versus the laboratory angles (θ_{lab}) and laboratory angles (θ_{lab}) versus center of mass angles ($\theta_{\mathrm{c.m.}}$) are shown. The energy loss in the target has been taken into account by assuming the reaction taking place in the center of the ^{9}Be target. The region delimited by the red dashed lines shows the coverage of the CD detector.

The beam intensity is expected to be 1×10^{6} ion per second. A ^{9}Be target of the thickness of 0.8 mg/cm^2 will be used (compared to 0.2 mg/cm^2 and 0.6 mg/cm^2 in our initial proposal at the lower beam energies of 0.61 and 1.22 MeV/u, respectively). Fig. 2 shows the kinematics of the ^{9}Be(^{11}Be,^{10}Be)^{10}Be*(2^-) reaction at 1.55 MeV/u. The CD detector will be positioned 40 mm downstream of the target. It results in an angular laboratory coverage of around 11° to 46°. The coverage of the CD detector is shown as the red dashed areas in Fig. 2, which is used to estimate the statistics. Using cross sections of the 2^- state with a halo (solid red line in Fig. 1), the expected beam intensity of 10^6 pps, the target thickness of 0.8 mg/cm^2, the coincidence efficiency (3%) of the γ-ray, and the solid angles of the CD detector, the estimated ^{10}Be(2^-) events per hour in every two strips are plotted as a function of the laboratory angles in Fig. 3(a). The requested **12 shifts** allow for reasonable statistical uncertainty of the angular distribution, see Fig. 3(b). We expect to collect about 3000-5000 charged-particle+γ coincident ^{10}Be(2^-) events in total.

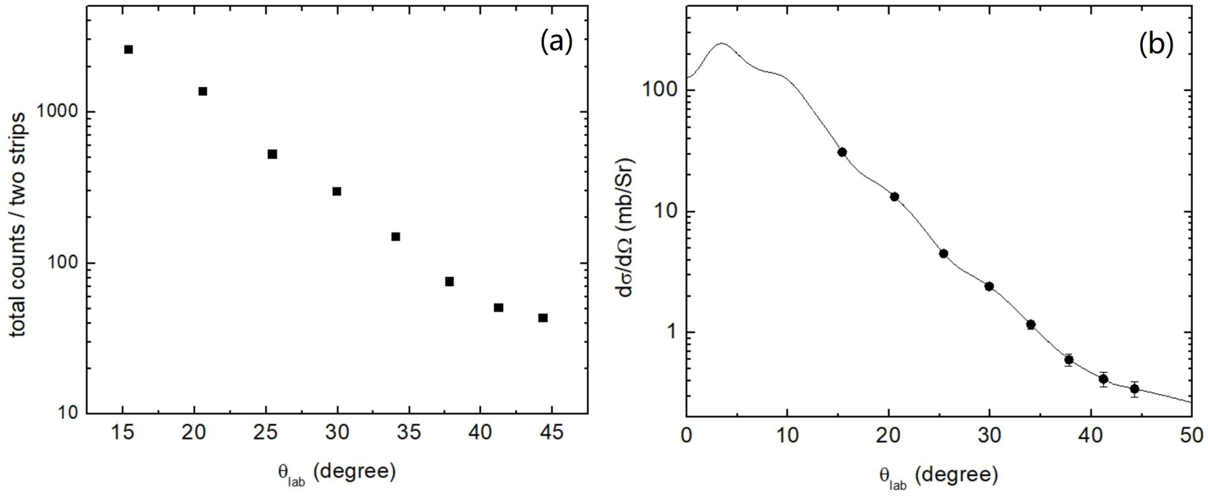

Figure 3: (a) Black squares: estimated counts of the ^{9}Be(^{11}Be,^{10}Be)^{10}Be*(2^-) transfer reaction events per hour in every two strips of the CD detector. (b) Black solid line: Transfer cross sections in the laboratory frame as a function of the laboratory angles for E_{lab} =1.55 MeV/u predicted by theory (see Fig. 1). Black disks: measured cross sections in the laboratory frame with the statistical uncertainties.

Question 2*: A clear description of the experimental signature that the authors hope to find and that will be the smoking gun for demonstrating the existence of a halo structure.*

The primary signature of the presence of a halo in the final 2^- excited state of ^{10}Be is twofold. First, the measured cross section should exhibit an angular distribution similar to the theoretical prediction shown in Fig. 1. This result has been obtained within the ADWA using a halo-EFT description of the final nucleus. This model assumes that ^{10}Be in its 2^- state can be seen as a ^{9}Be in its $3/2^-$ ground state to which a neutron is loosely bound in the $s_{1/2}$ partial wave. Were that state to exhibit a significantly different structure, e.g., a strong 2α-2n structure, the transfer cross section will by no means lead to the typical cross section for an s-wave to s-wave transfer shown in Fig. 1.

Second, if the final state exhibits a halo, we expect the cross section to be large. This is partially shown by the black solid line in Fig. 1, which corresponds to a calculation without a clear halo in the final state. That calculation still relies on a ^{9}Be($3/2^-$)$\otimes$n($1s_{1/2}$) description of the final state. However, the magnitude of the ANC of the final state has been significantly reduced to mock up the absence of a halo. This enables us to show that the cross section scales perfectly with the square of the ANC of the final state. The absolute measurement of that cross section (see Question 3) will provide us with the actual magnitude of the tail of the wave function, i.e., its ANC. As discussed in our answer to Question 1, see especially Fig. 3, the statistical uncertainty we expect for this experiment will enable us to pin down that value quite precisely. This will provide a very stringent test to nuclear-structure calculations in, e.g., microscopic multi-cluster models and *ab-initio* no-core shell models (NCSM) [1, 2].”

A more accurate estimate of the absence of a halo in the final state would require a 4-cluster description of the final state, which is beyond the scope of this preliminary study. However, as indicated in our original proposal, the comparison of the cross section for the transfer to the 2^- excited state with that to other neighbouring states will help us confirm the presence of a halo. These other states, and in particular the close-by 0_2^+ state, exhibit strong 2α-2n structures [3, 4]. Accordingly, the cross section for the transfer to these other states, in addition to being much smaller than for the halo state, should also exhibit a very different angular distribution than the one shown in Fig. 1, which will also be measured to confirm this point.

Question 3*: The current proposal describes a very model-dependent analysis that relies on the measurement of relative cross sections. In order to interpret results, these reactions and the corresponding nuclear states must then be described in the same theoretical framework. This seems to be outside of the reach of the considered halo EFT. The authors should convincingly explain how results will be confronted with theoretical modeling.*

The INTC recommends that the authors further consider the possibility for measuring the absolute cross section. This observable would provide a much clearer signal to be confronted with theoretical modelling.

Because one of the goals of our proposal is the extraction of the ANC of the 2^- excited state of ^{10}Be, we have always planned to measure the absolute cross section for the transfer ^{9}Be(^{11}Be,^{10} Be)^{10}Be$^*(2^-)$. The ANC is indeed the key nuclear-structure observable, which provides the information about the magnitude of the halo in a nucleus. This observable can be inferred from state-of-the-art calculations, such as the aforementioned NCSMC.

In our initial proposal, we have mentioned that comparing the transfer cross section to this state with that to other neighboring states, which most likely do not exhibit a neutron halo, would help us to ascertain the presence of a halo in the 2^- excited state. It seems that our proposal was not very clear on this point because our goal was never to measure only relative cross sections, we apologize for this lack of clarity.

We will therefore look at that reaction in different ways: absolute cross sections measured as a function of the scattering angle and its comparison with the cross section for the transfer to other states, in particular, the 0_2^+ state which has a dominant α-cluster configuration [4]. As mentioned above, the experimental signature of the halo structure will be primarily the angular distribution and the enhancement of the total cross section. The comparison with other neighboring states will confirm this result.

In the following, we show how we will determine the beam intensity. A few runs will be performed with a gold foil target of thickness 1 mg/cm^2. At the available beam energy, the cross section will be almost purely Rutherford, which will be used to normalize the beam intensity. Since the beam intensity may vary with time, it will also be monitored by the elastic scattering events on the ^{9}Be target. According to our calculations, even just with the ^{9}Be target, the beam intensity can be determined within 10-20% uncertainty.

We will measure the elastic scattering differential cross sections with the CD-detector from 25 to 50 degrees in the c.m., which will be used to monitor and estimate the beam intensity. Owing to the large cross section, there will be about 2000 particles per second of elastic-scattering events, so the statistical uncertainty will be small. The elastic scattering differential cross sections shown in Fig. 4 have been calculated using the halo-EFT description of the incoming ^{11}Be. We consider two optical potentials to describe the ^{11}Be-^{9}Be interaction to estimate the model-dependency of the elastic-scattering cross section. At forward angles, where the reaction is Coulomb dominated, the uncertainty related to the nuclear part of the optical potential is nearly nil, whereas at larger angles, where the nuclear interaction kicks in, it can reach about 20%.

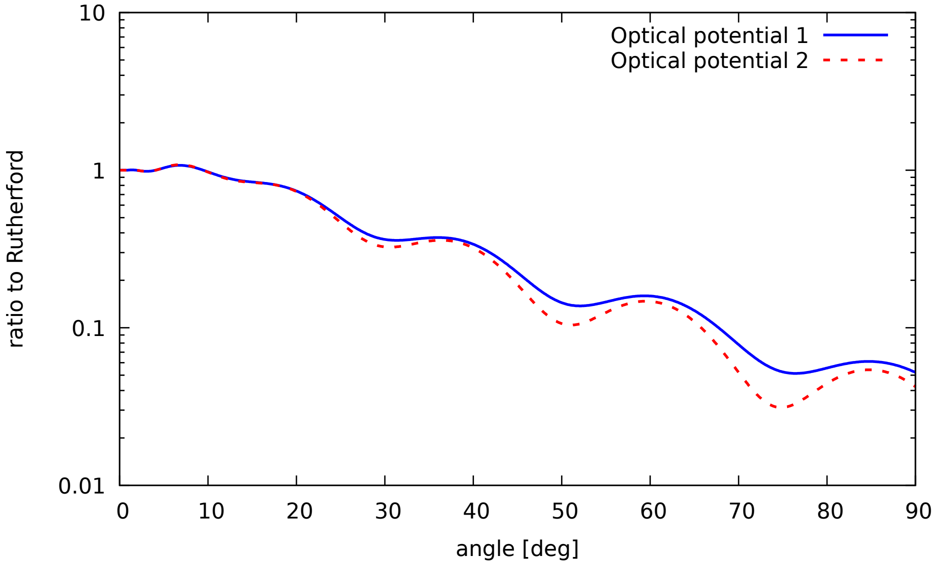

Figure 4: Elastic scattering cross sections as the ratio to Rutherford at E_{lab}=1.55 MeV/u using different ^{11}Be-^{9}Be optical potentials shown as blue solid line and red dashed line. The different potentials were chosen to estimate the theoretical uncertainty they have in the elastic scattering cross section.

Summary of our reply:

We propose a measurement of the ^{9}Be(^{11}Be,^{10}Be)^{10}Be*(2^-) transfer reaction to investigate the possible existence of a halo in the ^{10}Be(2^-) excited state at ISOLDE with MINIBALL and a set of CD detector array. In total, we request **12 shifts** of beam time at 1.55 MeV/u. The absolute cross section and angular distribution will be measured to confirm the existence of the halo structure in ^{10}Be(2^-). If ^{10}Be(2^-) is a halo nucleus, the shape of the transfer cross sections will agree with our theoretical calculations. The angular distribution of other excited states, in particular the 0_2^+ state, which has a dominant α-cluster structure, will also be measured in comparison with the 2^- state and the calculation to provide further confirmation. Beam intensity will be determined by the elastic scattering events on the ^{9}Be target and a gold foil. If successful, this method could then be applied systematically to study the presence of neutron halos in the excited states of nuclei.

References

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[3] Y. Ogawa, K. Arai, Y. Suzuki, K. Varga, Nucl. Phys. A, 673 (2000) 122-142.

[4] Y. Kanada-En'yo and M. Kimura, Clusters in Nuclei, Ed. C. Beck, Lecture Notes in Physics 818, 129 (2010).