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Studies of light exotic nuclei: Combining reaction and beta-decay data

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Even though being the subject of intense scrutiny during the last decade halo nuclei still offer unanswered questions. One way of adding confidence to the conclusions obtained in the often difficult experiments is to probe the same physical observable in various ways. The prominent example in this contribution will be the orbital structure of the two halo neutrons in ^{11}Li probed both via beta decay and high-energy reaction experiments, but other aspects of these two experiments will also be mentioned.

1. INTRODUCTION

As the production methods for radioactive beams become more and more perfected [1] and the experimental set-ups become correspondingly refined we are reaching a stage where more detailed questions on the structure of drip line nuclei can be asked. Of particular interest are the halo nuclei [2, 3] that have been the subject of many experiments during the last ten years. I shall here present new data on halo nuclei stemming from reaction experiments and beta-decay experiments. The use of two different probes gives the opportunity to cross-check against systematic uncertainties arising e.g. from the choice of model for the data interpretation. Although many experiments already has looked at the properties of ^{11}Li , the best known example of a halo nucleus, there are still open questions concerning its structure and I shall concentrate here on this nucleus.

2. THE ^{11}Li BETA-DECAY

Beta-decay is a well-understood probe of nuclear structure and can thus, although limited in scope, add valuable information also on halo states through observation of decays leading to or from them. This has been the driving force behind our experiments performed at the PS-Booster ISOLDE facility during the last years, see e.g. [4] for an account of our earlier work. For ^{11}Li , whose decay scheme is outlined in figure 1, it is probably safe to exclude Fermi transitions (unless the isobaric analogue state mixes strongly with the $^9\text{Li}+p+n$ continuum) and the beta decay therefore proceeds via Gamow-Teller transitions. i.e. through conversion of a neutron to a proton accompanied by a spin flip. The structure of the ^{11}Li ground state will be

reflected through the pattern of population of daughter states. Generally speaking, one might expect a retardation of the decay due to non-complete overlap between the halo neutrons in ^{11}Li and the nucleons in excited states in ^{11}Be . Transitions into continuum states thus becomes imaginable, the first subsection deals with such decays. From decays to states in ^{11}Be of known structure we can also expect to be able to extract detailed information, this is the subject of the second subsection. The final subsection discusses general features of the decay, including transitions to highly excited states in ^{11}Be where the transition matrix elements (the B_{GT} -values) become large. Conclusions drawn from such decays will naturally be more model independent due to the larger overlap with the ^{11}Li ground state.

Figure 1: The ^{11}Li decay scheme. Note that most decays proceed to particle unstable levels in ^{11}Be and that a substantial part go to highly excited states where many decay channels are open.

As seen in figure 1 many decay channels are open for the excited states populated in ^{11}Be . The experiment aimed for a full characterization of the decay and therefore

had to include detection of gamma rays, neutrons as well as heavy charged particles. For the latter a telescope consisting of a gas delta-E counter and a Si surface barrier E counter was used. By implanting the low energy (60 keV) ^{11}Li beam from ISOLDE into the front window of the gas counter we obtained a low threshold for detection of the particles, details of this set-up are given in [5]. Large liquid scintillator counters were placed around the collection point for detection of the beta-delayed neutrons, that have a branching ratio of more than 90 %. The delayed gamma rays, coming both from the decay of the first excited state in ^{11}Be and from decays of excited states in ^{10}Be fed through neutron emission, were detected in separate set-ups described in [6].

2.1. Beta-delayed deuteron emission

Beta decays directly to continuum states might yield much more information about the mother state than decays through excited states in the daughter nucleus since the spatial overlap matrix elements will constitute an integral transform of the original spatial wave function (only modified by the possible final state interaction, in the case of no interaction the matrix elements reduce to Fourier transforms). The most favourable direct decay branch for two-neutron halo nuclei would be beta-delayed emission of deuterons, a process that already has been observed for ^6He , see [7, 2] and references therein. Several theoretical calculations of the corresponding direct beta-decay to deuteron continuum states for ^{11}Li have been performed [8, 9]. They predict a branching ratio of order 10^{-4} and a deuteron spectrum that typically peaks at a few hundred keV, but show also that both the total branching ratio and the deuteron spectral shape depends sensitively on the structure of ^{11}Li and on the $d+^9\text{Li}$ final state interaction. However, the decay rate is mainly determined by the outer spatial parts of the wave function, showing that we here are sensitive to the halo degrees of freedom.

The events recorded in the gas telescope on the deuteron energy loss curve are shown in figure 2. Unfortunately, beta-delayed triton emission is also allowed and has a larger Q-value (see figure 1). Tritons and deuterons cannot be separated at these low kinetic energies and we therefore had to resort to indirect methods in order to distinguish the two decay branches.

The PS-Booster operates in a pulsed mode with a minimum time of 1.2 s between the proton pulses that produce the ^{11}Li activity in the ISOLDE target. This fortunate feature allows us to make use of the decay time distributions. After 150 ms the ^{11}Li activity has died away (measured halflife 8.2 ± 0.2 ms) and only a long-lived charged particle component is present. This is composed mainly of alpha particles from the decays of ^{11}Be and ^8Li , fed via decays to the first excited state in ^{11}Be and beta-delayed triton emission, respectively. However, a careful analysis of the energy and time spectra revealed the presence also of alpha particles from the decay of ^9Li , fed via beta-delayed deuteron emission. The ^9Li component was, although statistically significant, not easily separated from the ^{11}Be component and in order to ensure its presence we searched for delayed coincidences between deuterons emitted in the decay of ^{11}Li and alpha particles emitted in the decay of ^9Li . The events recorded are shown

Figure 2: The total energy spectrum of hydrogen ions (deuterons and/or tritons) emitted in the decay of ^{11}Li in experiments at (a) SC-ISOLDE and (b) PSB-ISOLDE. In the latter spectrum the histogram denotes a possible background from beta particles, in the former the background has been subtracted. Taken from [5].

in figure 3. The coincidence efficiency is distorted since the recoiling nuclei of highest energy can go out of the collection foil, but the spectrum nevertheless shows clearly the presence of deuterons of low kinetic energy followed by ^9Li alpha particles (the spectrum of these peaks below 500 keV). The distribution of delay times had a halflife of $0.22^{+0.18}_{-0.07}$ s which indicates that a major part of the activity is ^9Li .

Having thus established the presence of both beta-delayed deuterons and tritons we can use the analysis of the delayed alpha activity to extract total branching ratios for the two decays. The total branching ratio for tritons is $(2.0 \pm 0.5) \cdot 10^{-4}$ and a lower limit for the branching ratio for deuterons is $(1.5 \pm 0.5) \cdot 10^{-4}$ (a precise upper limit cannot be given at the moment due to uncertainties concerning the ^9Li alpha spectrum at low energies). Although an energy spectrum cannot be deduced it seems likely that the deuterons occur mainly at low kinetic energy. Due to phase space restrictions most events above 1 MeV in figure 2 will anyway be tritons. This result will not yet allow a detailed test of the structure of the ^{11}Li ground state, but already excludes part of the parameter space in the theoretical calculations. To reduce the

Figure 3: Energies of correlated particles: a $Z = 1$ charged particle detected in ^{11}Li β -decay and an alpha particle (from ^8Li or ^9Li) registered from 0.15 to 0.9 s later. Taken from [5].

uncertainties in the calculations measurements of the deuteron- ^9Li interaction at low relative energies would have to be performed. This should be possible at the coming generation of radioactive nuclear beam facilities.

2.2. The decay to $^{11}\text{Be}(320 \text{ keV})$

The transition to the first excited state in ^{11}Be at 320 keV is the only one that feeds particle stable states, the ground state can only be populated in a first-forbidden decay. The structure of the first excited state can in the lowest approximation be described as a $p_{1/2}$ neutron around a ^{10}Be core and the decay into it will therefore require that a $p_{1/2}$ neutron from the ^{11}Li halo turns into a $p_{3/2}$ proton in ^{10}Be . The decay rate therefore depends on the size of the $(p_{1/2})^2$ component in the ^{11}Li halo, on the spatial overlap between the relevant $p_{1/2}$ and $p_{3/2}$ orbits and on the overlap of ^9Li with the “remaining” part of ^{10}Be . Shell model calculations [10] indicated a substantial sensitivity to the amount of $(p_{1/2})^2$ in the halo. This quantity is of great interest since the detailed structure of the halo has turned out to be rather elusive so far. However, the experimental branching ratio needed confirmation since the two existing measurements did not agree and we have therefore remeasured it.

Several independent measurements were performed in order to cross-check against systematic uncertainties and particular attention was given to the calibration of the Ge-detectors employed [6]. The end result was a branching ratio of $(6.3 \pm 0.6) \%$ that converts into a $\log ft$ value of 5.73. This value points towards a $(p_{1/2})^2$ component

of less than 50 %, which first of all indicates that a careful treatment of the sd-shell components are needed, secondly that the $p_{1/2}$ orbit might not necessarily be of large spatial extent since it does not dominate the halo structure. A new independent shell model calculation has therefore been performed [11] that, although differing in predictions for large $(p_{1/2})^2$ components, also result in a value for the $(p_{1/2})^2$ component in the ^{11}Li halo of 30–40 %. There is thus clear indications that the major component of the two-neutron halo wave function must reside in the (sd)-shell. It is interesting that both p- and sd-components are needed. Such a configuration mixing allow for spatial correlations between the two neutrons and might reflect the pairing between them.

2.3. Other aspects of the decay

The complete beta-strength distribution will of course also depend on the structure of ^{11}Li and any retardation due to the presence of the halo (to its spatial extension or to sd-shell components in it) should show up here. As seen from figure 1 the total halflife is mainly given by the transitions to states up to about 7 MeV excitation energy in ^{11}Be . It is very satisfactory that the shell model calculations mentioned in the last subsection [11] also succeed in reproducing the total halflife. A pure p-shell configuration would give a halflife around 2 ms [12], i.e. a factor of four too short. The good agreement obtained when sd-shell components are allowed adds confidence to the conclusion that they dominate the halo structure. The basic idea here is not new, Barker and Hickey [13] argued almost 20 years ago that the ^{11}Li halflife indicates a pure p-shell occupancy of only about 30 %.

As mentioned earlier the transitions with large B_{GT} -value are of particular interest since the daughter states in this case have a large spatial overlap with ^{11}Li . Such strong decays to states a few MeV below the mother states are seen systematically in neutron rich nuclei [14] and might be due to a lowering of the Gamow-Teller resonance [15]. One such transition has been identified for ^{11}Li . It reaches a state at excitation energy 18.1 MeV in ^{11}Be and has a B_{GT} larger than 1.0 ± 0.3 . A detailed discussion of this transition is given in [16] so I shall only repeat the main features here: the level is very close to the threshold for deuteron emission, but it seems unlikely that the beta-delayed deuteron emission takes place through the level since the reduced width for the deuteron channel in this case would be larger than the Wigner limit. Also, the main decay branch is via alpha emission — there is a strong suppression of the decay to the ground state of ^{10}Be . It is hoped that the striking decay pattern of the state combined with the large B_{GT} -value will give sufficient restrictions for theoretical calculations to allow deductions concerning the ^{11}Li structure.

3. HIGH-ENERGY REACTION EXPERIMENTS

The halo phenomenon has been known for many years [2], but only attained the present level of “fame” after showing up in high-energy nuclear reaction experiments [3]. Most of the information derived today about halo systems still stem from reaction experiments that for technical reasons mainly take place at beam energies from

around 25 A·MeV to above 1 A·GeV. The coming generation of radioactive nuclear beam facilities will allow experiments to be performed also at lower energies and thus add to our knowledge, but this by no means imply that the high-energy experiments will become obsolete. Important developments in our understanding are still taking place here. I shall illustrate this with examples from a complete kinematics experiment carried out at the GSI, preceded by a short general discussion on the reaction mechanisms involved at the high energies.

3.1. Remarks on reaction mechanisms

An attractive feature of the high beam energies is that one can employ the Glauber model for the analysis, see e.g. [17]. Put briefly, one can neglect the internal motion (and forces) in the nuclei during the collision. The present understanding of how the reactions proceed can be summarized briefly as follows, see [2, 18, 19, 20] and references quoted therein for a more complete account.

The basic interaction can be either a strong interaction, if the nuclear density distributions for the target and projectile overlap, or a Coulomb interaction, also effective at larger distances (but only giving a substantial contribution for heavy targets). Due to this interaction the projectile halo nucleus breaks up (I shall neglect elastic scattering and transitions to excited states here). This can take place via absorption of the halo or the core on the target or via transfer of energy and momentum to either the core or the halo nucleons. This distinction is not unique, in practice one might treat e.g. a violent inelastic collision of a halo neutron with the target as effectively being an absorption of the neutron since it will come out removed far in velocity from the other fragments. Furthermore, since the halo and core are spatially correlated there is a non-negligible probability that both interact in the sense that even though a momentum transfer basically goes to the neutron, the core wave function will also be modified in that parts of it can be absorbed by the target. See [2, 19] for recent expositions of this argument. Finally, if enough fragments emerge from the collision with sufficiently low relative velocities final state interactions might play a substantial role. The extreme limit of this is of course if the core and all halo nucleons survive and make up a resonance, an excited state in the original halo nucleus [21], but also less extreme cases will lead to observable effects in the recorded momentum distributions etc. [22, 23].

3.2. Results from a complete kinematics experiment

Most of the remarks just given are nicely illustrated by the experiment taking place at the GSI on fragmentation of ^{11}Li and ^{11}Be . Part of the results from this experiment have already been published [24, 25, 26, 27], details of the experimental procedures can be found in these papers and in the theses [28, 29, 30, 31].

The high efficiency of the detectors, in particular of the neutron detector LAND [32], eases the construction of statistically significant invariant mass plots even up to excitation energies of 10 MeV. The neutron-multiplicities for the halo-removal channel recorded in LAND are shown in figure 4 for different incoming drip-line nuclei. For ^{11}Li on C and Pb targets one detects two outgoing neutrons in coincidence with a

Figure 4: Neutron multiplicities recorded in LAND following break-up of ^{11}Be , ^8He and ^{11}Li into the one- and two-neutron removal channels. Taken from [31].

^9Li fragment in more than 20 % and about 50 % of all reactions, respectively. For both targets one sees in the invariant mass spectrum two peaks, that if interpreted as resonances in ^{11}Li has excitation energies of 1.1 ± 0.1 MeV and 2.3 ± 0.3 MeV, respectively [33]. States at similar excitation energy in ^{11}Li have been observed by Bohlen et al. [34] (one level at 2.47 ± 0.07 MeV as well as two higher lying states) and Korshennikov et al. [35] (levels at 1.25 ± 0.15 MeV, 3.0 ± 0.2 MeV as well as two higher lying states). There is a reasonable agreement between these independent observations and it therefore seems likely that fragmentation of ^{11}Li into ^9Li and two neutrons to a large extent proceeds through excited states.

The $^9\text{Li}+n$ invariant mass spectra also contain interesting information. They point toward the existence of low-lying resonances in ^{10}Li at excitation energies 0.15 ± 0.03 MeV and 0.65 ± 0.27 MeV. An independent confirmation of this interpretation can be obtained by studying the neutron transverse momentum distribution in this channel [26]. At low relative momentum between a neutron and the ^9Li core the final state interactions will dominate and strongly influence the observed line profile, reproduced in figure 5. This will also occur for break-up of ^{11}Be into ^9Li and a neutron, and since one here knows that the neutron initially is in an s-wave (the halo neutron in ^{11}Be) one can even deduce that the lowest level in ^{10}Li also must have an s-wave neutron. Going back to ^{11}Li one then observes that a pure $(s_{1/2})^2$ or a pure $(p_{1/2})^2$ configuration for the ground-state will not fit the observed distribution. However, a wavefunction with about equal contribution from the two configurations will fit nicely [26]. A more careful calculation [20] gives a p-state admixture of 20–30 % with the s-state in ^{10}Li positioned at about 50 keV and the lowest p-state at around

Figure 5: The neutron transverse distributions recorded in coincidence with a ^9Li fragment after break-up of ^{11}Be (upper part) and ^{11}Li (lower part), reaction energies as indicated. The drawing on the right illustrates the creation of the ^{10}Li intermediate system by one-nucleon removal from the two projectiles, see text for details. Taken from [30].

500 keV. These values are consistent with the energies given above and with the p-state admixture deduced from the beta-decay experiments as quoted in section 2.2. It is reassuring that two so different probes give consistent answers for the structure of the ^{11}Li halo. Concerning the properties of ^{10}Li , a critical account of earlier work on the low-lying levels can be found in [36], our results are in agreement with the conclusions drawn there.

As an illustration of the level of understanding let us look at the widths of the momentum distributions following break-up of ^{11}Li on a light target. The theoretical results will be taken from Garrido et al. [20] (note that this calculation assumes the effect of absorption on the “non-interacting” particles to be small, the predictions might therefore in some cases be too large, cf. [19]) and the experimental numbers mainly from our GSI experiment. If the core breaks up and thus effectively is removed, the only possible final state interaction is between the two neutrons. This gives a theoretical width about 39 MeV/c that can be compared with the experimental number [25] 41 ± 4 MeV/c. In the ^9Li channel the most likely outcome is to have one neutron going along the ^9Li fragment, see figure 4, and it is the n-core final state interaction that matters. Since these interactions depends sensitively on the structure of ^{10}Li it is of course hard to make model independent predictions, but this will mainly affect the neutron distribution as the core momentum will not change as much due to the f.s.i. The calculation gave neutron widths around 30 MeV/c whereas the experimental number is [26] 36 MeV/c. The width of the ^9Li distribution is calculated to be about 55 MeV/c to be compared with the experimental [24] value of 49 ± 3 MeV/c for the longitudinal distribution and 45 ± 4 MeV/c for the transverse distribution. The slight discrepancy could be due to the neglect of absorption on the ^9Li wavefunction mentioned earlier.

However, puzzles still exist. As observed in [24] the longitudinal and transverse core momentum distributions had roughly the same width in the ^9Li channel also for the heavy Pb target, which is contrary to the naive expectation that the Coulomb deflection on this target would give rise to a considerable broadening of the transverse component. A similar situation occurs for ^{11}Be breaking up into a ^{10}Be fragment on a Pb target. Both the longitudinal and transverse width of the ^{10}Be momentum distribution is about 50 MeV/c, the latter one is reproduced in figure 6. This phenomena still has to be reproduced in theoretical calculations, see [37] for a first step in this direction. It is all the more striking since the transverse width in break-up into ^{10}Be on a light target (76 MeV/c) actually is significantly broader than the longitudinal one (again about 50 MeV/c). The transverse width is approaching the neutron width of 98 MeV/c that is known to be broadened due to diffraction on the target nucleus. The longitudinal width is significantly larger than the one observed at lower energies [38] (41.6 ± 2.1 MeV/c) and also larger than the 40.7 MeV/c calculated in [19]. On the other hand the neutron widths seem well understood as discussed in [26].

4. A BRIEF OUTLOOK

There are certainly still missing bricks in our understanding of the reaction exper-

Figure 6: Transverse momentum distribution of ^{10}Be fragments from break-up of ^{11}Be on a Pb target at 460 A-MeV.

iments and also still details to unravel in the beta-decay. But we are clearly getting closer to an overall understanding of the structure of ^{11}Li . Very encouraging in this respect are the converging answers concerning the orbital structure of the halo neutrons coming from the two types of experiments.

The results presented here stem from the experiments IS320 and S034 performed at ISOLDE and at the GSI. They are the work of many collaborators whom I should like to thank warmly.

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