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Halo-nuclei at ISOLDE

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Nuclear halo states are studied experimentally with a wide range of techniques. We review the results coming from ISOLDE, emphasizing the beta-decay experiments. Some general comments on the role of beta-decays for halo research are given. We outline the possibilities for low-energy reaction experiments arising from REX-ISOLDE.

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1. Introduction

Halos have caught the interest of (nuclear) physicists during the last decade. States with a seemingly simple few-body structure placed close to a threshold can develop an unusually large spatial extension. The detailed study of this phenomenon has already given many results as reflected in the recent review papers [1–4], but questions remain, in particular concerning two-neutron halo systems. We refer to the listed review papers for an in-depth account of halo structures and our present knowledge on them and concentrate here on the aspects relevant for experiments done at the relatively low energies present at ISOLDE.

Although halo structures could also be present in excited states they are easier to observe and have therefore mainly been investigated in ground states. As halo states should be close to a threshold this implies one is close to the nucleon drip lines; since proton halos are retarded by the Coulomb barrier the neutron drip line will offer more cases. Beta-decay will be fast for neutron drip line nuclei, in most cases giving halflives of order 10 ms. One might ask why experiments at ISOL-facilities at all are competitive for such nuclei, since recoil mass separators have the advantage of much shorter time delays between production and measurement [5]. There are two aspects in the answer to this question. The first is that in spite of substantial decay losses of the relevant isotopes (for the 8.6 ms halo nucleus ^{11}Li the decay loss is about a factor 1000) ISOLDE has comparable final yields, i.e. the “primary yield” is much higher than at recoil mass separators. The second is that the low-energy ISOL beam is beam-optically well-defined and allows for experimental methods not feasible at fragment separators. In beta-decay experiments one can work with thin geometrically well-defined sources; in the future post-accelerated beams of good quality will also be available. A particular feature at the present ISOLDE that also deserves mentioning is the pulsed production and release (due to the use of a synchrotron for the primary beam); for short-lived activities this can be used to separate in time the signal from the background.

Beta-decays in nuclei far from stability will typically involve large Q_β-values and low nucleon separation energies in the daughter nuclei. Beta-delayed particle emission will be important, especially for the higher excitation energies that often are of interest due to the higher reduced transitions rates (an effect of the "Gamow Teller Giant Resonance"). Reviews of beta-decay far from stability can be found in [6,7]. We shall employ the same definition of beta-strengths, B_F and B_{GT}, as in [8]:

$$ft = \frac{K}{G_V^2 B_F + G_A^2 B_{GT}} \tag{1}$$

where $K/G_V^2 = 6141 \pm 4$ s and $(G_A/G_V)^2 = 1.59 \pm 0.01$.

The next section covers beta-decay experiments. Some general comments are followed by a discussion of the results obtained up to now. We mainly discuss physics issues and refer to the original papers for details of the experimental procedures. The following section describes the coming low-energy reaction experiments and the aims set for the first round at REX-ISOLDE. The final section contains our conclusions.

2. Beta-decay experiments

A halo-structure in a state could affect the beta-decay in the following different ways [9,10]. Firstly, the spatial extension of the halo state might reduce the spatial overlap with daughter states. This might be seen either in specific well-understood transitions or as a general reduction of beta-strength. Secondly, the halo particle(s) might beta-decay more or less independently from the core. This might give rise to specific patterns in the decay, see subsection 2.4 below, or, if the halo is quite extended, could lead to decays going directly to continuum states. Beta-decay can furthermore be helpful in establishing details of the structure of the halo state via the patterns observed in the decay. For this, one of course must understand the structure of the daughter states.

We shall elaborate slightly on the second point. Let $\mathcal{O}_\beta$ be the beta-decay operator (we shall mainly consider allowed Fermi or Gamow-Teller decays). Assuming that the halo state can be factorized into a core and a halo part one then formally gets:

$$\mathcal{O}_\beta|\text{halo state}\rangle = \mathcal{O}_\beta\left(|\text{core}\rangle|\text{halo}\rangle\right) = \left(\mathcal{O}_\beta|\text{core}\rangle\right)|\text{halo}\rangle + |\text{core}\rangle\left(\mathcal{O}_\beta|\text{halo}\rangle\right) \tag{2}$$

Both terms on the right hand side are needed in order to have the correct isospin in the final state. Approximations have been made in the literature where only the part where the core is unchanged [11] or only the part where the core changes [12] was considered. Equation (2) will only describe the beta-decays of halo nuclei well if the right hand part, to a good approximation, is an eigenstate of the daughter nucleus (or a combination of eigenstates, if the core beta-decay leads to several levels). This is illustrated in figure 1. The model can at most be expected to hold for the large terms from the $\mathcal{O}_\beta|\mathrm{core}\rangle$ part.

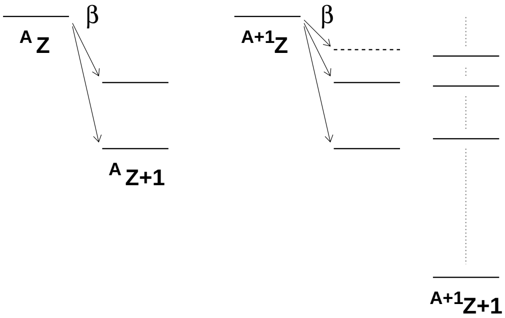

Figure 1. Schematic model of beta decay of a one-neutron halo. Ideally the decay of the core (left) and the halo contribute separately (solid and dashed lines at right). The true eigenstates in the daughter nucleus might differ somewhat (extreme right).

Let us, for example, look briefly at the decay of ^{11}Be. To a good approximation it is described as an s-wave neutron around a ^{10}Be core, so we should consider the beta-decay of ^{10}Be. The only energetically allowed decay mode is a second forbidden transition to the 3^+ ground state of ^{10}B, but by comparing to the ^{10}C mirror decay, one would expect large decay strengths to the 1^+ excited state at 0.718 MeV ($B_{GT} = 3.44$) and to the isobaric analogue state at 1.740 MeV (B_F close to 2). The Q-value of ^{11}Be is 11.506 MeV, so its isobaric analogue state at 12.56 MeV in ^{11}B cannot be populated. Contributions from the "core decay" in equation (2) will thus correspond to the configuration: 1^+ excited state in ^{10}B plus an s-wave neutron. There is experimental evidence that the ^{10}B ground state plus s-wave neutron configuration is spread out over several states in ^{11}B from 9.2 MeV to 12 MeV [13]. The excited state configuration might behave similarly since the only appreciable decay branch from ^{11}Be ($B_{GT} = 0.35$) goes to the 9.876 MeV state in ^{11}B. We could expect the remaining strength from this configuration, as well as from the "^{10}Be plus proton" part, to be situated at an excitation energy of 11-12 MeV. This does not yet prove the applicability of equation (2), but we shall nevertheless employ it later on when discussing observed decay patterns.

Isobaric analogue states (IAS) of halo states would be interesting to study [14], but are only available in beta-decay for proton rich nuclei. We thus postpone a discussion of this subject to the next section, but shall comment briefly on isospin conservation in connection with halo states. One should be careful not to confuse isospin non-conservation with non-perfect spatial overlap of analogue states. Numerical estimates [15] show that the former in light nuclei, even for extreme halo states, only give isospin mixing probabilities of order 10^{-4}. The overlap between analogue states can, even for normal nuclear states, easily differ by appreciably more, see e.g. [16]. The latter effect is of course large when halo states are involved as seen clearly in the schematic calculations in [15]. Note that detailed calculations [17] for the IAS of ^{11}Li also indicated that isospin still is good.

2.1. ^{6}He

The main decay branch of ^{6}He, with $B_{GT} = 4.75$, goes to the ground state of ^{6}Li. The only excited state within the Q_β window has a spin and parity of 3^+ and will not be fed in allowed decays. This is therefore the ideal case for searches for beta-decays directly to continuum states. When one of the two halo neutrons in ^{6}He beta-decay, one ends up with a proton-neutron-α configuration. The overlap with the ground state of ^{6}Li is rather large, but since ^{6}He is spatially more extended the "outer parts of its wavefunction" will rather overlap with continuum states. Only the d + α channel is energetically open and the total decay rate will thus also depend on the extent the halo neutrons in ^{6}He overlap spatially with the deuteron wavefunction.

The beta-delayed deuteron emission was first seen in this nucleus about ten years ago [18]. The deuteron spectrum is continuous and probably extends down to below 100 keV. This is difficult to see experimentally, in particular since the total branching ratio is of order 10^{-5}. The two experiments performed at ISOLDE [18,19] have lower cut-offs around 300 keV. They differ in the value extracted for the branching ratio; the latest value is $(7.6 \pm 0.6) \cdot 10^{-6}$ for deuterons above 350 keV in energy. A further experiment has been performed at TISOL, but the results have not yet been published. A check of the branching ratio would be valuable, as would an experiment going down to about 100 keV deuteron energies.

The low value of the branching ratio presented a problem at first [18]. Naive calculations of the direct decay process as well as R-matrix calculations (assuming decays to proceed though the tails of the levels in ^{6}Li) were both more than an order of magnitude above the data. Several detailed investigations assuming a direct decay process [20–23] or extending the R-matrix approach [19,24] have followed. The low intensity is now understood as being due to cancellation effects that in the direct decay model take place between inner and outer parts of the wavefunction. This makes the process harder to observe (and to predict), but will in principle allow for very detailed tests of the wavefunction of ^{6}He provided good data can be obtained.

2.2. ^{8}He

Several measurements of the decay of ^{8}He have been performed, the latest one [19] (from ISOLDE) focused on the large beta-delayed triton branch that was measured to be $(8.0 \pm 0.5) \cdot 10^{-3}$. The ^{8}He configuration is expected to be an alpha particle surrounded by four neutrons, so the decay might contain features similar to the ones of ^{6}He, although ^{8}He is more bound. A detailed treatment has been given in terms of R-matrix many-level many-channels theory, see [25] and references therein. One conclusion is that a transition of large B_{GT} goes to a highly excited state in ^{8}Li, which explains e.g. the large triton branch. The excitation energy E^{*} and the B_{GT} value extracted are around 9.7 MeV and 4.75, but the precise values could depend somewhat on the channel radius used.

An alternative approach, starting from few-body models of the nuclei, has also been attempted [26]. Although beta-decays directly to the α+t+n continuum could be excluded, it was suggested that the decay of the highly excited state in ^{8}Li go directly to the continuum. This would lower the extracted values for E^{*} and B_{GT}. As shell-model calculations generally give larger values for B_{GT} than extracted experimentally, it was later suggested [27] that some of the “missing strength” might be found as decays to the ^{6}Li+n+n channel. The available energy is just 1.37 MeV, but calculations [27] indicate branching ratios could lie in the range 10^{-5}–10^{-4}.

2.3. ^{11}Li

The large Q-value for ^{11}Li and the low particle separation energies in ^{11}Be imply that many decay channels are open and that the decay is quite complex. The early work on the decay scheme mainly took place at CERN, see [8] for references. The β-NMR measurements of the magnetic dipole [28] and electric quadrupole moments [29] using optically polarized atoms at SC-ISOLDE should also be mentioned.

A beta-delayed deuteron branch is expected, as in ^{6}He, to give rather direct information on the halo structure. Theoretical calculations of the process [30,11] could not give a unique prediction of the deuteron spectrum as the deuteron-^{9}Li interaction is not known, but indicate that the total branching ratio is around 10^{-4}. An ISOLDE experiment [31] succeeded in showing that the deuteron branch is present. Due to the presence of a beta-delayed triton branch, also of the order of 10^{-4}, one could not extract separate energy spectra for deuterons and tritons. Both components could be shown to be present by correlating with the daughter nuclei (^{9}Li and ^{8}Li, respectively, the pulsed structure of the PSB-ISOLDE beam was essential for this technique to work). The deuteron spectrum probably peaks at lower energies than the triton spectrum, but new experimental techniques must be brought into play to settle this and to find the final branching ratios.

The decay rate of ^{11}Li to the first excited state in ^{11}Be (a p-wave halo state) should be sensitive to the amount of $(p_{1/2})^2$ admixture in the halo [32]. Since early experiments differed on the branching ratio for this transition it was remeasured at ISOLDE [33] as well as at MSU [34] and at RIKEN [35]. The weighted average of 7.0 ± 0.4 % indicates that the $(p_{1/2})^2$ component constitutes at most 50% of the halo wavefunction. In essence this argument stems from Barker and Hickey [36] who pointed out that the theoretical halflife of ^{11}Li is much too short if only p-shell components are allowed. Including sd-shell components (that go to higher excitation energies in ^{11}Be) will increase the halflife[1]. Therefore the shell-model calculations in [33] were also required to fit the total halflife. Other recent shell-model calculations [34,39] do not give this number, but give B_{GT}-distributions.

The decay to states above the neutron-threshold in ^{11}Be is presently being studied. Beta-delayed single neutron spectra [34] and beta-neutron-gamma triple coincidences [35] have been published and suggestions for the decay scheme up to about 10 MeV excitation energy are given. Similar data from ISOLDE are being analysed. These latter data include charged particle spectra and coincidences and thus also allow the upper excitation energy region to be probed, see fig. 2. A strongly fed state at 18 MeV energy has been established [40] from several decay branches. From its decay pattern it seems to be mainly sensitive to the $(p_{1/2})^2$ component in ^{11}Li and the preliminary analysis again points to a contribution below 50%.

The decay of ^{11}Li seems to be rather fragmented and is superficially similar to the ^{9}Li core decay. This is what one would expect from equation (2), but detailed tests of the model have not yet been performed. For the previously discussed isotopes the model is trivially applicable for ^{6}He (since ^{4}He is stable) and will not work for ^{8}He, since ^{6}He does not seem to be a good core for this nucleus.

2.4. ^{9}Li and the phenomenon of large B_{GT} values

The nucleus ^{9}Li is not a halo nucleus, but lies at the neutron dripline. Its decay has been studied carefully at ISOLDE and analysed within the R-matrix theory [41]. It includes a transition with a B_{GT} of 5–6 at an excitation energy of 11.8 MeV. As for ^{8}He, an alternative analysis involving three-body decays of the states fed in the beta-decay has been attempted. Preliminary results [42] point to a lower B_{GT}-value for the high-lying transition. However, it is striking that the four well-studied nuclei at the neutron drip-line, ^{6,8}He and ^{9,11}Li, all have transitions with rather large B_{GT} going to states a few MeV below the initial state [8]. Several explanations have been offered for this phenomenon. It might be related to the existence of halos in this region; more specifically the "2n → d" transition that occurs in the ^{6}He decay could be involved also in the other cases. Support for this has been given in shell-model calculations [43] on the

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[1] Note that configuration mixing is similarly used to explain the halflife of ^{12}Be [37,38].

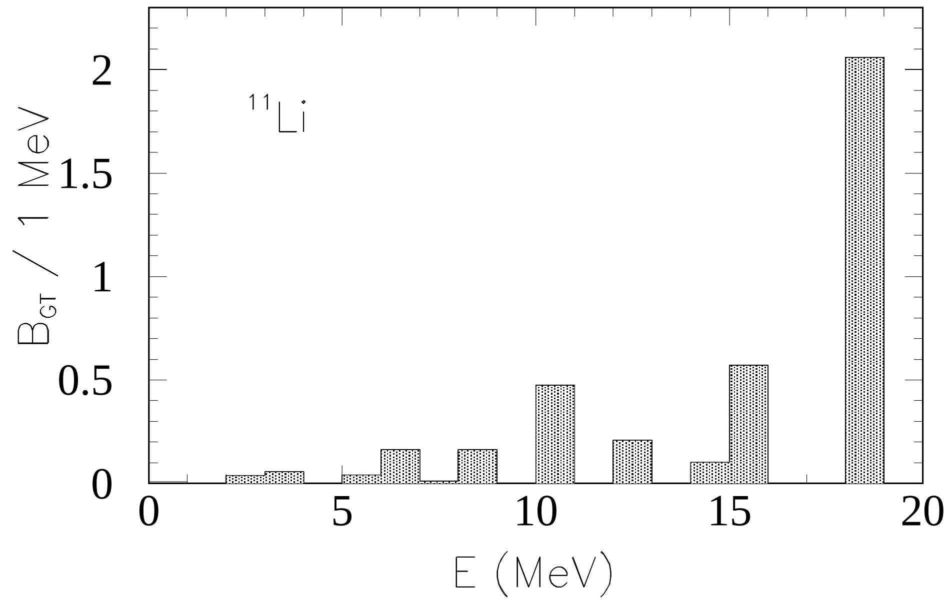

Figure 2. Preliminary experimental B_{GT}-distribution for the decay of ^{11}Li. The uncertainties for the higher excitation energies are rather large, but strong feeding to a state at 18 MeV is seen clearly.

(probably unbound) doubly magic nucleus ^{28}O where transitions showing this feature have been identified. Finally, it has been argued that the Gamow-Teller Giant Resonance (where most of the B_{GT} strength is situated) comes down in energy for these light very neutron-rich nuclei [44]. The different explanations may not necessarily exclude each other.

2.5. ^{17}*Ne*

The first-forbidden beta decay of ^{17}Ne into the first excited state in ^{17}F has been studied recently. The parent and daughter states have both been mentioned as candidates for halo states, see figures 1 and 2 in [4]. The decay rate is therefore of interest, in particular since the log(ft) value is fairly low (which implies that the decay is probing larger parts of the wavefunctions). An experiment at ISOLDE [45] found a branching-ratio of 1.65 ± 0.16 %, roughly a factor of two larger than expected by extrapolation from the previously measured mirror decay. A remeasurement at RIKEN [46] gave the consistent value of 1.56 ± 0.20 %.

No complete calculation of the different decay rates in the two mirror systems has been performed yet, but two different suggestions have been offered. Shell model calculations [45] where the size of individual orbits were allowed to vary could reproduce the difference if the valence proton s-orbit increased in size. In [47] it was argued that the major determining factor was a charge-dependent s-occupancy for the initial states. A definite explanation probably requires that other properties of the mass 17 nuclei are also included in the calculations. (A recent treatment of these nuclei [48] looked at the allowed decays, but for the first-forbidden transition overlooked that the operator change parity for the nucleon and thus concluded incorrectly that the ^{16}O+nucleon configuration in the final state does not enter for the transition probability.)

2.6. Be-isotopes

The recent development of a laser ion source [49] has improved the ISOLDE radioactive beam quality considerably for several elements, one of them being Be. This has already been used for an accurate measurement [50] of the magnetic moment of ^{11}Be. It is hoped that this can reveal the amount of configuration mixing in the ground state (halo) wavefunction.

The decay of ^{12}Be is known to go mainly (more than 99%) to the ground state of ^{12}B as shown in figure 3, see e.g. [51]. The decay of ^{14}Be might be as simple: The experimentally identified beta-delayed neutron branches, from measurements done at MSU [52] and RIKEN [53], show most decays go to an unbound state at 1.28 MeV. Theoretically it has been suggested [12] that the decays of ^{14}Be could be thought of as two spectator neutrons around a decaying ^{12}Be core, but detailed Generator Coordinate Method calculations placed the final state levels too high in energy. Shell-model calculations are consistent with the observed data [53], but then disagree with an earlier measurement of P_n-values [54]. To clarify the situation, a recent experiment at ISOLDE [55] remeasured these P_n-values and found the decay to be compatible with 100% one-neutron emission (the branch to particle bound states is less than 4% and multi-neutron emission at most contributes at the 1% level). The resulting decay scheme in figure 3 fits well with the factorization hypothesis lying behind equation (2), and one would therefore expect the beta decay of the halo neutrons to be seen in transitions at high excitation energy. These have not yet been looked at experimentally.

2.7. Other experiments

Up to now beta-decay at the neutron dripline has been studied at ISOLDE mainly for the lightest elements, the only exceptions being the exploratory study [56] of the heavy Ne isotopes and the detailed investigations of the decay of the heavy Na isotopes, see [57] and references therein. We shall end this section by mentioning experimental results for heavier elements from MSU, GANIL and RIKEN. However, none of these have so far been related to halo physics.

Halflives are now determined, although not necessarily with high precision, even for most nuclei at the dripline, see e.g. [58,59] (in the latter work P_n values were also measured). More detailed information is available for nuclei which are

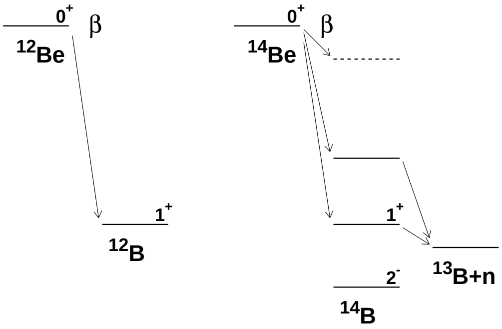

Figure 3. The beta decay of the two-neutron halo nucleus ^{14}Be proceeds mainly to a 1^+ state just above the neutron threshold in ^{14}B. The same decay pattern is found for the core nucleus ^{12}Be; this supports the factorization assumption used in equation (2). One could expect the beta decay of the halo neutrons to be reflected as transitions to high excitation energies in ^{12}B.

a few neutrons away from the dripline. Beta-delayed neutron spectra have been measured for ^{15}B [60], ^{17}B [61], ^{17}C and ^{18}C [62] and ^{19}C [63].

3. Reaction experiments

Although a wealth of structural information regarding halo nuclei has been obtained from decay studies, the complementary information yielded in reaction-type experiments is crucial to understand these systems. Until now, reaction studies have mainly been performed at high energies (10 - 1000 GeV/u) using radioactive beams from recoil separators [5], typically aimed at dissociation of the halo nucleus on various targets into its three- or two-body components. In this case, the reaction mechanism is rather clear-cut and can be disentangled by the target choice; on light targets nuclear effects (Glauber-like) dominate and on heavy targets an additional Coulomb dissociation cross section constitutes the dominating part. Typical observables are reaction cross sections, energy and momentum distributions and correlations between the constituents.

These experiments at relatively high energies have proven very fruitful, but to reach a lower energy region with sustained beam quality is not possible at a recoil separator. Thus, facilities are now under construction [64,65] where instead a low-energy radioactive beam produced in an ISOL-facility is post-accelerated. This will open up a new energy range also for reactions involving halo states.

The emerging post-accelerator REX-ISOLDE [64] will give the opportunity to exploit the rich diversity of radioactive beams already currently available at ISOLDE also for low-energy reaction experiments. To convert the singly-charged ions from the ISOLDE facility into higher charge states suitable for acceleration, a novel scheme for cooling, bunching and charge-state breeding will be employed, with a minimum total transfer time as low as 20 ms and an overall efficiency better than 10%. A recent experiment pointing towards the physics questions that can be pursued at REX-ISOLDE is the RIKEN reaction studies [66] at 64 MeV/u of

^{11}Li(p,n)^{11}Be* and ^{11}Li(d,2n)^{11}Be*. The former reaction should "mimic" both Fermi and Gamow-Teller decays, the latter only Gamow-Teller. The IAS of the ^{11}Li ground state could be identified and its width extracted. The small observed Coulomb displacement energy was associated with the large extent of the halo and the width pointed towards an appreciable $(s_{1/2})^2$ halo configuration in ^{11}Li. Both observations have been supported in detailed calculations [17].

3.1. Few-nucleon transfer reactions

REX-ISOLDE will deliver radioactive ion beams with energies between 0.8 and 2.2 MeV/u. In this region, transfer reactions by light ions, utilised since decades for stable beams and targets, become available as a tool for nuclear spectroscopy. However, when going towards the drip lines using radioactive beams, two crucial differences exist; the experiments naturally have to be performed in inverse kinematics and the beam intensities available for most interesting radioactive beams are low. This calls for a careful optimisation of the chosen reaction and the experimental set-up [67].

States that are relevant for understanding halo structure can be populated and studied also in multi-nucleon transfer reactions. In [68,69] the relation between the production cross section, the number of nucleons transferred and the Q-value of the reaction is discussed. The cross sections strongly decrease with the number of nucleons transferred, and are further diminished by the low probability of transferring a cluster consisting of only neutrons or protons. Furthermore, an increasingly negative Q-value when an exotic system is created from stable or long-lived nuclei also prohibits the reaction. For one-nucleon transfer using radioactive beams, especially one-neutron pick-up, these considerations are not as critical. One-neutron pick-up reactions are discussed in detail for several Mg-isotopes impinging on a deuteron target in [70] and some parallels are drawn to the lighter halo systems. The low neutron separation energy of the deuteron, together with the separation energy close to zero of the populated state in the exit channel, ensures that the reaction is well matched. This gives a maximum in the reaction cross section already at $E_{lab} \sim 3-5$ MeV/u. Furthermore, the signal-to-background conditions should improve, as the main selection is already made in the ISOL-separator and not after the binary reaction has taken place. Thus, few-nucleon transfer reactions using REX-ISOLDE beams can be expected to constitute a very important tool in our understanding of halo nuclei.

Currently, two experiments concerning halo nuclei are approved at REX-ISOLDE. One experiment [71] will attempt to probe the unbound subsystems of ^{11}Li and ^{8}He, the resonances in ^{10}Li and ^{7}He respectively, by one-neutron pick-up reactions. The core-neutron subsystems of two-neutron halos will in general be unbound, but they can reveal details on the interactions in the full three-body system and it is therefore important to study them. Unbound systems in the vicinity of nuclear halo states have been studied extensively using various methods [68,72–79] which concentrate upon the ^{10}Li subsystem of ^{11}Li. As seen in a recent compilation in [79], the multi-particle transfer reactions seemingly populate only p-states, whereas invariant-mass like analysis of break-up reactions at high- and intermediate energy also finds low-lying s-wave strength in the ^{10}Li system. The proposed experiment will hopefully help to clarify this situation.

3.2. Elastic resonance scattering

The second approved experiment [80] will use the "elastic resonance scattering"-method [81] to populate states above the particle-emission threshold in ^{10}Be and ^{17}N in order to extract information regarding the isobaric analogue states in the unbound nuclei ^{10}Li and ^{17}C. In this experiment, the incoming radioactive beam is directed towards a thick gas target (eg. methane) where the incoming ions are decelerated and eventually stopped. Whenever the relative energy of the decelerating ion and a proton from the gas corresponds to a resonance in the ^{9}Li+p and ^{16}C+p system respectively, the cross section for scattering increases drastically. (A direct measurement, instead of drawing conclusions via the isobaric analogous states, would naturally be preferred, but would require a neutron gas target.) This method was used successfully for neutron-deficient nuclei in [82] where states in ^{11}N were populated, see fig. 3 in [82]. Several states could be identified and the same parity inversion of the lowest resonant state is found as in the mirror nucleus ^{11}Be, which has a one-neutron halo.

For the outlined experiment with neutron-rich beams, the situation is somewhat more complicated than for ^{11}N where only $T = 3/2$ states were populated. In the case of ^{10}Be, both $T = 1$ and $T = 2$ states are populated, but only the latter are interesting. However, due to the many different decay channels open for the $T = 1$ states at high excitation energy, these states give rise to a broad contribution. In contrast, the decay of the $T = 2$ states through many of the energetically possible channels is isospin forbidden, and yield a relatively long-lived state, see fig. 4. Thus, the protons emitted from these states should form narrow peaks and a clear identification seems feasible.

4. Conclusion

Studies of halo nuclei at low energy have, so far, mainly been an ISOLDE speciality. Important information as well as constraints for the theoretical modelling has come out from optically polarized atomic beam experiments as well as beta decay experiments. The efforts here supplement the ubiquitous intermediate- and high-energy reaction experiments and will, in the near future, be extended by precision low-energy reaction experiments. We expect that ISOLDE experiments will continue to provide essential information on halo nuclei in the coming decade. Detailed decay studies of nuclei above mass 11 and

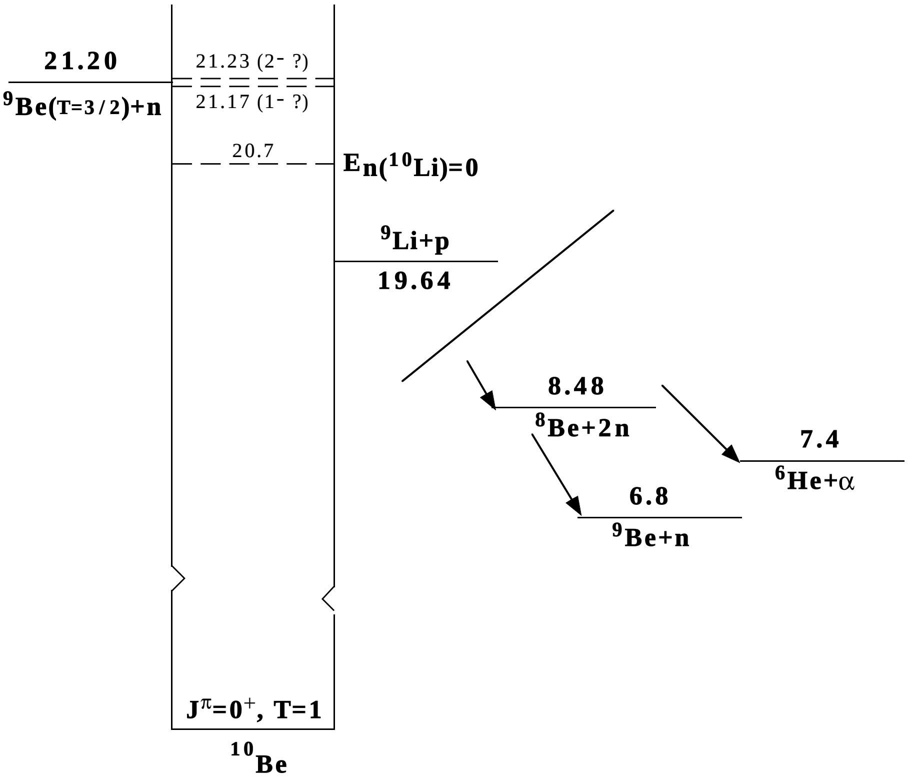

Figure 4. Schematic view of the resonance states in ^{10}Be. When populating the isobaric analogue $T = 2$ state, decays to the final states delimited by the thick line are isospin forbidden. Thus, the majority of the decays proceed through the allowed ^{9}Li + p channel, with a possibly minor contribution from the also isospin allowed ^{9}Be+n channel.

reactions probing barely bound and barely unbound states at the dripline should provide competitive data.

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