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PROPOSAL TO THE ISOLDE COMMITTEE

DECAY PROPERTIES OF THE HALO NUCLEUS ^{11}Li

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Abstract

During the past years a considerable experimental effort has been devoted to the production and study of nuclei close to the neutron and proton drip-lines. The most spectacular phenomenon encountered is the occurrence of neutron halos in the loosely bound neutron rich nuclei.

Another interesting feature, observed at ISOLDE, which most likely is connected to the halo structure, is the very strong (super-allowed) Gamow-Teller beta transitions to highly excited states which are systematically observed for the lightest neutron rich drip-line nuclei. These transitions might be viewed as arising from the quasi-free beta decay of the halo neutrons.

It is proposed to make a detailed study of the beta strength function for ^{11}Li, a nuclide having a half-life of 8.2 ms and a Q_β-value of 20.73 MeV.

So far only a lower limit of the Gamow-Teller transition rate to highly excited states ($\approx$ 18.5 MeV) in the daughter nucleus has been obtained from measurements of beta-delayed tritons (and deuterons). The corresponding total transition rates can,however, only be determined if, in addition, the energy spectrum of delayed neutrons is measured. The high energy part of the neutron spectrum will be measured by the time-of-flight method using 4 large liquid scintillators and applying pulse-shape discrimination techniques. For neutron energies below 2 MeV ^{3}He spectrometers will be used. The dynamics of the multi-neutron emission process will be studied by neutron-neutron angular-correlation measurements using an array of nine small scintillators.

Measurements with an improved detector telescope for charged particles will provide a firm determination of the beta-delayed triton branch and a conclusive measurement of a possible deuteron branch.

A beam time of 30 shifts is requested.

Introduction

During the last few years the light neutron-rich nuclei have been discussed in a large number of experimental as well as theoretical publications. The main references are quoted in ref. [1]. The most spectacular phenomenon encountered is the occurence of neutron halos in loosely bound neutron rich nuclei. Experimental evidence supporting the halo structure involve observation of extended matter radii, narrow transverse momentum distributions of both neutrons and charged fragments and measurements of spin, magnetic and electric moments. Studies of properties of halo nuclei proceed along two lines, namely through *i)* reaction experiments involving radioactive ion beams and *ii)* measurements of β transition rates to highly excited states in the daughter nucleus. This proposal concerns the β-decay properties of ^{11}Li according to point *ii)*.

i) Coulomb dissociation of halo nuclei

Most of the experimental information on the neutron halo stems from high-energy reaction experiments involving the nucleus ^{11}Li. The first evidence appeared in total cross-section measurements with 790 MeV/u lithium beams on low-mass targets, where a large increase of the matter radius of ^{11}Li was deduced [2]. This was interpreted as an effect due to the low binding energy of the the last pair of neutrons forming an extended halo. These features can be understood qualitatively in a simple phenomenological model [3] where ^{11}Li is represented as a di-neutron orbiting a ^{9}Li core. The essential ingredient is the low binding energy of the last neutrons that leads to the increase in size of the system. This interpretation was strikingly confirmed with the measurement of a narrow component of the momentum distribution of ^{9}Li, obtained from fragmentation of the ^{11}Li beam [4]. By investigating the dependence of the cross-sections on the charge of the target, Coulomb dissociation was shown [5] to be important at the heaviest targets, supporting the idea that strong electric dipole transitions occur at low excitation energies in these nuclei. This line of thought was further corraborated recently [6] with the observation of neutrons from break-up reactions of ^{11}Li at 30 MeV/u, both the large cross-sections and the narrow momentum distributions were prominent at this beam energy.

ii) Strong Gamow-Teller transition rates to highly excited states

Experimental information [1] suggests that very fast ("super-allowed") beta transitions occur systematically in the decays of light neutron-rich nuclei and with a pattern that may have interesting implications for nuclear structure. The term "super-allowed" refers to a transition of essentially single particle strength, that is with log*ft* of about 3.5, typical of decays connecting mirror nuclei and a few transitions connecting certain states in the lightest nuclei. The reduced transition probabilities B_F and B_{GT} for magnitude to the Gamow-Teller sum-rule value of 6 for a neutron pair with I=0, T=1. This behaviour may be understood semi-quantitatively from the following three models, which do not exclude each other.

(i) If all interactions in a nucleus were spin and isospin independent, the allowed beta decays would connect the members of a degenerate Wigner supermultiplet. Since the Coulomb energy shifts are of the order of some MeV in a light nucleus and the spin-dependent interaction energies are of the same order, the strong transitions seen in our experiments are close to where the supermultiplet strength should be, but they are, of course, a good deal weaker than the full sum-rule value 3(N-Z).

(ii) As mentioned above it has become clear that at the neutron drip line, and in particular for the case of ^{11}Li, the last neutron pair gives rise to the formation of a neutron halo extending far beyond the nuclear core. The reason for this is the low binding energy of this pair, which allows it to travel far from the core by quantum-mechanical tunneling. The physical separation of the halo from the core suggests that transitions involving the halo neutrons may take on their full single-particle value. For electric dipole transitions this prediction [6] has been verified experimentally in several experiments. For beta decay one would by analogy expect to observe super-allowed decay of the neutron pair to a deuteron, free or bound, and with a reduced transition probability of 6 and a decay energy of the order of 3 MeV which agrees well with the results shown in Fig. 1. Experiments to search for beta-delayed deuteron emission from light nuclei are in progress; this process was detected for the first time in the decay of ^{6}He [9] and preliminary results [10] from the evaluation of data from the ^{11}Li decay indicates the possible presence of a beta delayed deuteron branch.

(iii) Calculations by Poves et al. [11] emphasize the influence of intruder states. To simplify the argument they consider the hypothetical doubly-magic nucleus ^{28}O in a large shell-model calculation with a restricted valence space permitting proton and neutron excitations into the *fp* shell. They find that, contrary to the naive expectation, the ground state is dominated by an intruder state with one neutron pair in an I=0, T=1, $(fp)^2$ configuration and that the beta decay goes predominantly to a state at 18 MeV (the Q value is assumed to be around 20 MeV) with a neutron and a proton in the same spatial state with I=1, T=0, and with a reduced transition probability B_{GT}=6.9. They point out that the picture of a di-neutron (the halo) decaying into a deuteron again seems adequate; the energy release of about 2 MeV is similar to what is observed experimentally (Fig.1).

Summary of experimental results

The B_{GT} values for the strongly fed levels mentioned above are collected in Table 1, which also gives the excitation energies and natural widths of the levels involved. There is a strikingly similar pattern in these decays as the strong feeding in all cases goes to levels a few MeV below the Q-value, a point that we illustrated in Figure 1 which shows the experimental strength functions; the large B_{GT} values are seen to line up when the energy is measured from the <u>initial</u> states.

For the case of ^{11}Li, however, the amount of experimental information is insufficient and the proposed experiment aims at a determination of the beta strength to highly excited states in the daughter nucleus ^{11}Be.

TABLE 1

Strong Gamow-Teller beta-decay branches of drip-line nuclei.

Decay	Level Energy (MeV)	Level Width (MeV)	Emitted Particle	B_{GT}	log *ft*
$^6He \rightarrow ^6Li$	0.0	Stable	-	4.75	2.91
$^8He \rightarrow ^8Li$	~ 9	~ 1	n, t	3.14	3.09
$^9Li \rightarrow ^9Be$	11.81	0.40	n, α	5.6	2.84
$^{11}Li \rightarrow ^{11}Be$*)	~ 18.5	~ 0.5	xn, t	> 0.5	< 4

*) Only the triton branch is included in the calculation of B_{GT}.

Decay properties of ^{11}Li

^{11}Li is the heaviest drip-line nucleus which for the moment can be produced at ISOLDE in large enough amounts to allow for more detailed spectroscopic studies. It is particle stable and has a half-life of 8.5 ms [12]. It has no known bound excited states and its mass has been determined by mass spectrometry leading to separation energies for one and two neutrons of 1050 ± 260 keV and 247±80 keV, respectively [12], and to a Q-value of 20.68 MeV [12]. The large beta-decay window and the low particle separation energies in the daughter ^{11}Be give many open channels for beta-delayed particle emission: Over the years delayed n, 2n, 3n, t, α and γ have been identified. Figure 2 shows in a condensed form the present knowledge of the decay scheme [12] of ^{11}Li and the energy relations for various possible decay channels. The main features available of the beta decay are still not detailed enough to give the beta strength function, let alone the complete decay scheme. The observation of a delayed-triton branch [10,13] shows that there is a considerable strength to states at about 18.5 MeV excitation in ^{11}Be. Charged particle events [1] registered by a detector telescope consisting of a gas ΔE-detector and a silicon surface barrier E-detector show recoiling ^{10}Be and ^{9}Be nuclei from one and two neutron emission, respectively. Because of cut-off effects in the detector telescope the total intensity of these events only represents a lower limit of the delayed neutron branches deexciting levels in the 18.5 MeV region.

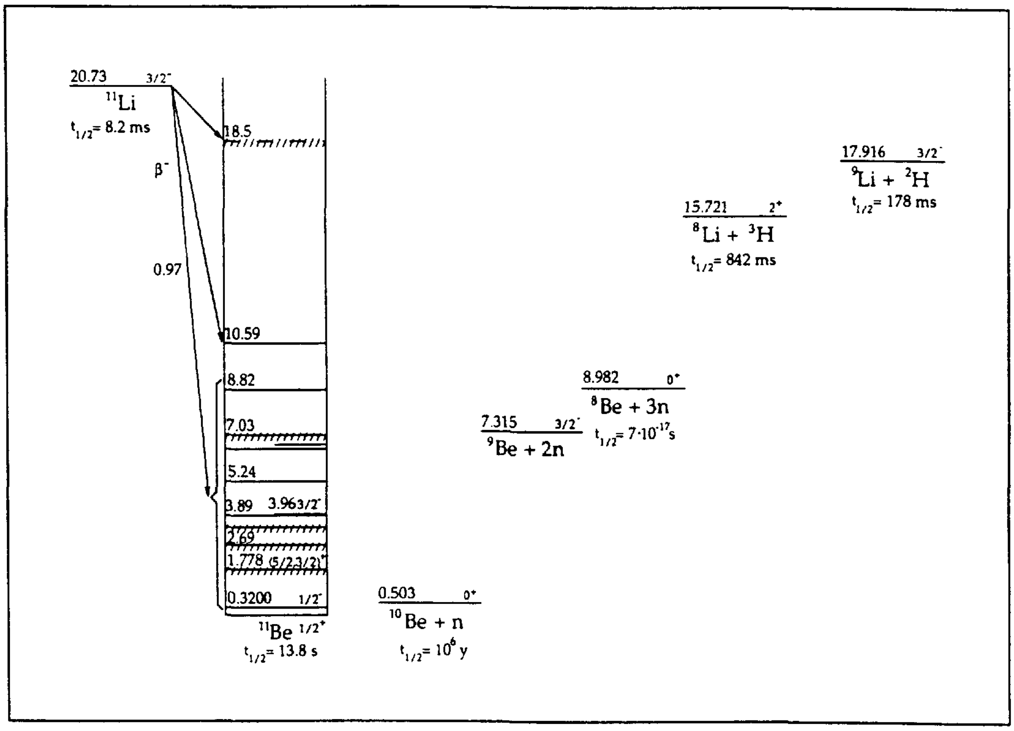

Fig. 2 Present knowledge [12] of the decay scheme for ^{11}Li and energies of possible final (or intermediate) states after different delayed particle emission processes.

The aim of the proposed experiment is to determine the absolute branching ratios for the different delayed particle branches originating from the excitation energy region around 18.5 MeV in the emitter ^{11}Be.

Gamow-Teller transition rates to broad, highly excited states

In order to extract information on the beta-feeding to excited states in ^{11}Be one has to take into account that the daughter states, after both beta decay and particle emission might be broad. Note that fig. 2 does not include the excited states, several of which are broad, of the decay products ^{10}Be, ^{9}Be and ^{8}Be after one, two and three neutron emission respectively. Also recoil effects have to be taken into account and this gives rise to a relatively complicated procedure to extract the absolute beta feeding. The analysis of the experimental data will be based on the R-matrix theory and the main ideas of the evaluation procedure are given in [14,15] and references therein. Since a complete outline of the analysis is rather lengthy we just mention the basic principle that spectral shapes and transition rates are proportional to the product of the statistical rate function, the penetrabilities for charged particles and neutrons and the shapes of the broad levels described by Breit-Wigner distributions.

Experimental techniques

The Gamow-Teller transition rate to a highly excited state ($\approx$ 18.5 MeV) in the daughter nucleus ^{11}Be can be deduced only if all the partial branching ratios for delayed particle emission are determined. Since the Q_β-value is high and the separation energies for one, two and three neutrons are low (see fig. 2) the neutron energy spectrum could be expected to have a range well above 10 MeV. Furthermore several beta-delayed charged particle emission channels are energetically possible. Of these the beta-delayed triton branch has been determined [1,13] to be 1.6 10^{-4} while at present only indications [10] of a deuteron branch exist. The general lay-out of the proposed experiment is schematically shown in fig. 3. Not included in the figure are neither the fast, thin plastic scintillation detector which will provide the start signals for the time-of-flight measurement by registering the beta particles nor the ΔE-E detector telescope for detection of the charged delayed particles and the recoiling daughter products ^{10}Be, ^{9}Be and ^{8}Be.
The experiment can be regarded as composed of four different, complementary but simultaneously performed measurements:

i) Energy measurements of charged delayed particles and recoils using a ΔE-E gas detector-telescope

ii) Time correlation measurements by utilizing the pulsed-beam structure for identification of daughter activities

iii) Energy measurements of high-energy (>2 MeV) neutrons by time-of-flight techniques

iv) Energy measurements of low-energy (<2 MeV) neutrons using ^{3}He-spectrometers

Below, the basic considerations behind each subexperiment are shortly described.

i) In a previous experiment [10] performed at ISOLDE using a low-energy detector telescope [19], consisting of a silicon surface-barrier E-detector and a gas ΔE-detector, energy spectra of charged beta-delayed particles and recoils were recorded. The energy cut-off of the telescope was around 400 keV for tritons and deuterons and 800 keV for recoiling Be nuclei and work is in progress to increase the sensitivity. With the improved detector telescope the proposed experiment will, as an extremely important result, provide a firm determination of the beta-delayed triton branch and a conclusive measurement of a possible deuteron branch.

To minimize the energy loss for low-energy charged particles the ^{11}Li ions can be collected on the entrance window of the gas detector. As an extra benefit this increases the solid angle of the telescope.

Because of the small difference in energy loss for tritons and deuterons no unambiguous discrimination between these particles can be expected from the telescope spectra. However, in combination with complementary data from the time correlation measurement (see *ii*) the problem could be solved by identifying the decay of the known beta-delayed particle emitting daughter nuclides ^{8}Li and ^{9}Li.

ii) By taking full advantage of the novel pulsed-beam structure at the ISOLDE-facility the background free period of 2.1 s between pulses will be used to study the decay of short lived daughter products. This is a powerful, alternative method to determine branching ratios. The decay characteristics of ^{11}Li makes this nucleus a perfect case for optimal application of the time correlation method.

iii) The low efficiency of neutron detection and also the moderate resolution of time-of-flight experiments make any accurate mapping of the beta strength next to impossible with present-day techniques. We nevertheless propose to take a first step, using some of the best and largest detectors that exist. This should give a useful value or a limit for the beta-decay matrix element. We feel that only if we make a first attempt can there be progress towards solving this important problem.

For neutron energies above about 2 MeV a time-of-flight method, in combination with pulse-shape discrimination, will be used. Four large liquid scintillators [18] (BC 501) of diameter 12" and thickness 2" will be placed at distances between 1 and 4 m from the source position thus subtending solid angles of 0.56, 0.14, 0.063 and 0.035 % respectively. The final detector set-up will depend on the production yield of ^{11}Li. The energy resolution will vary between 8% for a flight path of 1m and 1.5% for a flight path of 4 m if only the geometrical dimensions of the detectors are considered. The intrinsic efficiency of the detectors varies between 20% and 15% for neutrons in the energy range 2 to 10 MeV. For a study of the dynamics of the multi-neutron emission process neutron-neutron angular-correlation measurements will be performed using an array consisting of 9 small liquid scintillators (BC 501) of diameter 2" and thickness 4" placed at a distance of 0.5 m from the source position and covering an angular range of $\pm 17^{o}$.

The interpretation of the beta-delayed neutron spectra might be obscured by possible neutron emission to states, in the final nucleus, which deexcite by emission of gamma quanta. Since the liquid scintillators themselves are sensitive to gamma radiation, neutron-gamma coincidences will be simultaneously registered. For the same purpose also large volume gamma detectors could be used.

iv) For low-energy neutrons, especially those from the decay of the daughter product ^9Li, the experiment is feasible only if an alternative detection method is applied. High resolution ^3He spectrometers [16,17] will be used for the neutron-energy range up to around 2 MeV.

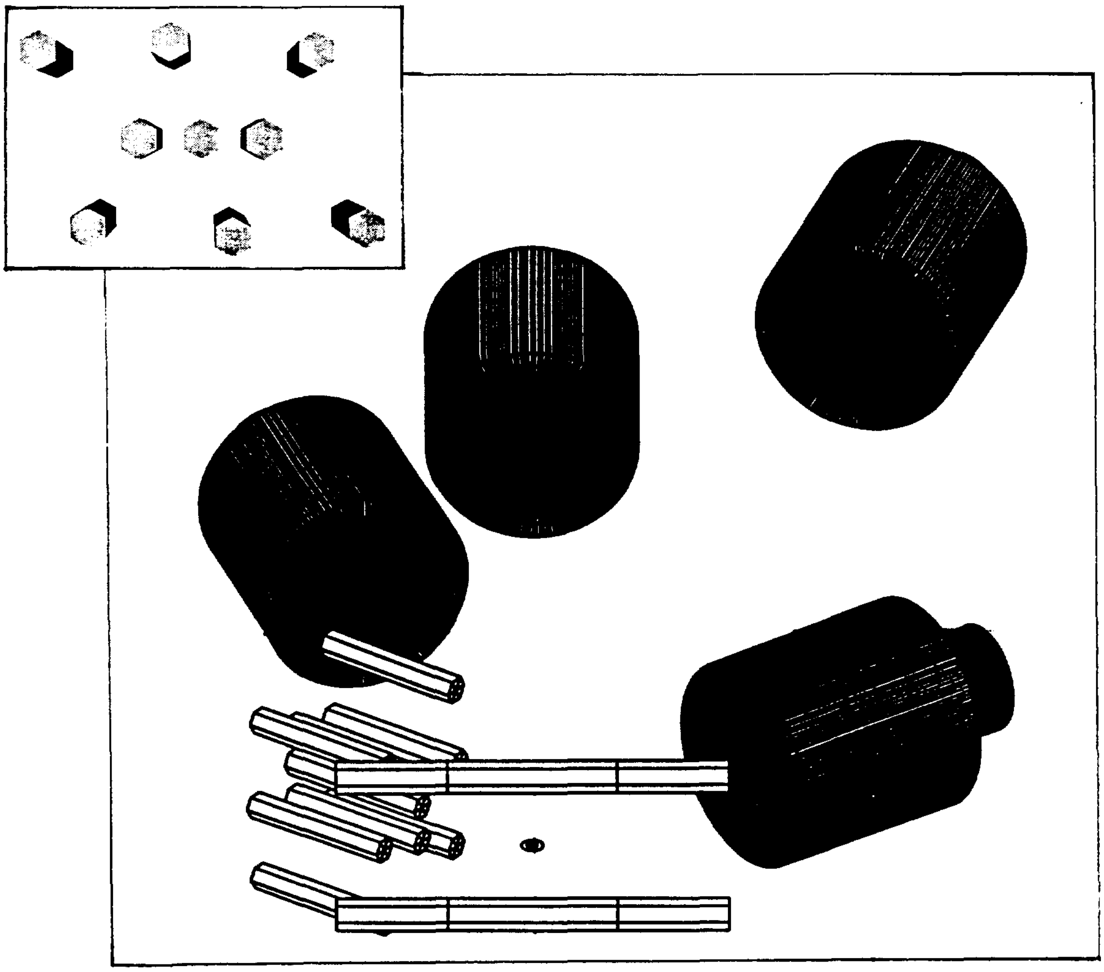

Fig. 3. Schematic view of the experimental set-up with 4 large liquid scintillators placed at distances of 1, 2, 3 and 4 m from the source position and an array of 9 small liquid scintillators at 0.5 m from the source. The inset shows the geometry of the array. The ^3He spectrometers are positioned just above and below the source. Not included in the figure are the start detector and the telescope for detection of charged delayed particles and recoils after neutron emission.

Estimate of count rates and request for beam time

For an assumed production yield of 10^3 atoms s^{-1} for ^{11}Li, with P_n = 100%, the estimated beta coincident total count rates and count rates of neutrons originating from the excitation energy region around 18.5 MeV are 28 700 and 29 respectively in one detector placed at a distance of 1 m from the source position. For the estimate a neutron branching ratio of 1 / is assumed from the excitation energy region of interest. For the neutron detector an intrinsic average detector efficiency of 17% is used while the beta detector will subtend a solid angle of 35%.
The higher proton beam energy at the new ISOLDE facility will increase the production cross section. Further, it has been shown that the pulsed beam structure reduces the delay time in the target which is of utmost importance for short-lived nuclides like ^{11}Li. It can thus be expected that considerably higher production yields than assumed above are within reach.

For the ^3He spectrometers the efficiency [16] is in the range 10^{-3}-10^{-4} for neutron energies up to around 2 MeV.

For obvious reasons the background level of neutrons in the new experimental area is unknown but the pulsed operation of the new ISOLDE facility should be an important advantage since the detectors can be gated off for the relevant time period following each beam pulse. It is important that prior to the experiment and at a conveniant period in the ISOLDE schedule to have the possibility to investigate the pulsed background conditions during a few parasitic shifts.

For data taking the ISOLDE VAX computer and the GOOSY acquisition system will be used

Based on the estimated production yield and calculated count rates a total beam time of 30 shifts is requested.

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