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Observation of the ^{11}Li(βd) decay

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and the ISOLDE collaboration

Abstract

Experimental data from the decay of ^{11}Li show for the first time the presence of beta-delayed deuterons with a branching ratio larger than 10^{-4}. To distinguish between βd and βt events the decays of the daughter nuclei ^{9}Li and ^{8}Li were identified in the energy and decay time spectra. Furthermore, a time correlation analysis between the βd events and the subsequent daughter decays was performed.

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The beta-delayed deuteron decay (βd), as observed experimentally for ^{6}He [1, 2], appears to proceed directly from the mother nucleus to continuum states. Even though rather different theoretical models have been brought into play [3, 4, 5, 6] they all conclude that the continuum states must be included if a model is to describe the data. This decay mode, of interest in itself, allows the extraction of detailed information on the spatial extent of the decaying state, and thus provides an important tool for the study of halo states [7, 8]. The present letter reports on a search for the βd process in the decay of the most studied halo nucleus, ^{11}Li. Recent theoretical calculations [9, 10] give branching ratios for this decay of order 10^{-4}, which is close to the previously observed branching ratio for beta-delayed triton (βt) decay of ^{11}Li [11]. The Q-values for the βd and βt branches are [12] 2.70 ± 0.03 MeV and 4.90 ± 0.03 MeV, respectively. Since low-energy deuterons and tritons are hard to distinguish experimentally, the βt branch will constitute the main "experimental background" for the βd events.

Some years ago decay studies of several light neutron-rich nuclei were performed at SC-ISOLDE (CERN). The most important feature of that experiment [2, 13] was a telescope detector consisting of a thin gas detector placed in front of a Si surface barrier detector that allowed the detection of low-energy charged particles. Some ^{11}Li results obtained in this experiment have already been published [14]; we show here in figure 1a the energy spectrum of charge-one ($Z = 1$) particles, i.e. tritons and/or deuterons. In spite of a large improvement compared to the older experiment [11], the presence of a tail from beta particles prevents safe conclusions to be drawn about the region below 800 keV. Since that is the region where the main part of the deuterons were expected to appear, a new experiment was needed.

For the new experiment, performed at the PSB-ISOLDE with a comparable yield of ^{11}Li, several improvements were made in the set-up. Most important, the ^{11}Li beam from ISOLDE was implanted directly into the front window of the telescope (about 250 ions per second) as illustrated in the inset in figure 1b. The solid angle of the Si detector seen from the front window was 2.5 % of 4π, the one of the beta-detector was 33 %. Careful checks (on-line with calibration sources and later off-line with monoenergetic beams of various charged particles from the Aarhus Tandemaccelerator) were made of the performance of the telescope in order to obtain a reliable energy calibration also for the lowest energies where the energy loss in the gas counter becomes large. A crucial improvement, compared to SC-ISOLDE, is that the primary proton beam at PSB-ISOLDE is pulsed (with a period of 1.2 s). We collected the ^{11}Li ions for 50 ms starting 3 ms after proton impact on the target, thus decay time analyses can be performed. A more complete description of the experiment will be published elsewhere [15]. The total energy spectrum recorded for tritons and/or deuterons is given in figure 1b. Some beta particles might appear in the polygons in the ΔE-E plot used to define $Z = 1$ events. An estimate of this background is obtained from the ^{9}Li data, where no d or t are present, and is shown as the shaded histogram; a contribution could thus be present below 500 keV. This question will be addressed in the discussion of total intensities at the end of the paper. Note that the cut-off anyway is lower than in figure 1a.

Since the energy loss curves for deuterons and tritons (see the inset in figure 4) cross at a few hundred keV, we cannot even with perfect resolution distinguish deuterons from tritons via the energy loss signal in the telescope. In order to disentangle the βd and the βt components we must invoke also the decays of the daughter nuclei, ^{9}Li and ^{8}Li, respectively. Both nuclei have large $\beta\alpha$ branches and are therefore detected efficiently in the telescope. The α-spectra are in both cases rather featureless, but peak in different energy regions. The halflives of the two isotopes are 178 and 840 ms, respectively; thus a combination of energy and time signals may allow to distinguish clearly between the two isotopes. This method of looking for daughter decays has the important advantage that a signal is obtained also for deuterons and tritons with energy below the threshold in the telescope. However, a basic complication is that the daughter nuclei due to the particle emission in many cases will get sufficient recoil energy to escape from the implantation foil again. This will occur in particular for emission of a triton, mainly due to its larger mass. The recoil energies can be estimated from figure 1. A second complication is that the beta-daughter ^{11}Be (fed in 6.4 ± 0.4 % of the ^{11}Li decays [15]) also decays through $\beta\alpha$ emission [16]. These alpha particles overlap in energy with the maximum of the alpha distribution from ^{9}Li, but appear with the ^{11}Be halflife of 13.8 s.

The time distribution of all charged particles recorded is given in figure 2. One clearly observes the ^{11}Li component with a halflife of 8.2 ± 0.2 ms, consistent with the literature value [17] (the charge-one particles alone yield a halflife of $8.9^{+0.9}_{-0.8}$ ms), and a long-lived activity to which we now turn. The energy spectrum of this component is shown in figure 3. The main feature is the two peaks below 1 MeV stemming from the decay $^{11}\mathrm{Be} \xrightarrow{\beta} {}^{11}\mathrm{B}^{*}(9875\ \mathrm{keV}) \rightarrow {}^{7}\mathrm{Li} + {}^{4}\mathrm{He}$. Their position, width and relative intensity agree with previously published data [16]. The alpha spectrum from ^{9}Li was taken from short runs performed with this isotope during the experiment, whereas the one from ^{8}Li was taken from [18]. For the latter an extra correction was applied, as most recoiling ^{8}Li nuclei will go out of the foil. Since the recoil energy can become larger than one MeV, the ^{8}Li nuclei may even be implanted rather deeply in the surrounding material. The subsequent alpha particles therefore will give lower or higher detector response than alpha particles coming from the collection point. For ^{8}Li that stop in the beta-detector the alpha particles loose more energy before entering the Si detector. For ^{8}Li that end up in the front side of the Si detector one of the two alpha particles from the decay will be recorded in the Si detector and the energy loss of the other alpha in the gas will be added, so that the spectrum is shifted upwards. (If ^{8}Li end up on the walls in the gas counter there will be very few telescope coincidences.) The ^{8}Li alpha spectrum therefore will have a double-humped structure as seen in figure 3. A fit to the energy spectrum in figure 3 was made in which the relative intensity of the three nuclei were allowed to vary, it showed clearly that both ^{8}Li and ^{9}Li were present. The χ^2-value of the fit decreased from 168.2 to 161.7 (for 239 degrees of freedom) when the ^{9}Li component was introduced. Fits where no corrections were applied to the ^{8}Li component gave the same deuteron branch within error bars, one should note also that the statistics at high alpha energies is rather low. We use the known branching ratio of the ^{11}Be decays for the absolute normalization; the final numbers will be given below.

In order to confirm the presence of a βd branch a halflife analysis was made for the various components in the spectrum. The insets in figure 2 show the time distributions for the "late events" for the energy regions up to 0.4 MeV and above 1.5 MeV. For the former the contribution from ^{8}Li should be negligible and a fit was made where the known halflives of ^{11}Be and ^{9}Li were used. For the region above 1.5 MeV only ^{8}Li is expected to contribute; a single-component fit gave a halflife of $1.1^{+8.7}_{-0.5}$ s, which is consistent with our interpretation. The fits to the energy spectrum and the time spectrum are independent, but give consistent results.

Further independent evidence for the presence of the beta-delayed deuteron branch comes from a search for time correlations between charge-one particles detected in the

^{11}Li decay and alpha particles detected within the following second. Due to our small solid angles only few such events are expected, but there is essentially no background and a very clean signal is obtained. Actually, the geometry of the set-up will suppress the detection of the decay chain for triton emission, since most detected tritons are associated with ^{8}Li that recoil out of the detector front window and out through the hole in the annular beta detector. A fraction of the recoiling nuclei are deposited close to the hole in the annular detector so that also "high" energy tritons and deuterons (for energies above 170 keV and 280 keV, respectively, the recoiling ion can go out of the window) may be seen, but a correlation analysis is mainly sensitive to the deuteron decay chain $^{11}\mathrm{Li} \xrightarrow{\beta} \mathrm{d} + {}^{9}\mathrm{Li} \xrightarrow{\beta} \mathrm{d} + \alpha + \alpha + \mathrm{n}$. The correlated events are shown in figure 4. The energy distribution of the alpha particles indicates that they come mainly from ^{9}Li. The distribution of delay times between the charge-one particles and the alpha particles has a halflife of $0.22^{+0.18}_{-0.07}$ s which indicates that a major part of the activity is ^{9}Li. It is not possible to make a quantitative analysis of the intensities without detailed tracking of the recoil nuclei (which requires knowledge of the distribution of ^{11}Li on the front window), but a rough check indicates that the number of coincidences (see figure 4) within a factor of two is the same as expected from the number of singles deuterons and tritons provided the beta-background in figure 1b is small.

We finally turn to the question of absolute intensities of the βd and βt branches. With a normalization relying on the ^{11}Be delayed particles the amount of directly produced ^{11}Be in the ISOLDE beam must be negligible or well-known. Analysis of other data taken in this experiment [15] shows no evidence for direct production of ^{11}Be within an accuracy of one percent. Cross contamination from ^{8}Li and ^{9}Li is also negligible at mass 11. Hence, absolute branching ratios may be derived directly. From figure 1b we obtain a branching ratio for deuterons and tritons with energy above 500 keV of $(1.6 \pm 0.2) \cdot 10^{-4}$. If we neglect the possible beta background in the spectrum the ratio for energies above 250 keV is $(3.9 \pm 0.5) \cdot 10^{-4}$. In ref. [11] a branching ratio for tritons above 800 keV of $1.0 \cdot 10^{-4}$ was found, we get for the same region $1.2 \cdot 10^{-4}$, which is consistent. From the data in figure 3 we get a total branching ratio for tritons of $(2.0 \pm 0.5) \cdot 10^{-4}$. For the deuterons only lower limits for the total branching ratio may be found, since the alpha energy spectrum for ^{9}Li does not agree with the previously published one[1)] [19] and we therefore cannot correct properly for the effect of the alpha threshold (at 280 keV) in the spectrum. This effect can, however, at most amount to a factor of two. The values obtained are $(1.5 \pm 0.5) \cdot 10^{-4}$ from figure 3 and $(1.2^{+0.7}_{-0.5}) \cdot 10^{-4}$ from the independent analysis in figure 2. A comparison of all data thus indicates that *i)* the beta background in figure 1b is not severe, *ii)* the triton spectrum extends below 800 keV and *iii)* the main part of the deuteron energy spectrum is most likely at low energy, perhaps extending below the deuteron threshold at 250 keV.

In summary, we have obtained the first evidence for the βd decay of ^{11}Li with a branching ratio larger than 10^{-4}. Although no definite conclusion concerning the deuteron energy distribution can be made at present, the measured lower limit of the branching ratio already excludes a sizable part of the model parameter space in the theoretical calculations. (Large radii of the p(n)-^{9}Li optical potential in [9] are excluded, as are several ranges in the d-^{9}Li potential depth parameter in [10].) The present results hopefully will

1) The "kink" in the spectrum appears at different energies (roughly 0.75 MeV). Note that the two spectra in figure 4 in [19] do not agree internally on this point. This problem will be the subject of a separate paper.

encourage further theoretical work.

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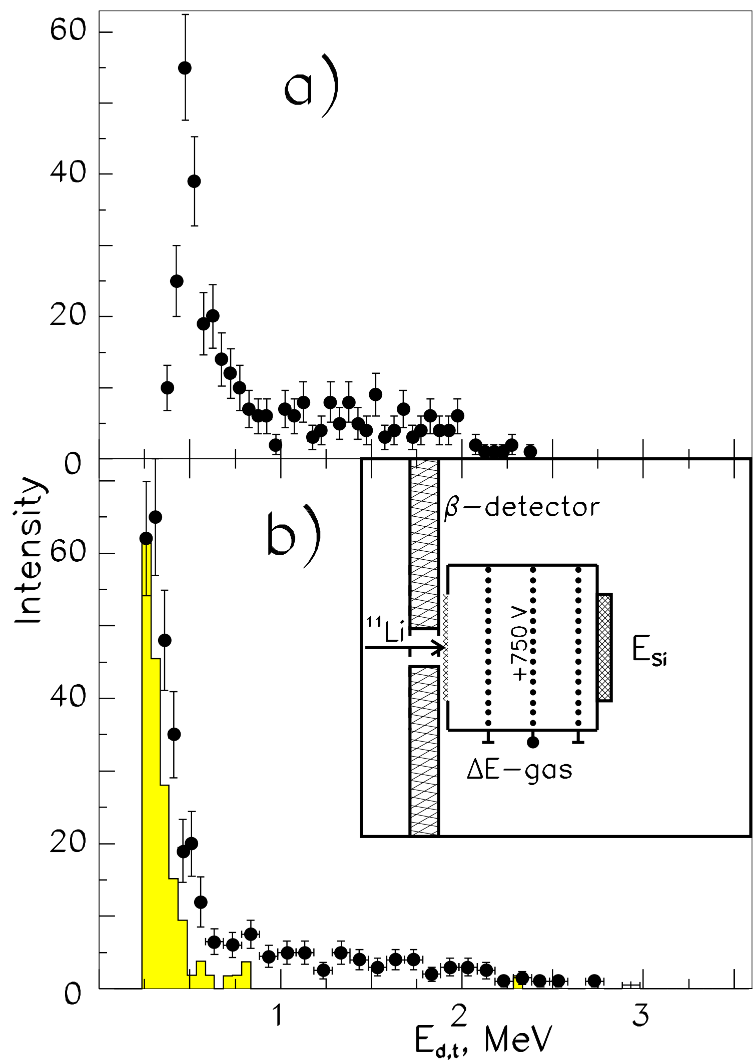
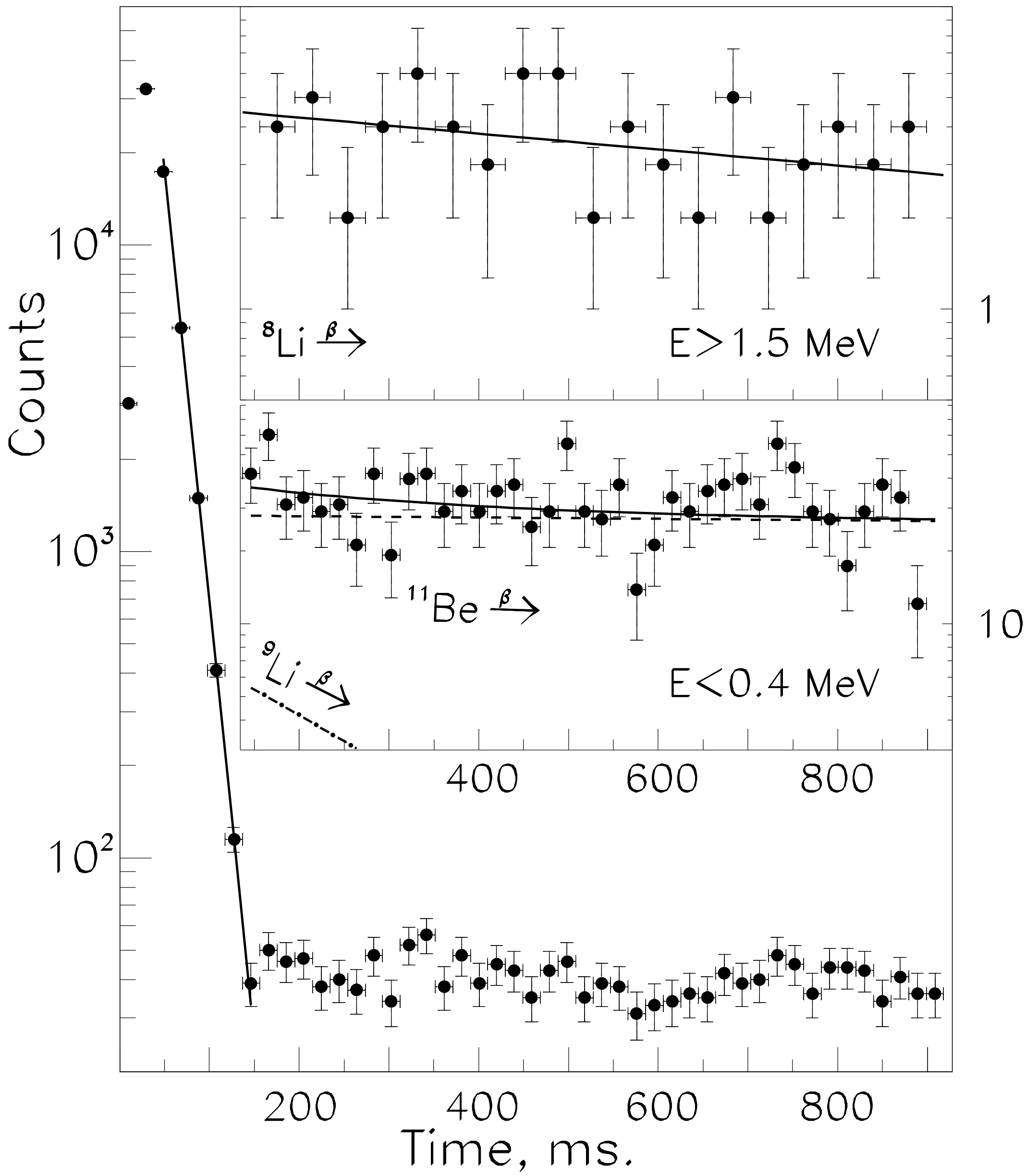


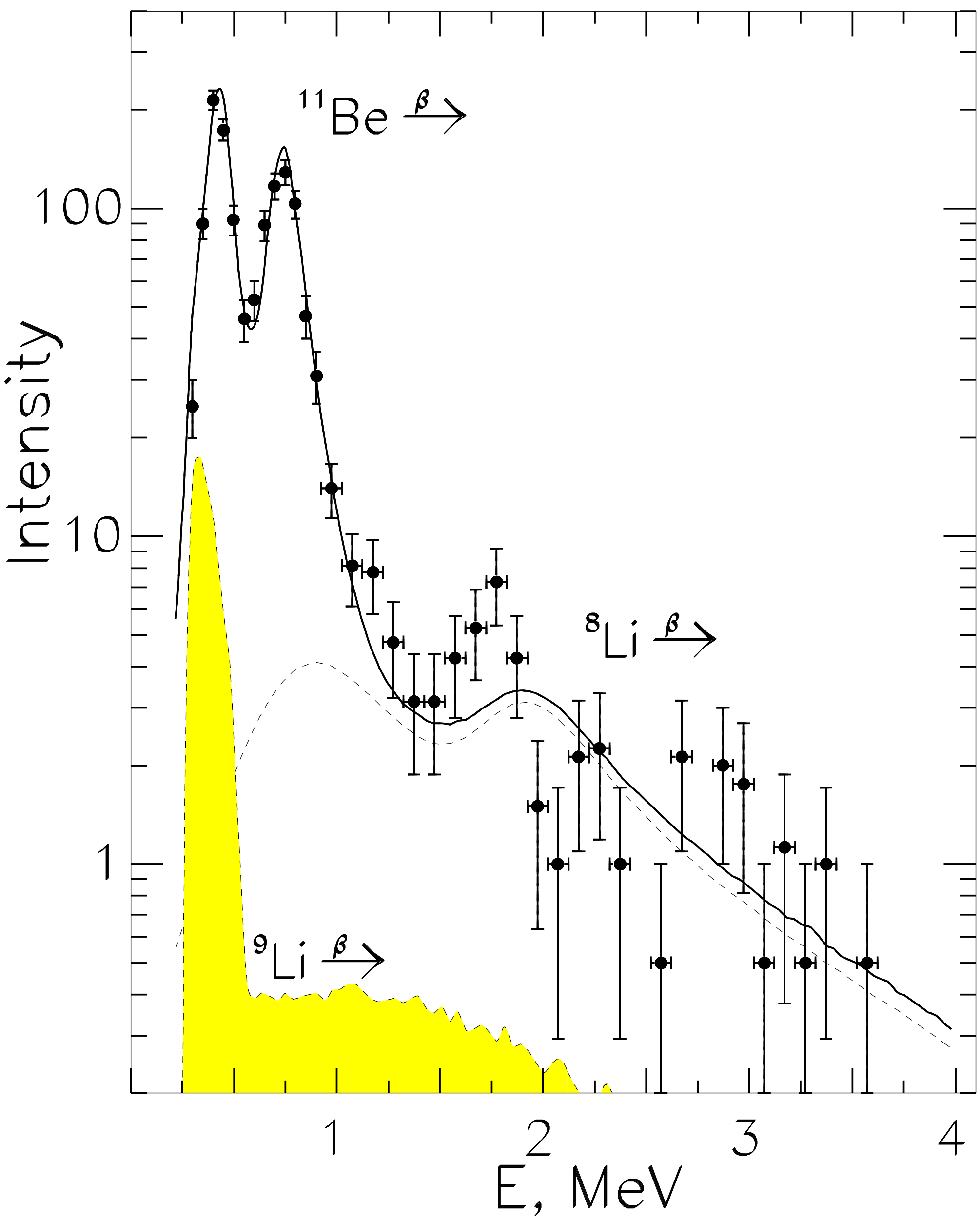
[Figure 1]

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. Note the different low-energy cut-offs. For the latter experiment a sketch of the set-up is shown as an inset. The 60 keV ^{11}Li beam passed a circular opening in the beta detector and was stopped in the 63 μg/cm^2 polypropylene window of the Gas-Si telescope. The gas detector was filled with 15 torr CF_4, the Si surface barrier detector had a thickness of 140 μm.



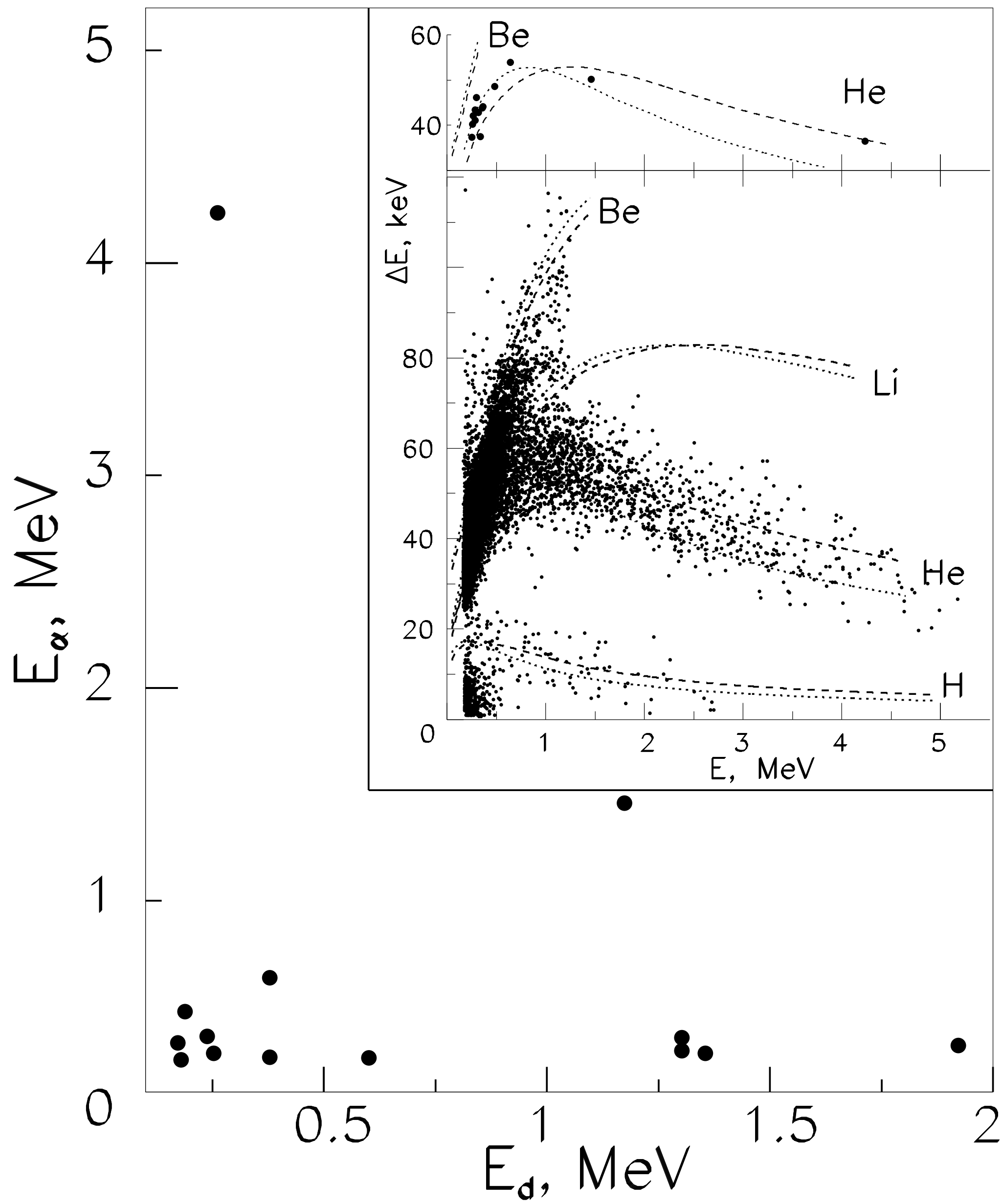
[Figure 2]

Count rate of beta-delayed charged particles as a function of time elapsed since ^{11}Li production. The main figure shows all data with a fit (solid line) to the ^{11}Li component. The two insets show the long-time distribution for two different energy regions (the energy spectrum is shown in figure 3). The solid line for $E > 1.5$ MeV is a one-exponential fit, the lines for $E < 0.4$ MeV are the result from a two-exponential fit using the ^{11}Be and ^{9}Li halflives.



[Figure 3]

Energy spectrum of $Z > 1$ charged particles corresponding to the long-time component in figure 2 (time greater than 150 ms). The solid line is a fit to the data containing the alpha and ^{7}Li particles emitted in the decay of ^{11}Be (the two low-energy peaks), the alpha spectrum of ^{9}Li (filled area) and the alpha spectrum of ^{8}Li (dashed line). See also text for details.



[Figure 4]

Energies (large dots) of correlated particles: a $Z = 1$ charged particle detected in ^{11}Li β-decay and an alpha particle (from ^{8}Li or ^{9}Li) registered from 0.15 to 0.9 s later. The upper inset shows the ΔE-E distribution of these alpha particles. The lower inset is the corresponding plot for all measured charged particles. The curves in the insets are the results of energy loss calculations for ^{2,3}H, ^{4,6}He, ^{8,9}Li and ^{9,10}Be ions entering the telescope, dotted curve for the lighter and dashed curve for the heavier isotope.