# Proton Dripline Studies at ISOLDE: $^{31}$Ar and $^{9}$C

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## Abstract

In this contribution examples of the application of new technologies to disentangle the mechanism of beta-delayed multiparticle emission are given. In particular the mechanism of $\beta$-delayed two-proton emission from $^{31}$Ar has be resolved and proved to be sequential, a preview of $^{9}$C-decay data is discussed.

## 1 Introduction

The elusive character of the two proton radioactivity, which allow for observing correlated emission of two protons from excited states fed in $\beta$-decay has caused quite some interest in the $\beta$2p decay channel. As the escape of the delayed proton pair require tunnelling through the potential barrier, the observation of energy and angular correlation between the protons could give information on the nucleon-nucleon interaction. However, this decay mode will compete with sequential emission where the first proton feeds a proton emitting state. The question of the mechanism of $\beta$2p concerns the relative importance of sequential and direct emission of the two protons.

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Due to the stability of the $\alpha$-particle and the fact that $^8$Be is unbound, the multiparticle break-up dominates the decay of very light proton rich nuclei. In the case of $\beta$-delayed multi-particle emission the nucleus breaks up into more than two particles. The kinematics of two-particle breakup is fully determined by momentum and energy observation. The main interest in $\beta$-delayed multi-particle emission is the fact that the mechanism of the break-up is not fully determined by energy and momentum conservation. As an example $^9$C $\beta$-decays to states in $^9$B that are all well above the p$\alpha\alpha$ threshold. Moreover, this decay mode is more favoured than that of $\alpha^5$Li. The mirror partner, $^9$Li has also large decay branches to n$\alpha\alpha$ final states. The latter has been fully explained in terms of sequential decays through both the $^5$He and $^8$Be channels [1], although components directly to n$\alpha\alpha$ states have also been suggested [2].

Two main features of ISOLDE have been used in this work. Firstly the fact that the radioactivity is extracted and transported to the detection setup with low energy and high beam quality. Secondly the pulsed structure of the beam with a frequency at maximum of 1.2 s/pulse. The latter allows, in case of short lived species, a determination of signal and background in the same pulse. The former makes it possible to stop the beam in a thin carbon foil resulting in a point like source and to use thin Si detectors to measure the particles emitted in the decay. We will report here on the study of the multiparticle decay modes of two proton drip line nuclei $^9$C (T$_Z$=-3/2) and $^{31}$Ar (T$_Z$=-5/2).

## Mechanisms of the $\beta$2p resolved for the decay of $^{31}$Ar

The progress in the understanding of the decay of $^{31}$Ar has come from the development and improvement in the detection system. To detect very exotic species the high efficiency of the setup is mandatory in order to compensate for the low yield. Furthermore to increase the efficiency of multiparticle detection it is necessary to use several detectors (efficiency proportional to twice the number of elements). Aiming for high granularity and large solid angle a setup was assembled to study at ISOLDE the decay of $^{31}$Ar with a rate of 3 ions/s. The set up consisted of a hemisphere of 15 Si p-i-n diodes and a 16x16 strips double sided Si strip detector, with a large area Si-detector placed behind to fully stop high energy protons and to allow for a good discrimination between $\beta$-particles and protons. With a total geometric solid angle of 25 % of 4$\pi$ divided in 271 segments ($\Omega_{2p}$=5.2 %), this setup combines excellent efficiency with good angular resolution.

To analyse the $\beta$-delayed two-proton data the multiplicity-two events were selected and the energy and positions of the two detected protons determined. Using energy and momentum conservation we then derive the recoil energy of the daughter nucleus and thereby reconstruct the full decay energy ($Q_{2p}$) of the event

$$Q_{2p} = E_1 + E_2 + \frac{m_p}{M_{^{29}P}} \left(E_1 + E_2 + 2\sqrt{E_1 E_2}\cos\Delta\Theta\right), \qquad (1)$$

where $E_i$ is the detected energy of the $i$th proton, $m_p$ is the proton mass, $M_{^{29}P}$ is the mass of the recoiling two-proton daughter and $\Delta\Theta$ is the angle between the two protons.

The recoil corrected 2p-spectrum, see [3], showed lines corresponding to individual 2p-transitions defined by their $Q_{2p}$-values. The Fermi part of the $\beta$-decay corresponds to the high energy peaks connecting the IAS with the lowest states in $^{29}$P. One can identify other peaks at lower $Q_{2p}$ corresponding to 2p-transitions from other states populated in GT-transitions, for more details in the identification and references to previous works see [3]. Notice that this is the first time two-proton emission has been observed and resolved from states fed in GT-decay.

The mechanism of two proton emission should be studied via the individual proton energy distribution and by looking to the angular dependence of the two-proton events. In sequential emission the individual proton energies depend on the intermediate state. Thus, the 1p-projected spectrum will peak at certain energies while in direct emission the proton spectrum is continuous. The angular distribution in direct emission is far from being isotropic while the angular dependence introduced by the momentum coupling in the sequential case is negligible.

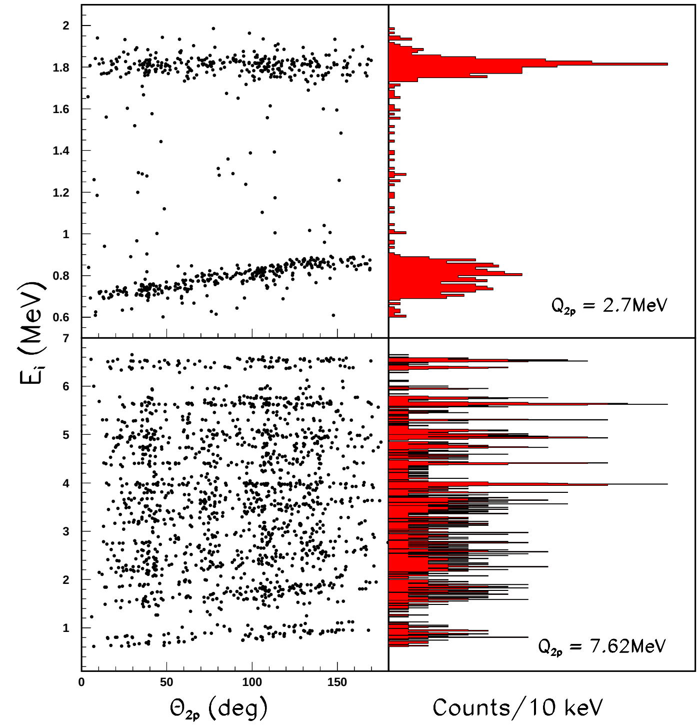

Fig. 1. Two individual proton projection spectra. On the right hand side the individual proton energies are displayed for the 2p-peaks at 2.7 MeV (top) and 7.62 MeV (bottom) center of mass energies. On the left hand side, the scatter plot of the energy of the same individual proton peaks versus the two-proton opening angle is shown. One can identify the second proton peak by its cosine dependence.

Fig. 1 shows the distribution of individual proton energies for two of the 2p-peaks. The upper half corresponds to the 2p-transition from a GT-fed state in $^{31}$Cl at 7.36 MeV ending in the g.s. of $^{29}$P. The bottom half display the distribution for the transition between the IAS and the ground state in $^{29}$P. In both cases the first proton is the one of higher energy, the second one is identified by its angular dependence (eqn. 1) as shown in the left part of the figure. The individual proton distributions confirm the mechanism as sequential and allow us to derive information about excited states in $^{30}$S.

## The case of $^{9}$C

The beta decay of $^{9}$C has been studied previously [4], comparison of mirror transitions in the A=9 chain shows unusual large asymmetries. An asymmetry value ($\delta = (ft)^{+}/(ft)^{-} - 1$) of $1.2 \pm 0.5$ is determined [1,4] in the decays to the $5/2^{-}$ states at excitation energy $\sim$2.4 MeV. The large uncertainty in the $\delta$ value mainly arises from incomplete knowledge of the $^{9}$C decay. A potentially larger asymmetry — and a much more interesting one — seems to exist in the decays to highly excited states at $\sim$12 MeV excitation energy fed with branching ratios of 2–3 %. The transition has been investigated in detail for $^{9}$Li and has [1] $B_{GT} = 5.6 \pm 1.2$. Only a lower limit on $B_{GT}$ value is given in [4] for the corresponding transition from $^{9}$C.

The possible asymmetry for the decay to the states around 12 MeV is interesting not only due to the fact that the individual $B_{GT}$ values are large (with large overlap in wave-functions, an unambiguous interpretation is much easier made), but also due to the special role played by this transition for the $^{9}$Li decay. It seems to belong to a class of high-$B_{GT}$ transitions observed [6] at the neutron drip line and has been suggested to be due either to a lowering of the giant Gamow-Teller resonance [5] or to the occurrence of "two-neutron → deuteron" transitions [6]. Knowing whether the mirror transition on the proton rich side has a similar strength would help greatly in identifying what causes the large transition strengths.

Using as in the case of $^{31}$Ar a CaO target, the $^{9}$C nuclei were extracted via the $A = 25$ CO$^{+}$ sideband. The beam of $^{9}$C ions was passed through a hole in an annular detector and implanted in a thin carbon foil (for details of the setup see [7]). When the $^{9}$C nucleus decays, the excited daughter nucleus $^{9}$B break into three charged particles: a proton and two $\alpha$-particles. These three particles were measured in coincidence. The sum of the three measured energies gives directly the excitation energy in $^{9}$B. The energies and angles of all fragments were measured in order to obtain the p$\alpha\alpha$ correlations. It has been possible to identify and determine the branching of each individual decay channel of the 12 MeV state. For the absolute normalization, the feeding to the $^{9}$B ground-state has to be determined, this part of the analysis is in progress.

## Summary and outlook

The studies presented here show the potentiality of the new technologies that allow to design setups with high efficiency for multiparticle detection. This fact in combination with high purity sources (ISOL-technique) and the use of low energy beams to produce point-like sources allows to extract information at the drip line of comparable quality to the one obtained near stability. A new era opens up with the low-energy radioactive beam facilities, where the same technique can be applied to other nuclei with difficult ionization properties.

## References

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