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# Beta-decay and exotic nuclei

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**Abstract.** Selected examples are given of how beta-decay can provide information on nuclei far from the line of beta-stability. Emphasis is put on beta-delayed particle emission, in particular processes with emission of several particles. The physics questions addressed include halo nuclei and multi-particle emission mechanisms. Muon capture on radioactive nuclei is discussed as an alternative way of accessing the region of high excitation energy.

**PACS.** 23.40.Hc Relation with nuclear matrix elements and nuclear structure

## 1 Introduction

A recent review [1] and a dedicated workshop [2] discuss the beta-decay of exotic nuclei in detail and I refer to them, as well as to other contributions to this conference, for a complete overview of how beta-decay presently contributes to our knowledge in nuclear physics, weak-interaction physics and nuclear astrophysics. Here I shall discuss beta-decay mainly for nuclei rather far from stability; essentially, only nuclei where beta-delayed particle emission plays a prominent role and continuum degrees of freedom therefore become important. At the end I shall discuss one way of going beyond the limitation set by the $Q_\beta$-values (a limit that is less severe far from beta-stability), namely the recently considered possibility of having muon capture on radioactive nuclei.

## 2 Beta-delayed particle emission

As a first step, let us look briefly at the energy relations in beta-delayed particle processes.

The $\beta^-$-delayed emission of $i$ neutrons from the nucleus ${}^AZ$ has a $Q$-value

$$Q_{\beta^- i\mathrm{n}} = Q_{\beta^-} - S_{i\mathrm{n}}({}^A(Z+1)) = Q_{\beta^-}({}^{A-i}Z) - S_{i\mathrm{n}} \; , \quad (1)$$

where the last expression involves the separation energies of the mother nucleus and the $Q$-value of a lighter isotope. A related formula applies to $\beta^+$-delayed emission of protons: replace $Q_{\beta^-}$ by $Q_{\mathrm{EC}}$ and use $Q_{\beta^+} = Q_{\mathrm{EC}} - 2m_e c^2$. The $Q$-value for other delayed particle emissions can be rewritten in the general form

$$Q_X = c - S \; , \quad (2)$$

**Table 1.** Parameters of eq. (2) for a nucleus ${}^AZ$.

| $X$ | $c$ (MeV) | $S$ |
|---|---|---|
| $\beta^-$p | 0.782 | $S_\mathrm{n}$ |
| $\beta^-$d | 3.007 | $S_{2\mathrm{n}}$ |
| $\beta^-$t | 9.264 | $S_{3\mathrm{n}}$ |
| $\beta^-\alpha$ | 29.860 | $S_{4\mathrm{n}} + Q_\beta({}^{A-4}(Z-1))$ |
| EC d | 1.442 | $S_{2\mathrm{p}}$ |
| EC ${}^3$He | 6.936 | $S_{3\mathrm{p}}$ |
| EC $\alpha$ | 26.731 | $S_{4\mathrm{p}} + Q_{\mathrm{EC}}({}^{A-4}(Z-3))$ |

where the constants $c$ and "separation energies" $S$ for the different processes are collected in table 1 (all separation energies refer to the mother nucleus ${}^AZ$; for delayed $\alpha$-emission a $Q$-value for the final nucleus enters). The determining factor for all the beta-delayed processes are the nucleon separation energies $S_{iN}$, and the processes will therefore occur preferentially in nuclei close to the driplines. The proton-neutron mass difference makes decays of neutron-rich nuclei energetically more favoured. The Coulomb barrier will also favour multi-neutron decays to corresponding multi-proton decays.

Figure 1 shows the nuclei for which beta-delayed emission of $i$ nucleons (up to four) is energetically allowed. The relevant $Q$-values are calculated from the masses tabulated in [3], but even though we lack data for neutron-rich nuclei (except for the very light ones) one clearly sees the larger possibilities at this side of the beta-stability line. Having a positive $Q$-value does not imply that a process occurs, in particular for multi-particle decays when the decay mechanism is sequential. The branching ratios for the exotic decay modes will also be small since these decays go to highly excited states, but the beta-decay matrix

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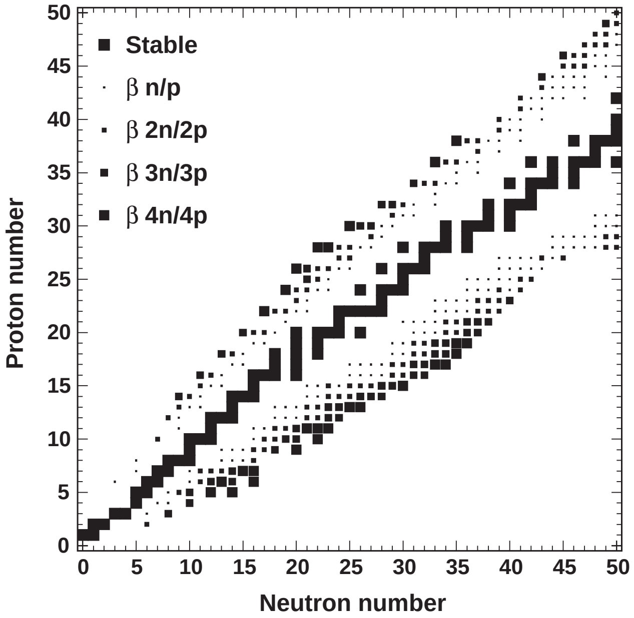

**Fig. 1.** Large squares denote beta-stable nuclei. Smaller squares mark nuclei for which beta-delayed emission of up to four nucleons is energetically allowed. The $Q$-values are calculated from the masses tabulated in [3].

elements will tend to be larger at high excitation energy (in some cases, *e.g.*, very proton-rich nuclei, one can reach the Gamow-Teller giant resonance) and it is therefore important to be able to detect these decays experimentally.

Many examples are known of beta-delayed alpha, one-proton or one-neutron emission. Apart from this, we have so far for proton-rich nuclei only seen eight cases of $\beta$2p emission. Earlier indications for the $\beta$3p decay in $^{31}$Ar have been shown [4] to be wrong. For neutron-rich nuclei more decay modes have been seen [3]: $\beta$2n has been seen in 15 cases, $\beta$3n for three nuclei ($^{11}$Li, $^{17}$B and $^{31}$Na) and $\beta$4n for $^{17}$B. However, it would be reassuring to get a confirmation of the observation [5] of the $\beta$4n branch since some of the multi-neutron branches determined in that experiment recently [6] were shown to be wrong. On top of this, $\beta$d emission is seen in $^{6}$He and $^{11}$Li, and $\beta$t emission in $^{8}$He and $^{11}$Li. Due to the very small $Q$-values that will lead to extremely small branching ratios, it seems unlikely that we will be able to see $\beta^-$p and EC d at the present generations of radioactive beam facilities, except for the case of the halo nucleus $^{11}$Be where $\beta^-$p could be hoped for [7] to have a branching ratio of about $10^{-8}$. The remaining process, EC $^{3}$He, might be measurable for some of the very proton-rich nuclei, but again a quite low branching ratio should be expected.

For beta-delayed multi-particle decays the particle emission could take place sequentially or simultaneously in a more or less correlated manner. So far most efforts have been spent on beta-delayed two-proton processes and all decays analysed up to now are consistent with being sequential. The most detailed investigations have taken place for $^{31}$Ar [8], the only case where two-proton decays have been seen from states fed in Gamow-Teller transitions (otherwise only decays from the isobaric analogue states are seen). I shall not touch upon the theoretical description of the decays here, but refer to [1] and to the contribution by Grigorenko (this issue, p. 125).

So far beta-decay is very competitive to nuclear reactions in extracting information on particle-unbound resonances in unstable nuclei. An example is the decay of $^{31}$Ar [8], where states in $^{30}$S could be seen through the two-proton decay branches. Resonances that can be reached from a ground state, *e.g.* via transfer, will in the future probably be seen better in reaction experiments at SPIRAL or REX-ISOLDE, but beta-decay will remain interesting far from beta-stability where for many emitted particles the nucleus is left in an excited state.

## 3 Light (dripline) nuclei

In this and the following section I shall give a few examples of the physics questions that have been addressed using beta-decay, and shall start with the very light nuclei close to the driplines. This is where the halo structure has been observed so far in nuclei. Beta-decay in halo nuclei has been reviewed recently [9] and I will here only report on recent activities.

It could be useful to base the discussion on the following simplified model. Let $\mathcal{O}_\beta$ be the beta-decay operator. In the approximation where the halo state factorizes into a core and a halo part, the beta-decay becomes

$$\mathcal{O}_\beta\left(|\mathrm{core}\rangle|\mathrm{halo}\rangle\right) = \left(\mathcal{O}_\beta|\mathrm{core}\rangle\right)|\mathrm{halo}\rangle + |\mathrm{core}\rangle\left(\mathcal{O}_\beta|\mathrm{halo}\rangle\right) . \tag{3}$$

For GT transitions at low excitation energy the first term alone can give states of good isospin (due to Pauli blocking), but at higher excitation energy the final states most likely will have to contain both terms in order to have the correct isospin, see, *e.g.*, [10]. There is so far very little experimental work on the isospin purity and halo states; low-energy reactions will hopefully be able to improve the situation in the coming years.

A nucleus that seems to match this simple model very well is $^{14}$Be. It decays mainly to a low-lying $1^+$ state (see [6] and references therein) just as $^{12}$Be, the only difference being that the final state is the ground state in $^{12}$B and a neutron unbound excited state in $^{14}$B. With the "core" decays being so similar, the interest naturally turns to the highly excited states. Somewhat surprisingly a recent experiment, see fig. 2 and the contribution by Bergmann, find very little strength. This is quite different to the case of $^{11}$Li and lighter nuclei [11].

Resonances in light nuclei tend to be quite broad and the spectra of beta-delayed particles will then become continous and often almost featureless. An extreme example of this is given by the $A = 9$ nuclei. Recent experiments at TISOL [12,13] and ISOLDE [14] have succeeded in measuring the beta-decay of $^{9}$C that in all cases goes to a $p\alpha\alpha$ final state. The present data indicate a surprisingly large asymmetry to the mirror $^{9}$Li decay in strong transitions to excited states at about 12 MeV, see the contribution by Tengblad for details (poster contribution, to be

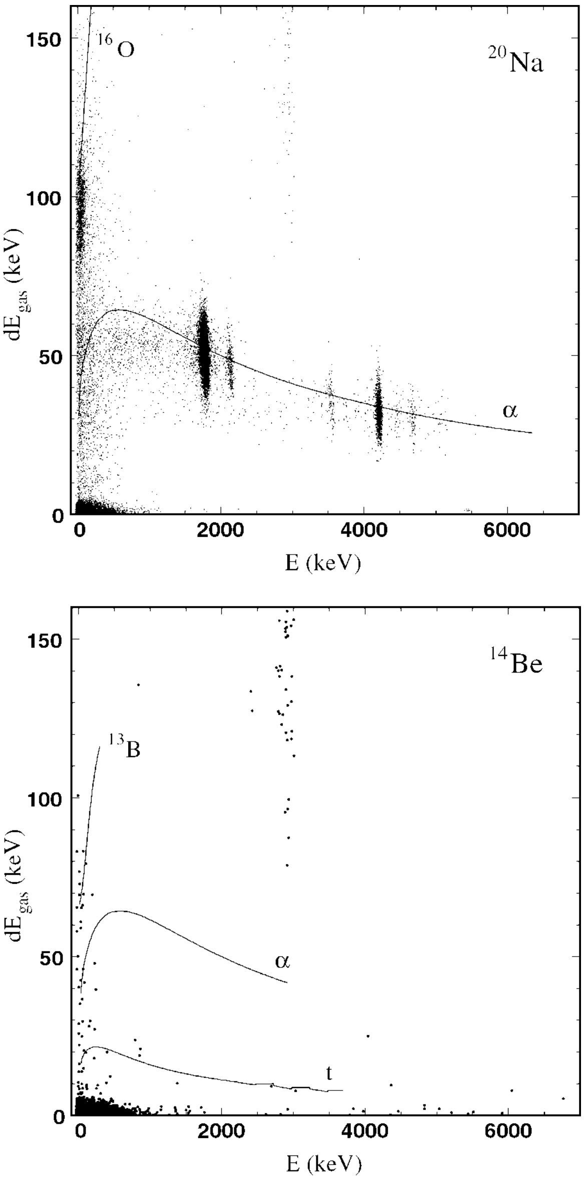

**Fig. 2.** Energy loss in a gas counter plotted *versus* the recorded energy in a following Si detector. The top part shows $^{20}$Na data, full lines are energy loss curves for alpha-particles and the recoiling $^{16}$O. The bottom part shows $^{14}$Be, including also the triton energy loss curve. Only a few counts are observed, corresponding to a quite limited $B_{\mathrm{GT}}$ strength.

published in *Exotic Nuclei and Atomic Masses* (Springer-Verlag, Heidelberg, 2002)).

## 4 Heavier nuclei

Detailed beta-decay experiments combined with good shell model calculations can give important spectroscopy information. A prime example of this is the neutron-rich nuclei around and above $N = 20$, where the structure is heavily influenced by the presence of 2p-2h intruder states. An ongoing program has recently given more details on the decays of $^{34,35}$Al [15] and $^{33}$Na [16] and thereby indicated a $7/2^{-}$–$3/2^{+}$ crossing in the low-lying structure of the $N = 21$ isotones.

Among the recent investigations of proton-rich nuclei one should note the first mapping [17] of the decay scheme of $^{35}$Ca, a $T_z = -5/2$ nucleus with a decay pattern parallel to the one of $^{31}$Ar mentioned above. Due to the many available decay channels the decay of the IAS is highly fragmented and does not presently allow for a final check of isospin mixing, *i.e.* the spread of the Fermi strength. This would be quite interesting to test when higher intensities of these isotopes become available.

When comtemplating the potential power of future radioactive beam facilities, it can be quite sobering to go back to the very first ISOL installation [18], 50 years ago. In this experiment (whose history is retold vividly in [19]) Kr isotopes produced by fission of uranium were separated on-line. Quantitative measurements were performed out to $^{91}$Kr, five neutrons more than the last stable Kr isotope, but activities were observed also at mass numbers 92 and 93. At ISOL facilities one has gone many neutrons further out in Rb, but until recently data for the heavy Kr isotopes only existed out to $^{94}$Kr (two radiochemical measurements on $^{95}$Kr has turned out to be wrong). A new ISOLDE experiment, see the contribution by Weissman (*i.e.* Catherall *et al.*, poster contribution, to be published in *Exotic Nuclei and Atomic Masses* (Springer-Verlag, Heidelberg, 2002)), has now given the half-life and $P_{\mathrm{n}}$ value out to $^{98}$Kr, twelve neutrons out from stability. We now reach out twice as far as at the first ISOL, but still have about twenty neutrons to add before we are at the dripline.

There are good physics reasons for trying to reach further out towards the neutron dripline, one of them being that this is where the astrophysical r-process takes place. The beta-decay properties of these nuclei is quite important for the understanding of the r-process and dedicated efforts during the last decade has already led us towards a more consistent picture. See the review [20] and the contribution by Fogelberg (this issue, p. 181) on the $^{132}$Sn region (as well as the nuclear astrophysics section contributions).

## 5 Muon capture

The strong energy dependence of the beta phase space factor implies that branches to states at high excitation energy will have a low branching ratio even though the matrix elements there normally are substantially larger than those to low-lying states. With $Q$-values that in most cases are lower than 20 MeV this limits the range that can be accessed through beta-decay. Some nuclear reactions can under certain conditions be used instead of beta transitions (the effective operators can be very similar) and will not be restricted in excitation energy. Another possible way of going beyond the $Q_\beta$-limit, but now still working with the weak interaction, is to employ muon capture. This process is very similar to electron capture, but gives a much higher available energy in the final state due to the muon mass of 105.658 MeV/$c^2$.

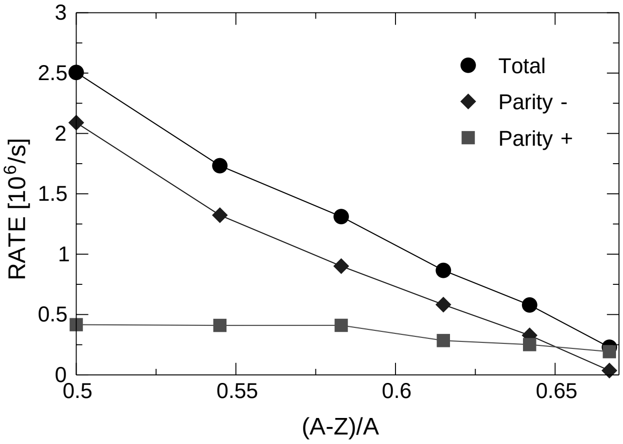

**Fig. 3.** The calculated [24] muon capture rate of $^A$Ca, $A = 40, 44, 48, 52, 56, 60$. Note the change of slope of the total capture rate at $^{44}$Ca. Partial capture rates to final states of positive and negative parity are also shown.

The many experiments on muon capture on stable isotopes are reviewed in [21,22]. It is well known that several multipoles contribute to the capture and that a broad range of excitation energies is reached, with an average excitation energy of 15–20 MeV. Recently, discussion on muon capture on radioactive ions have started, triggered by the plans at CERN of a high-intensity proton linac [23] for a muon neutrino "factory", but potentially including upgrades both of ISOLDE and the AD facility. A one-day workshop at CERN in February and a one-week workshop at ECT*, Trento, in May have served as focussing points for this discussion. I shall here only touch upon the physics implications of muon capture and refer to other contributions for more details.

Muon capture experiments will be hard and the experimental signatures will depend on the approach chosen. Once muons and the ions are at low relative velocity, atomic capture can occur. Auger transitions will dominate at first in the atomic cascade and give a highly charged ion (a potential signature in a trap or storage ring environment), muonic X-rays will be emitted at the end of the cascade and can also be used as experimental signal. Nuclear capture will then occur with a rate that for stable atoms above Na is larger than the natural muonic decay rate. The muon neutrino will on average take most of the energy and give a recoil daughter nucleus with a kinetic energy of some tens of keV for $A \approx 100$. The daughter nucleus is normally highly excited and will emit neutrons, gammas and sometimes also protons, alpha-particles etc. These radiations can be used to infer properties of the nuclear capture reaction.

An example of the physics that can be accessed in muon capture is given by the theoretical calculations of capture on neutron-rich Ca isotopes [24], see fig. 3. Due to the filling of neutron orbits the capture, that takes place mainly by "first forbidden" transitions for $^{40}$Ca, will gradually evolve so that "second forbidden" transitions will dominate for very neutron-rich isotopes such as $^{60}$Ca. The changes in rate will depend on how the nuclear structure evolves. Since highly excited states can be reached, the capture is dominated by transition to the giant resonances and their evolution can also be probed in experiments with high solid-angle coverage. The question of quenching of the different multipoles can also be addressed; capture on the proton-rich nuclei where allowed strength can be probed could be very informative.

Some of the isospin change in capture rates can already be probed in elements where the stable isotopes cover a large mass range. Only a limited range has been investigated so far [21,22] except for the very light nuclei. For the calculations mentioned above a measurement of muon capture on $^{48}$Ca might already suffice to test if the so-called Primakoff sum rule can be used to extrapolate capture rates from stable nuclei to very neutron-rich ones. (The prediction [24] is that the rates will be higher than a simple extrapolation from $^{40,44}$Ca, see fig. 3.) Experiments using enriched targets are on the way at PSI [25] and might give us a preview of what future radioactive ion beam facilities will offer.

## 6 Outlook

I have only been able to touch upon a few of the ways beta-decays can enrich our knowledge about exotic nuclei. With the improvements in experimental techniques we have seen over the last years and the promises of higher intensities of radioactive beams —even of qualitatively new probes such as muon capture— at the next generation of facilities, we can expect to learn much more about exotic nuclear structures through beta-decay in the coming years.

I would like to thank my coworkers in experiments at ISOLDE and elsewhere for many valuable physics discussions.

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