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BETA-DELAYED PARTICLE EMISSION FROM NEUTRON-RICH NUCLEI

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1. INTRODUCTION

The first neutron-rich radioactivity to be discovered was ${}^6\text{He}$ with a half-life of 0.8 s, produced and studied in the (n, α) reaction on ${}^9\text{Be}$ by Bjerge and Broström¹ in 1936. A wider field was opened up when medium-weight neutron-rich isotopes formed in neutron bombardments of uranium were identified by Hahn and Strassmann² in 1939, an observation that signalled the discovery of fission³ and the birth of modern nuclear physics. Already the same year, Roberts et al.⁴ reported that uranium continued to emit neutrons for one to two minutes after the end of an irradiation with neutrons; they suggested that the neutrons were caused by, or accompanied, beta and gamma radiation with the same period, about 13 s—an interpretation that turned out to be correct. It was soon realized that the beta-delayed neutrons are observed with the beta half-life of the mother isotope (the ‘precursor’), and that the neutron emission occurs from excited states in the daughter nucleus (the ‘emitter’). This process is illustrated in Fig. 1.

The extremely neutron-rich isotopes remain a major experimental challenge in the current research on far-unstable nuclei. It is certain that a very large number of unexplored neutron-rich

Fig. 1 Schematic level scheme illustrating the beta-delayed emission of one and two neutrons. The beta decay intensity is, apart from well-known phase space and Coulomb corrections, determined by the reduced beta transition probability S_β per unit interval of excitation energy. This quantity, called the strength function, see subsection 3.1, is strongly influenced by the two giant resonances: the isobaric analogue state (IAS) and the Gamow–Teller giant resonance (GTGR). For neutron-rich nuclei, both are situated outside the window of observation, and the tail of the latter leads to an enhancement of the intensities of the beta branches to high-lying levels. The arrows indicate the possible decay routes of excited states that exceed the binding energy of one or two neutrons.

isotopes exist, but we seem to lack the experimental tools for producing and observing them. In all but the very lightest elements the limit of prompt neutron instability, usually referred to as the ‘drip line’, appears to be completely out of reach. The situation is analogous to that prevailing in the region of the heavy elements, discussed in Chapter 9 of this book. In this region, the element $Z = 109$ has been reached, and one has gained confidence that the shell stabilization associated with the predicted ‘superheavy’ elements has begun to set in. Consequently, a large number of unexplored, but probably next-to-inaccessible, heavy isotopes must exist.

In the last few years there has been much progress in the methods for producing and studying very neutron-rich nuclei. This, in turn, has given many new physics results, among which we note the discovery of extreme decay modes such as beta-delayed emission of two and three neutrons, of tritons, of alpha particles, and of ${}^6\text{He}$; and there is also great progress in the study of neutron and photon spectra, spins, magnetic and electric moments, and charge radii of very short-lived and rare species. This research is the subject of the present chapter.

We begin by a brief outline of the limits to stability and of the experimental techniques that permit the approach to these limits. The process of beta-delayed emission of a single neutron is presented in Section 3, beginning with some of the main theoretical ideas that enter into the interpretation of neutron spectra such as the beta strength function and the concept of Porter–Thomas fluctuations. Following this, selected examples of decays by single-neutron emission are presented. Section 4 deals with the rare particle decay modes of neutron-rich nuclei: the beta-delayed emission of two and three neutrons, of tritons, and of alpha particles. Finally, we give in Section 5 examples of the physics emerging from studies of extremely neutron-rich nuclei.

The literature on delayed-neutron emission and neutron-rich nuclei is extensive, and any detailed referencing here would completely exceed the format of the present paper, which can only attempt to present the general picture and selected examples of recent work. Extended tabulations of experimental data on delayed-neutron precursors have been given on several occasions,^{5–8} and much additional information on new results and their interpretation can be found in or traced through the proceedings of recent conferences on far-unstable nuclei^{9–12} and recent specialized review papers.^{13–17}

2. THE LIMITS TO STABILITY

The study of nuclei away from the line of beta stability allows the experimentalist to observe decay modes (high excitation energies, particle decays) that are not encountered near the valley of beta stability. It also offers a new dimension in our understanding of nuclear structure, and selected data points in new regions of the nuclear chart not only provide additional insight but also help to see the old data in a fresh light. A good example of this is the phenomenon of reinforcing shell and subshell effects (see, for example, Ref. 16). An even more exciting possibility is that the structure of very neutron-rich nuclei is qualitatively different from that of nuclei near stability. There is experimental evidence that pairing is weakened significantly for large values of $N - Z$, and there are indications that neutron-rich nuclei may develop ‘neutron haloes’, possibly with a tendency towards neutron clustering. We shall touch on this subject in Section 5.

In the present section we address the question of the experimental tools and their inherent limits. The most basic limit is clearly the one at which prompt instability to particle emission sets in, but in many cases the experimental production cross-sections go to zero long before this limit is reached. As pointed out in the introduction to the present chapter, the heavier neutron-rich nuclei form a large, inaccessible region of this kind, and another example is probably provided by the proton-rich doubly-magic isotope ${}^{100}\text{Sn}$ discussed by Roeckl and Schardt in Chapter 1 of this book. A practical limit to the permissible degree of experimental sophistication is set simply by production rates; many products are formed in such small amounts that only the most simple characteristics are measurable.

Not all experiments are based on the detection of the radiations from radioactive nuclei formed in the experiments. Other techniques based on direct detection, such as mass spectrometry and recoil analysis, have been known for a long time and have especially served for measurements of reaction cross-sections. They are now of increasing importance in the study of far-unstable nuclei, and in particular the recoil techniques are being developed so that they can answer questions other than 'Stable? Maybe unstable?'. Some examples of these techniques are given in subsection 2.2.

Figure 2 gives a schematic overview of the experimental situation, about which we make the following remarks. All proton-rich nuclei¹⁷ up to Sc ($Z = 21$) predicted to be particle stable have now

Fig. 2 Nuclides detected experimentally and theoretical limits of stability. The upper part of the figure (courtesy of C. Ekström) shows the chart of the nuclides with the stable nuclei represented by black squares. The zigzag lines are the limits of known isotopes, whilst the two smooth lines indicate approximately the calculated limits to particle stability, which is zero binding energy for protons and for neutrons. It will be seen that experiments on medium-weight and heavy nuclei have reached the proton drip line, whilst the neutron drip line is far away. The lower part of the diagram, in part based on a similar one given in Ref. 17, shows the status as of 1986 for the light nuclei. The heavy line surrounds the area of isotopes known to be particle stable. Thin lines surrounding external squares represent nuclei which are predicted to be particle-stable and which remain unobserved. The stars mark the heaviest and lightest isotope for which the half-life is known experimentally.

been detected experimentally. The last one in this region, ^{22}Si with a proton excess of 6, was recently observed at GANIL (C. Détraz, personal communication). Other cases with as large or larger proton excess are not expected to be stable. The proton drip line has been reached (and crossed!) in a number of places in the heavier nuclei. Good examples are the ground-state proton radioactivities ^{147}Tm and ^{151}Lu , both with $N - Z = 9$, which decay by the emission of (Coulomb-delayed) 1 MeV protons to the ground state of the even-even daughter. These and other similar cases are discussed by Hoffmann in Chapter 2 of the present book.

Access to the neutron-rich nuclei is much more difficult. With the recent observation of ^{22}C (Ref. 18) all expected neutron-rich isotopes up to ^{23}N [$Z = 7$ (Ref. 19)] have been shown to be particle stable. The limit of particle stability has not been reached for any one of the heavier elements, and it is already far away at calcium ($Z = 20$). For caesium ($Z = 55$) it is expected to lie near $A = 175$, whilst the heaviest known isotope has $A = 152$.

In the following subsections we briefly illustrate the performance of the experimental techniques, but leave out all technical details as these can be traced through the references.

2.1 Electromagnetic Isotope Separation

This subject has been treated in review articles^{13,14} and the proceedings of specialized conferences.^{20,21} There are three main techniques for creating neutron-rich isotopes: i) high-energy fission, spallation, and fragmentation induced by high-energy protons and other light projectiles; ii) thermal fission with reactor neutrons; and iii) heavy-ion reactions, at lower energies through deep-inelastic processes and at high energies through fragmentation processes. All three give rise to complex mixtures of reaction products. The most general method for sorting these is electromagnetic isotope separation, first used by Kofoed-Hansen et al.²² and recently reviewed by Ravn.²³ In combination with a beam of 600 MeV protons, such as at ISOLDE linked to CERN's synchro-cyclotron, one obtains remarkably intense radioactive beams owing to the high penetrating power of the protons and hence the possibility of using very thick targets. This is illustrated in Fig. 3,

Fig. 3 Intensities of caesium beams obtained at ISOLDE by irradiation, with 1 μA of 600 MeV protons, of a 16.4 g/cm² uranium carbide target and of a 140 g/cm² lanthanum target. The normal beam intensity at ISOLDE is approximately 3 μA .

which is based on data by Ravn.²⁴ The yield distribution at high energy is much broader than the one obtained in thermal fission, and gives high-energy accelerators a certain advantage over nuclear reactors (see, for example, a similar figure in Ref. 14).

It is interesting to note that the intensity scale in Fig. 3 covers about ten decades, and that isotopes of about ten other elements are produced in comparable yields. For this reason there are stringent demands on the element- and mass-analysing power of the system. Recent progress in this field has been charted by Björnstad et al.,²⁵ who note that beams of 66 elements can now be produced. Few of those, though, have the purity and intensity obtained for the caesium isotopes, which represent the largest span observed for any element: from ^{114}Cs , next to the proton radioactivity ^{113}Cs (see Chapter 2), to ^{152}Cs , a total of 40 observed isotopes. Examples of recent observations of neutron-rich nuclei in reactor experiments or in fragmentation with heavy ions can be found elsewhere.^{26,27}

2.2 Recoil Separators and Heavy-Ion Reactions

A review of recoil separators has been given by Enge.²⁸ Examples of their applications can be found in Chapters 1, 2, and 9 of this book dealing with alpha radioactivity, proton radioactivity, and the heaviest elements, respectively. Recoil separators have been used for the investigation of fission fragments from thin sources of fissionable material placed in a nuclear reactor, such as the gas-filled spectrometer JOSEF²⁹ and at the parabolic spectrograph LOHENGRIN,³⁰ but the most dramatic recent development has been the use of recoil spectrometers for the study of fragmentation reactions with heavy ions.

The main reactions used for producing neutron-rich products are deep-inelastic and two-body transfer reactions during peripheral collisions at relatively low energy³¹ and fragmentation reactions for ions at relativistic^{32,33} and intermediate energies (see the reviews by Détraz,¹⁷ Guillemaud-Mueller³⁴ and Guerreau³⁵). As an example of the power of this technique, Fig. 4 shows the mass distributions for the boron and carbon isotopes measured recently with the LISE spectrometer³⁴ at the GANIL cyclotron.¹⁸

The clean spectra obtained with the projectile fragmentation method immediately suggests to develop this technique further, so that it can serve to provide more detailed spectroscopic information. Experimentally this is rendered difficult by the high penetration power of the energetic fragments, but much progress has been made in the last few years. Several experiments have

Fig. 4 Mass distributions¹⁸ of boron and carbon isotopes obtained from 44 MeV/u ^{40}Ar impinging on a 166 mg/cm² tantalum target during 30 hours of measuring time. The isotope ^{22}C was seen here for the first time.

determined the radioactive half-lives of recoil products by implanting them in special detection systems. Beta decays were detected at the Bevalac,³⁶ the MSU cyclotron,³⁷ and at GANIL^{38,39} by gating-off the accelerator's beam whenever a recoil was observed. In the GANIL experiments, also gamma rays were detected with a large Ge detector.

Masses of nuclei far from stability may be obtained from multinucleon transfer reactions with heavy ions. A recent example is the mass of ^{33}Al , which was determined from a three-proton reaction $^{48}\text{Ca}(^{36}\text{S}, ^{33}\text{Al})^{51}\text{V}$ at the Daresbury tandem.⁴⁰ The mass excess seems to indicate that $N=20$ is a good shell closure for ^{33}Al . This is in contrast with the behaviour of the isotones of Na and Mg^{41,42} which appear to be strongly deformed.

A powerful method for measuring masses of reaction fragments has been developed at GANIL.^{17,43} It uses the magnetic spectrometer SPEG together with a time-of-flight measurement along a 100 m flight path, and achieves mass values with a precision of better than 500 keV. The main problem still is the systematic errors, and improvement to about ± 200 keV is reported to be in sight.

A very interesting experiment by Tanihata et al.^{44,45} has used an analysed recoil beam of 790 MeV/u to bombard thick targets. A second spectrometer behind the target determined the transmission and hence the interaction cross-sections. From these, the strong interaction radii (r.m.s.) shown in Fig. 5 were deduced. The most surprising feature is the large increase in radius between ^9Li and ^{11}Li , which, according to estimates made by Tanihata et al.,⁴⁴ cannot be a kinematic effect of the low binding energy of ^{11}Li (see Sections 4 and 5). They therefore interpret the effect as being due to either a long 'tail' in the matter distribution or a large deformation. The latter possibility is not supported by optical experiments;⁴⁶ these indicate spin and parity of $3/2^-$ for ^{11}Li , which is the shell-model prediction for this doubly-closed-shell plus one nucleon system. We mention in Section 5 that the appearance of a neutron halo is a logical direct consequence of the low binding of this system.

Fig. 5 Root-mean-square matter radii^{44,55} for neutron-rich isotopes of He-Be and for ^{12}C .

2.3 Beyond the Limits of Stability

It is possible in certain cases to observe low-lying states in unbound nuclear systems as broad resonances. As examples⁴⁷ we note ^7He with a natural ground-state width of 160 ± 30 keV for the decay to $^6\text{He} + n$ with $Q = 0.44$ MeV, and ^9He observed in $^9\text{Be}(\pi^-, \pi^+)$ and unstable towards $^8\text{He} + n$ by 1.14 MeV.

3. BETA-DELAYED EMISSION OF SINGLE NEUTRONS

Neutron emission from excited states populated in beta decay is the process unique to neutron-rich nuclei, and in the following we give examples for both light and heavy systems. In the former, the neutron-emitting states often have an appreciable fraction of the single-particle strength and hence large widths, but apart from the special experimental techniques associated with neutron detection, the neutron spectroscopy of the light nuclei is just spectroscopy as usual. In the heavier nuclei, on the other hand, the upper part of the spectrum of excited states becomes exceedingly complex, and the states are of the same character as those studied as resonances in neutron reactions. For these states, and also for the proton-emitting states in neutron-deficient nuclei (see the chapter by Hagberg and Hardy), the best description is in terms of the compound-nucleus model. The application of this model to beta-delayed particle emission has been discussed in detail elsewhere;^{48,49} in the following we give a brief and entirely qualitative outline of the main ideas.

3.1 Compound-Nucleus Model of Beta-Delayed Neutron Emission

Typical excitation energies of the emitter states are 4 to 10 MeV, implying that the spacing between levels of the same spin and parity at the top of the spectrum will be of the order of 1 eV to 1 keV only. Experience shows that for such states the wave function is very complex, and that the amplitudes for the individual configurations can best be described as random on a local scale. The observable—and theoretically predictable—quantities are then averages and fluctuations around these averages. It is maybe worth underlining that the randomness introduced here is of another kind than that encountered in other areas of statistical physics. The states observed are, of course, of the same physical nature as the simple ones lower down in the spectrum, no less ‘real’. What the statistical model does is to treat them as the random outcomes of a process that can be defined mathematically, but this is without an experimental equivalent: to ask for ‘more samples’ of the resonances in ⁸⁷Kr has no meaning, although we can easily generate such samples on the computer. An additional complication in neutron emission experiments is the relatively modest energy resolution—typically at best 10 keV—and hence modest sensitivity. For these reasons it is important to remember that states will be missed experimentally and that the spectra will most often contain unresolved parts.

As the intermediate states are relatively long-lived, one may treat separately the formation of a state in beta decay and its subsequent decay by particle and gamma-ray emission. In the first approximation, there is no need to introduce the beta-decay rates to individual states; we can go directly to the beta strength function $S_\beta(E)$, defined⁴⁸ as a product of the level density and the average reduced beta transition probability to the states at the excitation energy E . Let the energy available in beta decay be Q and let $f(Q - E)$ denote the statistical rate function, also a (universal) function of the atomic number Z . The total beta intensity per unit energy of final states at the energy E can then be written

$$b(E) = S_\beta(E)f(Q - E) / \int_0^Q S_\beta(E)f(Q - E) dE . \quad (1)$$

It is possible to subdivide $b(E)$ into components corresponding to different values of the spin I_i of the intermediate state i by introducing a spin weight factor $\omega(I, I_i)$. The intensity of particle x with kinetic energy E_x to the final level f can then be expressed by the usual compound-nucleus formula,

$$I_x^{if}(E_x) = \omega(I, I_i)b(E) \Gamma_x^{if}(E) / \Gamma_{\text{tot}}^i , \quad (2)$$

where the quantities Γ represent the average partial and total widths for the states i . The particle spectrum is obtained as the double sum over all intermediate and final levels, and the total particle branching ratio per beta decay is the energy integral of this spectrum.

Much of what is known about the beta strength function at high energy has come from the study of beta-delayed particles. For a general review we refer to the paper by Takahashi,⁵⁰ and note here only some main points. For nuclei with $N > Z$, the beta-minus strength function shows a strong increase with energy, whilst the beta-plus strength function changes much more slowly. This behaviour had, in fact, been predicted in a remarkably bold theoretical conjecture by Fujita and Ikeda^{51,52} and ascribed to what we today call the spin-isospin or Gamow-Teller giant resonance. As furthermore the allowed strength with multipole order zero—the Fermi transitions—can connect only to the isobaric analogue state, this theory provided an explanation of why the allowed beta decays of neutron-rich, heavier nuclei are so slow (see the schematic diagram in Fig. 1). The theory accounts also in a qualitative way for the different behaviour of β^- and β^+ decays observed in early analyses of beta strength functions.^{53–55}

As allowed beta decay arises from transitions connecting identical shell-model states or spin-orbit partners, any detailed description must start from the shell model or the Nilsson model and on top of this incorporate pairing and the collective effects. This is the approach taken in a series of papers by Klapdor⁵⁶ (and references therein), who has used such calculations to predict beta strength functions and half-lives and to calculate particle branching ratios. Extrapolations of these quantities to unmeasured nuclei away from stability are of special importance in connection with astrophysical theories of element synthesis. A simpler and much more schematic theory of beta strength has been developed by Yamada and his collaborators^{50,57,58} under the name of ‘the gross theory of beta decay’. This fixes the total strength by means of sum rules and introduces as the only free parameter the spreading width of the collective states. In spite of its simplicity, this model is able to account for the main features of half-lives and beta strength at high energies. The specific application of the gross theory to delayed neutrons has been discussed by Takahashi.⁵⁹ In Sections 3 to 5 we shall give examples of comparisons between experimental and calculated results.

3.2 Fine Structure and Fluctuation Phenomena

The compound-nucleus picture outlined in the previous subsection describes the observed intensities in terms of local averages of beta and particle decay widths. Fluctuations around these averages will, in many experimental situations, influence the spectra in a major way; we give here a summary aiming specifically at beta-delayed particle emission. General reviews of the fundamentals of fluctuation phenomena in nuclear physics can be found in the book by Bohr and Mottelson⁶⁰ and, in more detail, in the book by Lynn.⁶¹ The application to beta decay has been discussed in other papers^{14,48,62} and, with many details not found elsewhere, in Ref. 49. The fluctuation phenomena arise from the very complex nature of the wave function, which in any simple representation (e.g. the shell model) will have a very large number of components, all of them small. With Porter and Thomas we may assume that the amplitude corresponding to each configuration is distributed among the different states according to a Gaussian distribution with zero mean. This gives rise to fluctuations in the transition probabilities and in the level spacings, of which the former are the most important in the case of beta-delayed processes.

The basic law governing the fluctuations in the transition probabilities, the Porter-Thomas law, gives the probability density $P_{PT}(x)$ for observing a transition probability x in units of its average value and for a single reaction channel

$$P_{PT}(x) = (2\pi x)^{-1/2} \exp(-x/2), \quad (3)$$

where one notes that the expression is singular at the origin. This gives rise to a preponderance of weak transitions together with a small number of strong ones, which is one reason why the correction for unobserved transitions can be so delicate—and so important. In the usual case, the observed intensity will be influenced by a combination of several fluctuating quantities, most often leading to even more skew probability density distributions, some of which are discussed in Ref. 49.

Another, but usually much smaller, contribution comes from fluctuations in the nearest-neighbour spacing, which for a pair of levels with the same spin and parity is given by the Wigner law,

$$P_W(x) = \frac{1}{2}\pi x \exp(-\pi x^2/4), \quad (4)$$

where the spacing is in units of its average value. The variance of this expression is only 0.27 whilst that of the Porter–Thomas law is 2, and the role of density fluctuations is further reduced by the existence of a long-range order, so that the variance on the n^{th} -order spacing decreases much faster than as n^{-1} .

The primary interest in the fluctuations comes from the possibility that a peak, which in this model is spurious, may pose as an effect of nuclear structure. But in addition to this, it is possible to use the ‘noise level’ due to fluctuations for a measurement of nuclear level densities (see, for example, Ref. 14). One of the problems in this case is to establish the ‘true’ value relative to which the fluctuation amplitudes shall be measured. This can in some cases be done by applications of autocorrelation techniques (see Refs. 14, 49, and 62), which work well when the fluctuation amplitudes are relatively small.

For small level densities the analysis of fluctuations can be more problematic, and the most direct way is probably to use Monte Carlo techniques to generate pseudo-data as a basis for

Fig. 6 a) Experimental beta-delayed neutron spectrum from the decay of ^{135}Sb (Ref. 66), and b) a spectrum from a fictional nucleus studied in a Monte Carlo simulation.⁶⁵ The simulation used slowly varying strength functions corresponding to the mass and spin parameters of the real decay. There is thus no artificially created local nuclear-structure effect put into the calculation, and the appreciable fine structure still present comes mainly from the Porter–Thomas law. The complexity of this fine structure was demonstrated in Ref. 65 by an analysis, which showed that the three strongest lines in the simulated spectrum have contributions from about unresolved 200 single transitions.

comparisons. Some attempts have been made in this direction by Gjøtterud et al.⁶³ and by Hardy et al.^{64,65} An example of the latter calculation is shown in Fig. 6, where an experimental beta-delayed neutron spectrum⁶⁶ from the decay of ¹³⁵Sb is compared with a spectrum from a fictional nucleus studied in a Monte Carlo simulation.⁶⁵

3.3 Selected Examples of Delayed-Neutron Data

There exists a huge amount of experimental information on beta-delayed neutrons, and any attempt at a complete coverage would exceed the format of the present paper. For the convenience of the reader interested in special regions of the nuclear chart, we give in Table 1 a selection of references^{41,42,66 – 142} that were consulted during the preparation of the present paper.

Table 1

References to papers on delayed-neutron emitters

Isotope	References
He	67, 68
Li	69–76
B	77
N	78–79
Na	41, 42, 75, 76, 80–86
K Ca Sc	87–90
Cu	91
Ga As Br Kr Rb Sr Y	66, 75, 92–135
Ag In Sn Sb Te I Cs Ba	66, 93–96, 98–103, 105, 106, 109–112, 114, 119, 120, 122, 124, 130–132, 134, 136–142

Many experiments determine the absolute neutron branch p_n defined as the number of neutrons emitted per beta decay. For the relatively rare cases in which several neutrons are emitted, it is convenient to define the probability per beta decay p_{in} for the emission of i neutrons, where clearly

$$p_n = \sum_{i=0}^{\infty} i p_{in} \quad \text{with} \quad \sum_{i=0}^{\infty} p_{in} = 1. \quad (5)$$

The experiments usually determine p_n by absolute counting of betas and neutrons, where the latter are detected by 4π counting with a large paraffin moderator containing detectors for thermal neutrons. The great advantage of such a system is that the efficiency varies relatively little with the neutron energy, so that reliable results can be obtained even if the neutron spectrum is unknown. The absolute efficiency scale may be determined by counting neutrons from spontaneous fission, or from a reference isotope with known p_n . Since a frequently used standard has been ^9Li , it is of some importance that a remeasurement⁶⁹ based on (slow) beta-neutron coincidences has increased the p_n value from 35% to $50 \pm 4\%$. This, in turn, has changed a number of older p_n values. A specimen of results for light nuclei is given in Table 2*) and frequently updated tabulations are given in the papers of Mann.⁷ The data on the neutron spectra stem largely from experiments with gridded ^3He -filled proportional counters. The typical FWHM resolution of such a detector is about 12 keV at thermal energies and more like 20 keV at about 1 MeV. In order to get to the intensity distribution from the measured spectrum, one has to unfold the response function. A recent careful study¹⁴⁵ has shown that the response is complicated by recoil distributions of elastically scattered hydrogen and helium nuclei and by wall effects.

In the lightest neutron precursors, the spectra are often dominated by broad distributions, usually originating in broad levels but also in some cases due to multiple emission of neutrons. As an example, Fig. 7 shows the neutron spectrum following the decay of ^9Li , which has a half-life of 178 ms and which decays mainly to $^8\text{Be} + n$ and to $^5\text{He} + \alpha$. The neutron spectrum of ^{11}Li , to which we return in Section 4, is even more complicated owing to modes involving the simultaneous emission of two and three neutrons. The complexity of the break-up of the light nuclei causes our knowledge of their beta strength functions to be very limited. The $T, T_z = 3/2, 3/2$ nuclide ^{17}N was studied by Ohm et al.⁷⁹ The resolution with a ^3He spectrometer was sufficient for determining the natural widths of four excited states populated in the beta decay to ^{17}O .

Several experiments⁸⁴⁻⁸⁶ at CERN have studied the heavy isotopes of sodium produced with 600 MeV protons at ISOLDE and with 24 GeV protons at the Proton Synchrotron (PS). At ISOLDE the delayed-neutron spectra were measured⁸⁴ from the five precursors $^{27-31}\text{Na}$. Figure 8 shows the results for ^{29}Na as measured with a ^3He spectrometer, which has the disadvantage that its efficiency drops strongly above 2 MeV. As the neutron spectrum of this isotope extends up to approximately 10 MeV, an additional experiment based on the time-of-flight technique⁸⁶ was necessary in order to get a picture of the high-energy part of the spectrum shown in Fig 9. Lines were, in fact, found up to about 4 MeV kinetic energy, which for a neutron binding energy of about 5 MeV corresponds to beta feeding up to about 9 MeV excitation energy. The data agree well with a shell-model calculation, and a quenching factor of about 0.5 is found for the Gamow-Teller strength in agreement with the findings in the beta-plus decays of $^{32-33}\text{Ar}$. The latter have $Z > N$ so that both the quenched Gamow-Teller transitions to individual low-lying states and (part of) the collective state are observed.¹⁴⁶⁻¹⁴⁸

Another interesting sequence of delayed-neutron emitters is provided by the neutron-rich potassium isotopes, studied by Carraz et al.⁸⁷ (see the data in Table 3). Whilst the window ($Q - B_n$) for neutron emission increases monotonically with the mass number, the p_n values peak sharply for ^{49}K due to a shell effect which is based on a combination of gamma-ray and delayed-neutron data.⁸⁷

*) See Refs. 75, 80, 81, 83, 87, 88, 121, 125, 135, 143, and 144.

Table 2

Experimental and theoretical neutron branching ratios for some multi-neutron precursors

Isotope	$T_{1/2}$ (ms)	P_{in} (%)			P_{2n}/P_n (‰)			P_{3n}/P_n (‰)		$P_{2n}/P_{n+n} (\vartheta_0)^{*)}$ Theor. 2
		Exp.	Theor. 1 ^{d)}	Theor. 2 ^{d)}	Exp.	Theor. 1 ^{d)}	Theor. 2 ^{d)}	Theor. 1	Theor. 2	
³⁰ Na	48 ± 2 ^{a)}	30 ± 6 ^{a)}	13	43	4.2 ± 0.8 ^{b)}	7.2	1.3	0	–	–
³¹ Na	17 ± 0.4 ^{a)}	36 ± 6 ^{a)}	33	24.9	2.3 ± 0.5 ^{b)}	0.76	1.7	6 × 10 ⁻⁶	0.01	5.8 ^{d)}
³² Na	13.2 ± 0.4 ^{a)}	21 ± 8 ^{a)}	13.4	23.8	24 ± 5 ^{b)}	21	11	9 × 10 ⁻⁴	0.3	12 ^{d)}
³³ Na	8.0 ± 0.6 ^{a)}	52 ± 20	–	50.0	–	–	17.7	–	0.36	9 ^{d)}
³⁴ Na	5.5 ± 1 ^{a)}	–	–	42.3	–	–	30.7	–	1.9	16 ^{d)}
³⁵ Na	1.5 ± 0.5 ^{b)}	–	–	58.6	–	–	18.3	–	3.0	19 ^{d)}
⁵⁰ K	472 ± 4 ^{c)}	29 ± 3 ^{e)}	–	31.3	–	–	0.10	–	0	–
⁵¹ K	365 ± 5 ^{c)}	47 ± 5 ^{e)}	–	30.9	–	–	0.27	–	0	–
⁵² K	105 ± 5 ^{c)}	–	–	43.7	–	–	4.8	–	0	–
⁵³ K	30 ± 5 ^{c)}	100 ± 30	–	60.6	–	–	5.4	–	0.04	1.8 ^{d)}
⁵⁴ K	10 ± 5 ^{c)}	–	–	73.3	–	–	11.3	–	0.16	5.2 ^{d)}
⁵⁵ K	–	–	–	87.2	–	–	7.4	–	0.51	6.3 ^{d)}
⁹⁸ Rb	112 ± 4 ^{d)}	13.2 ± 2.1	8.6	17.8	0.38 ± 0.06 ⁱ⁾	0.28	0.5	–	–	–
⁹⁹ Rb	59 ± 4 ^{d)}	14 ± 3	–	17.4	–	–	0.17	–	–	–
¹⁰⁰ Rb	51 ± 17 ^{d)}	–	30.9	26.3	2.7 ± 0.7 ^{d)}	1.5	4.2	–	–	–
¹⁰¹ Rb	–	–	–	34.7	–	–	0.45	–	–	–
¹⁰² Rb	–	–	39	42.4	–	6	6.9	–	–	–
¹⁰³ Rb	–	–	–	48.2	–	–	5.0	–	–	–
¹³² In	–	4.2 ± 0.9 ^{j)}	–	6.5	–	–	0.3	–	–	–
¹³⁶ Sb	–	22 ± 7 ^{k)}	–	17.1	–	–	1.6	–	–	–

a) Ref. 81, b) Ref. 83, c) Ref. 88, d) Ref. 121, e) Ref. 87, f) Ref. 75, g) Refs. 143 and 144, h) Ref. 80, i) Refs. 125 and 135, j) Ref. 136, k) Ref. 120.

*) Not measured.

Fig. 7 Energy spectrum of delayed neutrons from ${}^9\text{Li}$ (G. Nyman, personal communication). The excited states in ${}^9\text{Be}$ can decay either into ${}^8\text{Be} + n$ (break-up energy 1.665 MeV) or into ${}^5\text{He} + \alpha$ (2.46 MeV). The peak at 682 keV originates in neutrons from a narrow state ($\Gamma = 0.77$ keV) at 2.43 MeV excitation energy in ${}^9\text{Be}$. The 682 keV line is recoil-broadened. The distribution below this peak is due to the feeding from the 2.43 MeV state to the tail of the broad ($\Gamma = 1.5$ MeV) 2^+ state in ${}^8\text{Be}$. The structure on the low-energy side of this hump has been shown¹⁴⁵ to originate in an instrumental effect: it stems from neutron scattering in the steel walls of the ${}^3\text{He}$ neutron counter, where the ${}^{56}\text{Fe}$ resonances give rise to the spurious peaks.

Fig. 8 Beta-delayed neutron spectrum from ^{29}Na (Ref. 84) measured with a ^3He filled proportional counter. The upper part of the spectrum shows the pulse-height spectrum and the lower part the spectrum obtained after a correction for the detector efficiency.

Fig. 9 The high-energy spectrum of beta-delayed neutrons from ^{29}Na measured with the time-of-flight technique.⁸⁶ Two large (2880 cm^2) plastic scintillators, placed 100 cm from the source, served as neutron detectors. They were operated with a threshold of 1 MeV for the recoil protons, which precluded the observation of the low-energy part of the neutron spectrum. The lines at 1.7 and 2.25 MeV were also observed in the spectrum taken with a ^3He detector (see Fig. 8).

Table 3

Branching ratios and energy windows for
delayed-neutron emission in potassium isotopes

Mass number	p_n (%)	$Q - B_n$ (MeV)
48	1.14 ± 0.15	2.0
49	86 ± 9	5.2
50	29 ± 3	7.6
51	47 ± 5	9.6

Fig. 10 The experimental beta strength function of ^{49}K (from Ref. 87), was deduced from measured γ spectra, $\gamma\gamma$ coincidences, and delayed-neutron spectra. It is shown here as the reduced Gamow-Teller transition probabilities per 0.1 MeV bins. The overall behaviour and also the absolute value of the strength is well reproduced in a calculation by Takahashi, who used 'the gross theory of beta decay'. The peaks at 6.5 and 9.5 MeV are due mainly to decays of neutrons in the $f_{5/2}$ and $f_{7/2}$ states, respectively, and are represented in the gross theory in an average fashion only.

The calculated beta strength function shown in Fig. 10, which is based on a combination of gamma-ray and delayed-neutron data,⁸⁷ agrees with a schematic calculation, but for understanding the details it is necessary to take the shell model into account.

We turn now to the heavier nuclei, in which the delayed-neutron spectra become increasingly complicated. The problem is mainly caused by the limits in resolution and sensitivity, but in addition the spins of the intermediate states are, except for special cases, unknown. It is therefore fortunate that there exists an experimentally unique case, the emitter ^{87}Kr , which can serve to bolster our

confidence in the interpretation of the more complex spectra. This has been studied in detail by Raman et al.¹²⁹ The main feature of this nucleus is that its excited levels can be reached both in the beta decay of ^{87}Br and in reactions of fast neutrons with a (stable) ^{86}Kr target. This, however, would not have sufficed, had there not been a fortunate overlap between the spins populated in the two cases. Very conveniently, the spin of ^{87}Br happens to be $3/2^-$, which permits the allowed beta decay to $1/2^-$, $3/2^-$ levels, also observable as p-wave resonances in neutron capture. Furthermore, the emitter has a $(50+1)$ configuration in the neutron shell; thus the level density is very low, and energy resolution is consequently less of a problem. The $5/2^-$ resonances are not seen in the neutron-absorption experiments but they are populated in the beta decay, and are observable through their gamma decay and through neutron emission above 150 keV kinetic energy.

Figures 11 and 12 show the neutron spectra emerging from the two experiments^{129,113} on the system $^{86}\text{Kr} + n$. The amount of detail provided by the cross-section measurement (Fig. 11) is impressive and shows the presence of 41 resonances, of which 35 could be assigned spin and parity. An estimate based on statistical arguments predicts the presence of an additional six unobserved resonances, so that one must assume the total number of low-spin states in the interval of 5.5 to 5.9 MeV excitation energy in ^{87}Kr to be (for each spin-parity combination) 13 ($1/2^+$), 11 ($1/2^-$), and 23 ($3/2^-$). Of these the s-states are not detectable in beta decay, so we expect the lowest 400 keV in Fig. 12 to contain 34 lines and, in addition, some lines due to the $5/2^-$ states. In fact, only 12 lines are observed experimentally. These experiments clearly demonstrate that in the most favourable case, that of ^{87}Kr , the beta-decay experiments can observe only a fraction of the true lines. This fraction, of course, is very much smaller in a typical case such as ^{135}Sb , shown in Fig. 6.

Fig. 11 The neutron total cross-section for ^{87}Kr in the neutron-energy range 0–400 keV as deduced from transmission experiments with a time-of-flight spectrometer.¹²⁹ The s-wave resonances can be identified through their interference with the non-resonant background. For the non-interfering p-wave resonances, the spins could in almost all cases be determined via the statistical weight factor obtained from the peak cross-section and resonance width.

Fig. 12 Beta-delayed neutron spectrum from ^{87}Br , which decays to $^{87}\text{Kr} + n$. The experiment was performed at the Mainz TRIGA reactor¹¹³ and used a ^3He spectrometer to detect the neutrons. The data, as presented here, have been corrected for detector response.

Since ^{87}Br is likely to remain the only case in which we can know experimentally the anatomy of a delayed-neutron spectrum, it is probably interesting to emphasize some of the conclusions emerging from this study. First of all, it is not surprising that only 12 lines can be observed. The theory of noise spectra may be applied to predict the density of peaks in a spectrum with a given resolution, and leads,⁴⁹ for a Gaussian half-width W , to an average density of $0.456/W$. Since the resolution was about 16 keV in Fig. 12, the observed peak density of about 0.03 is almost exactly that expected. The Monte Carlo simulation of the ^{87}Br spectrum carried out previously by Hardy et al.⁶⁵ was very fortunate in its choice of level-density parameters, and had almost exactly the correct number of levels: 14 ($1/2^-$) and 24 ($3/2^-$). Still, their spectrum looks ‘cleaner’ than the experimental one, which may reflect problems with the detector response function, which is notoriously complicated.¹⁴⁵ It is probably the effect of tails on the experimental lines that made Gjølterud et al. overestimate the ^{87}Kr level density.¹⁴⁹

Another case in which there is considerable gamma decay from states well above the neutron threshold is ^{137}I , studied in Ref. 141. The centrifugal barrier caused by the relatively high spins ($5/2$ to $9/2$) of the intermediate states provides a plausible explanation for this.

It was emphasized above, in connection with the ^{29}Na experiments, that the time-of-flight technique gives a greatly improved efficiency at high neutron energies. At low energies this technique may bring about a great improvement of the energy resolution, as illustrated in a recent experiment by D.D. Clark et al. (personal communication). They were able to reach an energy resolution of better than 2 keV and to detect, as shown in Fig. 13, the natural line width of the 14.4 and 26.7 keV neutron lines following the beta decay of ^{95}Rb . The data¹⁵⁰ also allowed conclusions to be reached regarding about the level density and d-wave strength function.

Fig. 13 Time-of-flight neutron spectrum of ^{95}Rb measured at the Tristan Facility at Brookhaven. The experiment (D. Clark, personal communication and Ref. 11) used beta particles detected in a plastic scintillator telescope as the Start signal, and the neutron Stop signal was provided by a ^6Li glass scintillator placed 50 cm from the source. The energy resolution was better than 2 keV below 50 keV energy. Note the logarithmic energy scale.

4. RARE DECAY MODES OF NEUTRON-RICH NUCLEI

It has been known for a long time that, for very neutron-rich nuclei, the high Q_β values and low neutron-separation energies will permit processes in which several nucleons are emitted following an initial beta decay. For only the particle-stable, neutron-rich isotopes up to sodium ($Z = 11$), more than 20 precursors for multinucleon emission are expected.⁷⁵ It is, however, only quite recently that these decay modes and the corresponding process on the proton-rich side of the nuclear chart—the beta-delayed emission of two protons—have been discovered. The reason is that although these experiments seem simple and are suggested by the crudest extrapolation of the mass table, they demand the production and observation, under clean conditions, of extremely rare species. The first case, found⁷⁰ in 1979, was the beta-delayed emission of two neutrons in the decay of ^{11}Li , soon followed by the observation⁷¹ of the, until now unique, case of three-neutron emission in the same nucleus. We begin by a discussion of the two- and three-neutron decays of ^{11}Li , then survey experiments on two-neutron modes in heavier nuclei, and finally treat charged-particle decays of ^{11}Li and of heavier neutron-rich nuclei.

4.1 The 2n and 3n Decays of ^{11}Li

This isotope, which has a half-life of only 8.5 ms, is almost certainly the heaviest particle-stable isotope of lithium, and is, in fact, only marginally bound. From a mass determination by Thibault et al.¹⁵¹ it can be deduced¹⁵² that the two-neutron separation energy to ^9Li is a mere 190 ± 110 keV, that the single-neutron separation energy to (unbound) ^{10}Li is 980 ± 260 keV, and that the Q_β value is as high as 20.76 MeV. Figure 14 shows a schematic decay scheme of ^{11}Li . It can be seen that only

Fig. 14 Decay scheme of ^{11}Li . The data are from the compilation of Ajzenberg-Selove.¹⁵³ The value of $3/2$ for the ground-state spin of ^{11}Li is a measured value obtained in a recent collinear-laser experiment at ISOLDE.⁴⁶

the ground state and first excited state at 320 keV in ^{11}Be are particle-stable. The thresholds for 1n, 2n, and 3n emission lie at 0.503, 7.315, and 8.887 MeV, respectively. The thresholds for charged-particle break-up into $^3\text{H} + ^8\text{Li}$ and $^6\text{He} + \alpha + n$ lie at 15.72 and 7.917 MeV, respectively. Owing to the complexity of the decay, it is very difficult to obtain precise figures for the beta strength to highly excited states in ^{11}Be , but the beta branch to the 320 keV state is known to be $9.2 \pm 0.7\%$ from gamma measurements.^{69,73} From this it can be deduced that 91% of the decays proceed via particle break-up, since the first-forbidden ground-state transition has negligible intensity as can be seen from the ratio⁷³ of gamma rays from ^{11}Li and from ^{11}Be .

The experiments on 2n and 3n emission used a mass-separated beam of more than 10^3 atoms per second from the ISOLDE Facility.¹⁵³ Already the singles neutron spectrum,⁷⁰ which showed a broad, continuous distribution extending up to 1.6 MeV, gave a hint that complex decays were present, but the proof required nn coincidences. This is experimentally difficult, and an early attempt⁷⁶ had failed, although we know with hindsight that the intensity of correlated events is high. The new experiments were based on a paraffin-filled 4π neutron detector equipped with 12 ^3He -filled counters. This detector had an efficiency for spontaneous fission neutrons of $20 \pm 1\%$, and in this connection we note that the energies of the fission neutrons resemble those encountered in the 2n and 3n experiments. Furthermore, a careful study¹⁵⁴ of the detector used here has shown that the efficiency varies little with energy, approximately as $\epsilon = (20.1 - 1.3E_n)\%$. The fact that the efficiency is almost independent of energy for the classical ‘long counter’ was the main reason for choosing this technique, and it will be seen below that this is essential for obtaining precise results.

The price paid for a constant and high efficiency at essentially all neutron energies is that the time response is very slow, dominated by the slowing down and diffusion time in the paraffin. From beta-neutron coincidences on ^9Li —a single-neutron emitter—it was found that the mean residence time of a neutron in the detector was $\lambda^{-1} = 89 \pm 1 \mu\text{s}$ with an exponential time dependence of the

intensity. Since this time is much longer than the response time of the detectors, it was possible to connect these in parallel, and to replace a multicoincidence requirement by a search for time-correlated events in a single string of neutron signals. We outline here how this was done.

With the aid of a microprocessor, a ‘flying clock’ was read with $1 \mu\text{s}$ precision at the arrival of each neutron, and the events were stored on tape and later analysed in a playback mode. Assume that one has D beta disintegrations per second in the neutron detector and that the branching ratios for the emission of i neutrons ($i = 0, 1, 2, 3, \dots$) are p_{in} . Even for a detector efficiency as high as 20%, it is clear that most correlated events will be lost. It is therefore convenient to introduce the rate R_s of correlated events of s neutrons actually occurring in the detector. This can be written

$$R_s = D \sum_{i=s}^{\infty} p_{in} \binom{i}{s} \epsilon^s (1-\epsilon)^{i-s}, \quad (6)$$

where $\binom{i}{s}$ is the binomial coefficient, and where we have introduced the assumed energy- and isotope-independent efficiency ϵ . We see that if the R_s are measured and the ϵ is known, we can solve the equations for the ratios of p_{in} . The question is how to extract the R_s from the data. Azuma et al.⁷¹ used a numerical analysis, in which the time interval θ following an initial neutron event was examined. If $(q - 1)$ neutrons were observed in this interval, the event was registered as a q -fold coincidence. The detection probability per unit time for a neutron belonging to the event is $\lambda e^{-\lambda t}$, and one can now calculate the apparent rate M_q^t of true q -fold events in the analysis

$$M_q^t = \sum_{s=q}^{\infty} R_s r_{sq}, \quad (7)$$

where r_{sq} is the probability that exactly $(q - 1)$ counts out of $(s - 1)$ possible ones fall inside the window θ . This is clearly given by

$$r_{sq} = \binom{s-1}{q-1} (1 - e^{-\lambda\theta})^{q-1} e^{-\lambda\theta(s-q)}, \quad (8)$$

and since λ is independently known we may, in principle, use the measured M_q to solve R_s . In reality, the equations become more complicated because it is important to include, in a precise way, the contribution of random events. To take an example: the random correlation between two single events will give a contribution to the doubles,

$$M_2^r = R_1^2 \theta e^{-R_1 \theta}, \quad (9)$$

and with corresponding (negative) contributions to the singles. Likewise, three single events or one double and one single may pose as a triple correlation leading to correction terms quadratic or cubic in the count rate. These corrections have been discussed in detail in Refs. 71 and 75; these also discuss the corrections for fluctuations in the source strength, which has different effects on the terms with different powers in the rates R_s .

The final analysis⁷¹ led to the values $p_{2n}/p_{1n} = (4.8 \pm 0.5) \times 10^{-2}$ and $p_{3n}/p_{1n} = (2.2 \pm 0.2) \times 10^{-2}$. The error limits assigned here are much larger than the statistical errors alone, and should include also possible systematic errors in the experiment and analysis (see the consistency checks represented in Figs. 15 and 16). These show, in particular, that the time correlation for the triples has the steeper slope predicted for true events and that the corrections within wide limits are independent of count rate.

Fig. 15 Distribution of the time interval between the first and the second neutron for coincident events in the ^{11}Li experiment. The data shown here represent 12 hours of counting at an average neutron rate of 22.9 neutrons per second. In the analysis, an event was recorded as a triple coincidence if two additional neutrons followed the initial one within a time interval θ , and as a normal coincidence ('doubles') if only one neutron was observed. The analysis shown here is for $\theta = 228 \mu\text{s}$. The curves do not represent a fit, but have been calculated from the (absolute) values emerging in the final analysis, and include the effect of random coincidences. Note that in the time distribution the slope of the true triple coincidences is twice as steep as those of the true doubles and the randoms.

Fig. 16 The conclusions about the intensities of two- and three-neutron emission from ^{11}Li come from a relatively complicated analysis of time correlations in a single string of neutron events observed with a large neutron detector (see Fig. 15 and the text). Here we demonstrate that the solutions to the equations, expressed as the ratios p_{2n}/p_{1n} and p_{3n}/p_{1n} , are stable to large variations in the count rate and in the arbitrarily chosen correlation time interval θ . In Fig. 16a the count rate was varied from 7.9 to 202.8 n/s, which is a very exacting test of the corrections for random events, since their intensity varies with the square to the cube of the counting rate. Figure 16b shows that for data taken at 7.9 n/s, the value of θ can be chosen freely from 79.8 μs to 456 μs . (From Ref. 71.)

In order to bring the neutron emission probabilities to an absolute scale, it is possible to use the remeasured value $p_n = 95 \pm 8\%$ by Björnstad et al.,⁶⁹ but a more precise evaluation emerges by using the absolute branch of 9.2% to the 320 keV first excited state. One further notes that the beta transition to the ground state is negligible, and also that apart from a likewise negligible triton branch (see below), all decays to higher excited states emit at least one neutron. We must therefore have $\Sigma_i p_{in} = 100 - 9.2 \pm 0.7\%$, which leads to

$$p_{1n} = 84.9 \pm 0.8\%, \quad p_{2n} = 4.1 \pm 0.4\%, \quad p_{3n} = 1.9 \pm 0.2\%,$$

and to $p_n = 98.8 \pm 1.6\%$, in good agreement with the directly measured value of $95 \pm 8\%$.

4.2 Other Cases of ($\beta, 2n$) Decays

More cases of beta-delayed two-neutron emission have been found in the last few years, all in the alkali elements, which are favoured for experimental reasons.²³ A summary of the experimental results^{75,80,125,135} is given in Table 2, which also gives the results of a calculation by Takahashi^{75,80} and by Lyutostansky et al.^{143,144} The sodium experiments⁸⁰ were carried out in parallel at ISOLDE and at a mass spectrometer¹⁵¹ placed at the CERN PS, where sodium isotopes were produced by bombarding an iridium target with 24 GeV protons. As shown in Fig. 17, the emission of two neutrons was revealed by the presence, in the long-lived daughter products, of radioactivity with mass number two units below the mass collected. There was good agreement between the gamma-spectroscopic measurements and the time-correlation measurements.

Fig. 17 Gamma-ray spectra from mass-separated samples of sodium isotopes.⁸⁰ Whilst the spectrum obtained at the mass setting 29.8 showed background lines only (Fig. 17b), the spectrum (Fig. 17a) obtained after a 10 h collection at the mass setting 30.0 showed several lines belonging in the mass-28 isobar (21.8 h ^{28}Mg and its daughter product ^{28}Al). These have been produced via beta-delayed two-neutron emission. From the absolute count rate of the gamma rays and that of the mass spectrometer, for ^{30}Na this method gives the value $p_{2n} = 1.15 \pm 0.25\%$, in good agreement with the value $1.30 \pm 0.25\%$ determined in a $2n$ time-correlation experiment.

Fig. 18 Distribution of the time intervals between neutrons from ^{98}Rb .^{125,135} The neutron detector was equipped with 40 ^3He tubes embedded in polyethylene and had an efficiency of 59%. The high efficiency led to a residence time for neutrons of only $\lambda^{-1} = 35 \mu\text{s}$, and permitted the observation of a 2n branch of only $0.060 \pm 0.009\%$.

Time correlation techniques have also been used to study the rubidium isotopes. Figure 18 shows the results of an experiment on ^{98}Rb carried out at the on-line isotope separator Tristan.^{125,135} The 2n branch in this case is only $0.060 \pm 0.009\%$, much weaker than the 2.7% branch observed from ^{100}Rb .⁷⁵

Experimental techniques still do not permit the determination of the excitation energies of the intermediate states responsible for the 2n emission. From the same gross-theory calculation by Takahashi⁷⁵ that was cited in Table 2, we show in Fig. 19 the estimated excitation energies for 1n and 2n emission. It appears that even this, rather schematic, calculation gives a good picture of the 1n and

Fig. 19 Calculated⁸⁰ ^{32}Na delayed-neutron intensities as a function of the excitation energy in the daughter ^{32}Mg . The total intensities are 13% and 4.5% for one- and two-neutron emission, respectively, in good agreement with experiment. The discontinuities in the distribution arise from the schematic treatment of pairing in the gross theory of beta decay.

2n intensities. Microscopic calculations of delayed-neutron intensities have been carried out by Klapdor⁵⁶ and also by Lyutostansky and Panov.¹⁴³ The latter group also considered the possibility that the two neutrons could be emitted as a bound intermediate state, the dineutron 2n . They predicted¹⁴⁴ that as much as 5–20% of the observed 2n events could be present in the form of 2n (see Table 2), but that the 2n spectrum from ^{33}Na would extend up to 1 MeV kinetic energy only. The search for spatial and energy correlations between pairs of neutrons detected in coincidence is clearly an interesting challenge for the next generation of experiments.

4.3 Charged-Particle Decays of Neutron-Rich Nuclei

Langevin et al.⁷⁴ began the study of the charged particles emitted in the beta-delayed break-up of ^{11}Be . Since the final nucleus after the 3n decay, ^8Be , is unstable towards the decay to two alphas with a half-life of 7×10^{-17} s, alpha particles are abundant, but evidence (Fig. 20) was also found for a decay channel leading to $n + \alpha + ^6\text{He}$ in an intensity of $0.9 \pm 0.3\%$. These experiments also indicated that as much as 0.3% of the intensity could originate near 18.5 MeV excitation energy in ^{11}Be . Since this energy lies above the triton threshold (see Fig. 14) this observation triggered a dedicated search for beta-delayed triton emission.⁷²

The ^{11}Li triton experiment used a specially designed counter telescope to permit particle identification at low energies and in the presence of an intense background of alpha particles. This telescope consisted of a ΔE gas proportional counter and an E silicon detector. This gave a clear identification of tritons⁷² with an intensity of $0.010 \pm 0.004\%$. We see that ^{11}Li is the most versatile delayed-particle emitter observed to date with six types of final particles confirmed: n, 2n, 3n, ^3H , ^4He , and ^6He .

Fig. 20 The intensity distribution⁷⁴ of ^{11}Li as a function of the sum $E_1 + E_2$ of two alpha-particle energies detected in coincidence. The low-energy resonance, marked '1', is interpreted as 3n break-up via a 9.4 MeV resonant state in ^{10}Be , whilst the continuum '3' represents direct 3n break-up of high-lying states in ^{11}Be . The resonance '2' is interpreted as evidence for break-up of excited ^{11}Be into $n + \alpha + ^6\text{He}$.

Another experiment⁶⁸ based on the same technique succeeded in detecting tritons in the decay ${}^8\text{He}$. In this case the threshold for break-up of the intermediate states in ${}^8\text{Li}$ to tritons lies much lower⁴⁷ than was the case for ${}^{11}\text{Li}$ (5.39 MeV for ${}^5\text{He} + {}^3\text{H}$ and 4.501 MeV for $\alpha + {}^3\text{H} + n$), and with about 12% of the beta decay to the resonance at 8.8 MeV, a relatively strong triton branch was to be expected. This was confirmed in the experiment, which led (Figs. 21 and 22) to the clear identification of tritons in an intensity of $p_{\text{triton}} = 0.9 \pm 0.1\%$.

Fig. 21 Demonstration⁶⁸ of beta-delayed triton emission in the beta decay of ${}^8\text{He}$. The figure shows the ΔE versus E plot of events detected with a thin C_3H_8 -filled ΔE proportional counter operated together with a 300 mm^2 and $100\text{ }\mu\text{m}$ thick Si surface-barrier detector. With a 2% solid angle the total rate was 100 ΔE - E coincidences per second. The total spectrum shown here represents 15 hours of data taking. The spectrometer had an excellent separation of alpha particles (the broad curve) and tritons, of which approximately 3500 events were recorded in the vicinity of the (calculated) curve.

Fig. 22 The measured energy spectrum⁶⁸ of the tritons from ${}^8\text{He}$. The curve is the result of a calculation which assumes that the tritons originate in a state at 9 MeV, which decays to the (unbound) ${}^5\text{He}$ ground state. The break-up energy for this process is then 5.39 MeV.

Beta-delayed alpha emission is a common decay mode throughout the nuclear chart for very neutron-deficient nuclei as discussed in the contribution by Hardy and Hagberg to the present volume. In connection with β^- decay, this mode is, in general, encountered for the lightest and heaviest isotopes only: ^8Li , ^9Li , ^{11}Li , ^{12}Be , ^{16}N , ^{212}Bi , and ^{214}Bi . Far away from stability, however, the Q_β values increase more quickly than the Q_α values decrease, and it should become possible to detect weak beta-delayed alpha branches. One such case has been discovered by Détraz et al.⁸² in ^{30}Na with intensity $(5.5 \pm 2.0) \times 10^{-7}$.

5. CONCLUDING REMARKS

The previous sections give examples of the state of the art in research on neutron-rich nuclei. In this concluding section we would like to illustrate, by means of a few examples, the kind of insight that such experiments can provide. We consider, first, nuclear spectroscopy.

One striking feature when nuclear properties are studied along extended chains of isotopes is the strong role played by mutually reinforcing shell- and sub-shell effects. This was one of the main themes in the review,¹⁶ and we offer only one example here in the form of Fig. 23. Nuclear physicists have known for a long time, from the properties of ^{88}Sr and ^{90}Zr , that the combination $(N,Z) = (50,40)$ appears to be near-magic. However, experiments^{155–158} away from the stability line have revealed that the combinations $(40,40)$ and $(60,40)$ favour strong quadrupole deformations. Furthermore, one notes that the approach to deformation proceeds quite differently in the two directions (Fig. 23): gradually towards ^{78}Sr and ^{80}Zr (Ref. 156) and very abruptly at $N = 60$, beyond which one finds ^{100}Sr , one of the most deformed nuclei known.¹⁵⁷ Other evidence, such as the magnetic moment¹⁵⁸ of ^{100}Zr , supports this interpretation. The sharp break at $N = 60$ presumably is due to the $d_{5/2}$ sub-shell closure at $N = 56$.

Fig. 23 Energies of the first-excited 2^+ states in even-even strontium ($Z = 38$) and zirconium ($Z = 40$) isotopes. A number of references to spectroscopic studies in this region of the nuclear chart can be found in Ref. 16; the ^{80}Zr point is from recent work by Lister et al.¹⁵⁶ The radii of the rubidium isotopes were measured by Thibault et al.¹⁵⁵ Note that the masses of the rubidium isotopes are known from direct mass spectrometry, see Audi et al.¹⁶¹

Fig. 24 The level scheme¹³⁶ of ^{132}Sn , a doubly-magic nucleus with 50 protons and 82 neutrons, as studied in the beta decay of ^{132}In . The interpretation is that the mother isotope has the configuration $(\nu f_{7/2}, \pi g_{9/2})7^-$, expected to be the lowest member of this multiplet. The beta decay via the $(\pi g_{9/2})^{-1}$ to $(\nu g_{7/2})^{-1}$ transition populates a doublet of states with spin-parity assignments 6^- and 7^- , of which the upper state decays by neutron emission only. The feeding to the 6^- level has a log ft value of 4.4 and is followed by gamma decay, presumably in competition with a weak neutron branch.

The doubly-magic isotope ^{132}Sn is rapidly becoming the best studied case of this kind away from stability, and probably one that is of an intrinsic interest comparable with that accorded to traditional workhorses of nuclear physics such as ^{48}Ca and ^{208}Pb . The strongly magic character of this system is clear from the fact that the first excited state lies above 4 MeV; see Fig. 24, which shows the levels fed in the beta decay¹³⁶ of 186 ms ^{132}In .

During the past few years it has been discovered that the intrinsic reflection symmetry is broken in a very limited group of nuclei near ^{225}Ra , so that it becomes convenient to represent the intrinsic wave function in terms of states that are not parity eigenstates (see Leander and Sheline¹⁵⁹). It has been predicted by Leander et al.¹⁶⁰ that a similar region will exist in the extreme ‘south-western’ corner of the rare-earth deformed region of the nuclear chart. Experimental data supporting this idea come from the direct mass measurements carried out at ISOLDE by Audi et al.¹⁶¹ and earlier work¹⁶²

Fig. 25 Evidence for a new region of stable octupole deformation near ^{145}Ba . The figure, based on Leander et al.,¹⁶⁰ shows the difference between experimental^{161,162} and calculated ground-state masses. The big dots indicate recent measurements; thus the long sequence of data is from direct determinations of caesium masses by Audi et al.¹⁶¹ and earlier work referred to therein. The calculations assumed reflection-symmetric shapes, and Leander et al. show that the local overbinding around ^{145}Ba can be understood by allowing permanent octupole deformations. The extent of the predicted octupole-unstable region is indicated by the dashed contour.

(see Fig. 25). It would clearly be very interesting to have detailed $\beta\gamma$ -spectroscopic studies in the region around ^{145}Ba .

Next we consider what the experimental data covering large spans in N and Z tell us about gross nuclear properties, and begin with the systematics of beta-decay half-lives. It may, in fact, happen that a particular half-life away from stability is in itself of special physics interest. Kratz et al.¹⁶³ point out that $(195 \pm 35) \text{ ms } ^{130}\text{Cd}$ is situated at one of the ‘waiting points’ on the astrophysical r -process path; that is, where the path comes near to the valley of stability. In this situation, the half-life should be reflected directly in the measured geophysical abundances, which, in fact, seems plausible from the existing data. In general, however, we are forced to rely on calculations of half-lives of very neutron-rich nuclei. Here the essential problem is the calculation of the beta strength function, discussed in a paper by Takahashi.⁵⁰ There are two approaches, one of which uses the gross theory of beta decay, which for our purposes can be thought of as a structureless analogy to the liquid-drop model of nuclear masses, and which contains very few free parameters—for allowed decays, only one. The other is the more ambitious approach of Klapdor,^{56,164} who calculates the rates from the shell model, including collective (giant-resonance) phenomena. In this case the number of parameters is quite large. This approach, however, is necessary for decays near stability with low Q -values so that the rates can be determined entirely by low-lying ‘lumps’ of allowed strength. Far away from stability, however, the simple theory does remarkably well. This was pointed out by Kratz,¹⁶⁵ who analysed the half-lives of 11 recently discovered neutron-rich isotopes and obtained for the ratio experiment/theory the values 0.81 (gross theory) and 1.95 (microscopic theory) after logarithmic averaging. A similar comparison (Fig. 26) carried out by Klepper¹⁶⁶ arrives at essentially the same conclusion, namely that the two models perform much more equally than their relative numbers of free parameters would lead one to believe. In view of this, maybe the most surprising feature is that nobody has attempted to update the parameters in the gross theory, so that it is

Fig. 26 This figure (from Klepper¹⁶⁶) examines the predictive power of formulas to calculate beta-decay half-lives. In order to avoid bias, it includes new data only, mainly for neutron-rich isotopes produced in deep-inelastic heavy-ion reactions, indicated in this diagram by the horizontal lines. The circles, open for half-lives longer than 60 s, are based on microscopic calculations by Klapdor et al.,^{56,164} and the stars are based on the gross theory of beta decay.⁵⁸

adjusted essentially to very short-lived, far-unstable cases, and so that the sum rules entering in the theory are corrected for quenching effects in a way that reflects our current knowledge of beta strengths.

Finally, we consider some systematic aspects of another gross property, the pairing energy. This is defined as the energy difference between the mass surfaces for even and for odd neutron or proton number. The empirical features of pairing have been surveyed by Jensen et al.,¹⁶⁷ who used Wapstra's new '1983 Mass Table'¹⁶² as the input data. They also searched for other periodic terms in the nuclear masses, in particular alpha clustering, but found that contributions of this kind must be quite small. As may be seen from Fig. 27, there was strong evidence for the necessity of a symmetry term in the pairing energy, which could best be parametrized on a form first suggested by Vogel et al.:¹⁶⁸ for neutrons

$$\Delta_n = 7.36 A^{-1/3} \left[1 - 8.15 \frac{(N-Z)^2}{A^2} \right] \text{ MeV}, \quad (10a)$$

and almost identically for the proton pairing energy,

$$\Delta_p = 7.55 A^{-1/3} \left[1 - 6.07 \frac{(N-Z)^2}{A^2} \right] \text{ MeV}, \quad (10b)$$

The neutron and proton pairing energies differ locally by small amounts in a systematic way, as can be seen from Fig. 28. The main conclusion is clearly that neutron and proton pairing are, on the average, equal, and that they are the strongest for $N = Z$. This behaviour does not seem to be contained in the usually accepted nuclear models, and Jensen and Miranda¹⁶⁹ suggest that an effective interaction term containing the coordinates of four particles—two neutrons and two protons—could be the way out. Interestingly enough, this is also the remedy proposed by Zawischa et al.¹⁷⁰ to account for the old problem of the even-odd staggering of the nuclear charge radii. It

Fig. 27 Neutron pairing energies calculated¹⁶⁷ (with a normalization factor of 1/4) from the mass diagram shown in the inset. The pairing is seen to decrease with increasing asymmetry. The data include all masses for even-even nuclei with $A > 40$ but excluding magic Z and N . The $A^{1/3}$ dependence gives the best fit, but the asymmetry effect remains also for an assumed $A^{1/2}$ dependence. The line is the least-squares fit corresponding to the formula given in the text.

Fig. 28 The local difference between proton and neutron pairing energies calculated¹⁶⁷ from the diagram shown in the inset with a normalization constant of 1/4. The line represents the average value of 109 keV to which corresponds a standard deviation of 255 keV, but it is clear that the deviations vary in a systematic way with the mass number.

could be that the symmetry term in the pairing energies and the staggering of the radii are serving as reminders of ingredients missing in our usual semiempirical description of nuclear structure.

It is instructive to extrapolate the symmetry correction term [Eqs. (10)] to the region of the neutron drip line. The result, that pairing should vanish there, is in disagreement with a strong theoretical prejudice: the independent-particle model suggests that the neutron system alone also should show pairing. It also runs counter to the systematics of observed, particle-stable isotopes near the drip line (Fig. 2), which in a striking, albeit qualitative, fashion shows that pairing indeed continues to play a role there: for all the six elements from helium to nitrogen, the heaviest stable

isotope has an even number of neutrons. In all these cases except one, the next lighter isotope—that is, with one neutron less—is neutron-unbound. In two of the six cases also the isotope with three neutrons less than the heaviest one remains unbound. Indeed, it seems as if stability at the drip line is largely an effect of pairing. The pairing force active there may, however, be essentially the nn force between free neutrons.

The radial distribution of the loosely bound neutrons in a nucleus at the drip line has been discussed in a recent paper,¹⁷¹ which takes its starting point in an observation by Migdal¹⁷² that a three-body system, for which the three possible two-body systems are unbound, can still have a bound state. Empirically, this is clearly the case for ^{11}Li , considered as ^9Li plus two neutrons. The force between two neutrons is almost strong enough to form bound ^2n , and with the stabilization provided by the ^9Li core, we may view the final state as this core coupled to a dineutron. One finds that the marginal binding of the dineutron leads to a neutronization of the nuclear surface, so that the nucleus becomes surrounded by a neutron halo extending to several times the nuclear radius. Simple estimates show that this effect can explain the large matter radius for ^{11}Li observed experimentally (Fig. 5). Another consequence of the loose binding near the drip line will be very large cross-sections for Coulomb stripping, since the cross-section varies in a way that is approximately inversely proportional to binding energy.

In conclusion, it seems as if the nuclei very near the neutron drip line are likely to have peculiar properties, of which the last few years have brought us the first experimental indications. Extrapolations based on analytic continuation of models and features developed in the well-known region are far from being safe, and could be very wrong in some cases. It is only two decades ago that the first nuclei situated at the drip line were observed as a kind of zoological curiosity. One decade ago, approximately, studies of their most essential properties began, but new techniques developed within the last few years, or still in preparation, promise that we will now be able to attack problems that offer some qualitatively new features. In the study of nuclei far from stability, the neutron-rich region seems to be the one that holds the most promise for the future.

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