peak. The Mont Blanc experiment mentioned above was of this type and obtained a lower limit on the half-life of 5×10^{21} y. In another underground experiment, reported recently by Avignone et al., *Phys. Rev. C* 34, 666 (1986), extraordinary measures were taken to surround the detector only with material that would not contribute substantially to the background (stainless steel screws, which showed contamination from ^{60}Co, were replaced with brass, and rubber O-rings were replaced with indium). After 9 months of counting, there was no visible peak at 2.04 MeV, and the half-life was deduced to be greater than 10^{23} y. These experiments are continuing, in the hope that continued improvements in sensitivity will enable both the two-neutrino and the neutrinoless $\beta\beta$ decays to be observed directly.

Although the theoretical interpretations are difficult, it may be that the search for evidence of neutrinoless $\beta\beta$ decay will be an important source of information on the fundamental character of the neutrinos. The emission-reabsorption process described above, for instance, is impossible for massless neutrinos with definite helicities (± 1), and so the observation of the neutrinoless $\beta\beta$ decay would immediately suggest that the "classical" properties of the neutrino are not correct.

9.8 BETA-DELAYED NUCLEON EMISSION

Gamma rays are not the only form of radiation that can be emitted from nuclear *excited* states that are populated following β decay. Occasionally the states are unstable against the emission of one or more nucleons. The nucleon emission itself occurs rapidly (so that it competes with γ emission), and thus overall the nucleon emission occurs with a half-life characteristic of the β decay.

For decays of nuclei only one or two places from the most stable isobar of each mass number A, the decay energies are small (1–2 MeV), and nucleon emission is forbidden by energetics. Far from the stable nuclei, the decay energies may become large enough to populate highly excited states, which may then decay through nucleon emission. A schematic diagram of this process for proton emission is shown in Figure 9.13. The original β-decaying parent is called the *precursor*; the nucleons themselves come from the *emitter* and eventually lead to states in the *daughter*.

Interest in delayed nucleon emission has increased in recent years in concert with experimental studies of nuclei far from stability. Additional interest comes from the importance of delayed neutrons in the control of nuclear reactors (see Chapter 13). However, the discovery of the phenomenon dates from the early history of nuclear physics—Rutherford in 1916 reported "long-range alpha particles" following the β decay of ^{212}Bi. The main branch in this β decay goes to the ground state of ^{212}Po, which in turn emits α particles with an energy of 8.784 MeV. (Since the α-decaying state is a 0^+ ground state of an even-even nucleus, the decay proceeds virtually 100% to the ground state of ^{208}Pb.) A small number of α's, however, were observed with *higher* energies (9.495 MeV, 0.0035%; 10.422 MeV, 0.0020%; 10.543 MeV, 0.017%). Lower energies would have indicated decays *to* excited states of ^{208}Pb, but higher energies must indicate decays *from* excited states of ^{212}Po. Similar behavior was observed in the decay of ^{214}Bi.

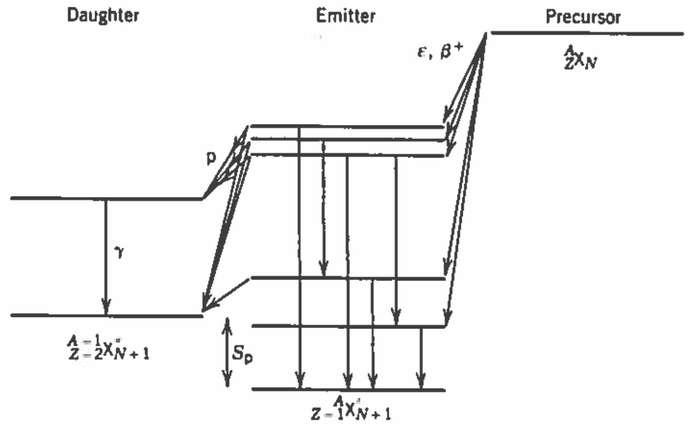

Figure 9.13 Schematic of β-delayed nucleon emission. The β decay of the precursor populates highly excited states in the emitter that are unstable with respect to nucleon emission. Note that the energy of the excited state in the emitter equals the sum of the energy of the emitted nucleon plus the nucleon separation energy between X′ and X″ (plus the small correction for the recoil of the emitting nucleus).

The calculation of the energy spectra of the emitted nucleons is a complicated process, requiring knowledge of the spectrum of excited states in the emitter, the probabilities for β decay from the precursor to each state of the emitter, and the probabilities of nucleon decay for each state of the emitter to the accessible states of the daughter. The difficulty is compounded in heavy nuclei by the large density of excited states—the average spacing between excited states at high energy may be of order eV, far smaller than our ability to resolve individual proton or neutron groups; thus all we observe in such cases is a broad distribution, similar in structure to the continuous distribution in β decay but originating from a very different effect. Because of these difficulties, we shall not discuss the theory of delayed nucleon emission; rather, we shall give some examples of experimental studies and their significance.

The energetics of β-delayed nucleon emission are relatively simple. Reference to Figure 9.13 shows immediately that the process can occur as long as the β-decay energy is greater than the nucleon separation energy: $Q_\beta > S_N$ (where N = n or p). Whenever this process is energetically permitted, there will always be competing processes; for example, γ decay of the emitting state or β decays to lower levels in the emitter that cannot decay by particle emission.

The information that we derive from β-delayed nucleon emission is mainly of two types: (1) Since the decay is a two-body process (emitted nucleon plus daughter nucleus), the nucleons emerge with a distinct energy, which gives directly the energy difference between the initial and final states. The energy levels in the daughter are usually well known, and so the energy of the emitted nucleon is in effect a measure of the energy of the excited state of the emitter. (2) From the relative probability of nucleon emission from different states in the emitter, we can deduce the relative population of these states in the β decay of the precursor. This provides information on the β-decay matrix elements. Because the highly excited states in the emitter are so close together, they nearly form a continuum, and it is more appropriate to consider a β-decay strength function $S_\beta(E_x)$, which gives the average β-decay intensity leading to excited states in the vicinity of excitation energy E_x. Usually there are few selection rules inhibiting β decay to states at this high excitation, and so the β-decay strength function is rather featureless and is roughly proportional to the density of states $\rho(E_x)$. However, there is always one particular state that is so similar in character to the precursor that the majority of the β decays populate that state (it has a particularly large Fermi-type matrix element). The state is known as the *isobaric analog state* (or simply, analog state) because its structure is analogous to the original decaying state in the neighboring isobar. The β-decay strength leading to the analog state (and its energy) can often be determined only through the technique of β-delayed nucleon emission.

As an example of a typical experiment, we consider the β-delayed neutron emission from ^{17}N, which decays by negative β emission to ^{17}O. Figure 9.14 shows three readily identifiable neutron groups, with energies 383, 1171, and 1700 keV; we assume that three excited states of ^{17}O are populated in the β decay and that each emits a neutron to form ^{16}O. Let us assume that these decays go directly to the ground state of ^{16}O. (This is certainly not going to be true in general, but ^{16}O has its first excited state at more than 6 MeV; we will see that it is not possible that the ^{17}N β decay could have enough energy to populate such a highly excited state.)

To analyze the energy transfer in the decay, we first need the neutron separation energy of ^{17}O; using Equation 3.26:

$$\begin{aligned} S_n &= \left[m(^{16}O) - m(^{17}O) + m_n\right]c^2 \\ &= (15.99491464\,u - 16.9991306\,u + 1.008664967\,u)931.502\,MeV/u \\ &= 4.144\,MeV \end{aligned}$$

This is the energy that must be supplied to remove a neutron from ^{17}O. Let's regard the initial state of the system as ^{17}O in an excited state with energy E_x. The initial energy is therefore $m(^{17}O)c^2 + E_x$. The final energy is $m(^{16}O)c^2 + E_x'$ $+ m_n c^2 + T_n + T_R$, where T_n is the neutron kinetic energy and T_R is the energy of the ^{16}O recoil, which must occur to conserve momentum. We have included a possible excitation energy of ^{16}O in the term E_x'; later we will show it must be zero in this case. Energy conservation gives

$$m(^{17}O)c^2 + E_x = m(^{16}O)c^2 + E_x' + m_n c^2 + T_n + T_R$$

or

$$E_x = E_x' + T_n + T_R + S_n \tag{9.43}$$

which is a general result. The recoil correction is obtained by application of conservation of momentum, yielding

$$T_R = T_n\left(\frac{m_n}{m_R}\right) \approx T_n\frac{1}{A-1} \tag{9.44}$$

where m_R is the mass of the recoiling nucleus. Since this is a small correction, we can approximate m_n/m_R by $1/(A-1)$. The final result is

$$E_x = E_x' + \frac{A}{A-1}T_n + S_n \tag{9.45}$$

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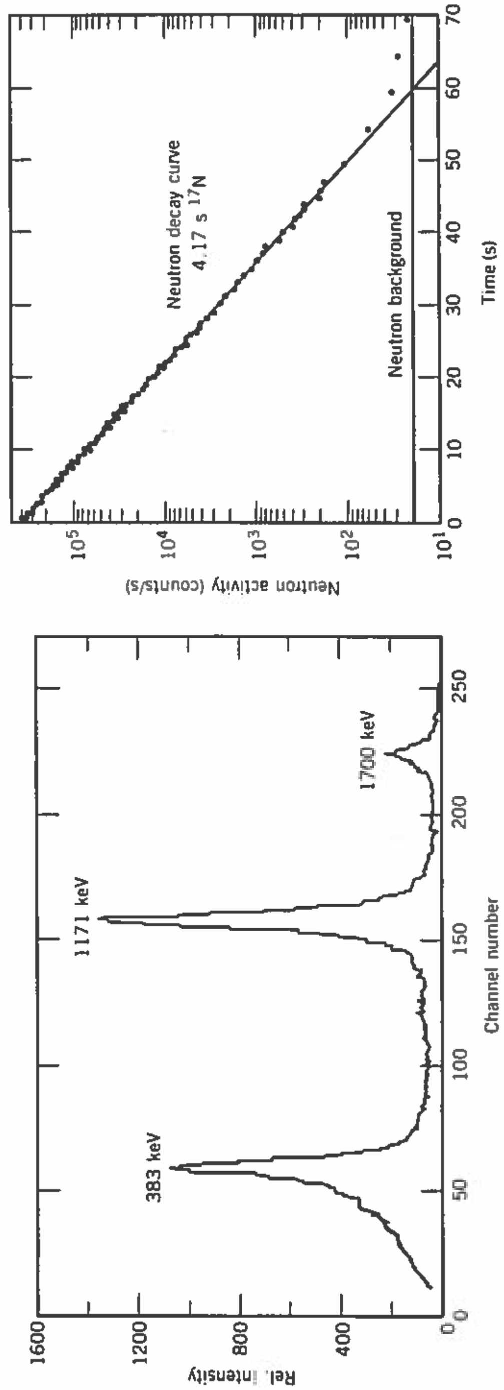

Figure 9.14 Beta-delayed neutrons following the decay of ^{17}N. The neutron energy spectrum is shown at the left; the decay of the neutron activity with time is at the right. From H. Ohm et al., *Nucl. Phys. A* **274**, 45 (1976).

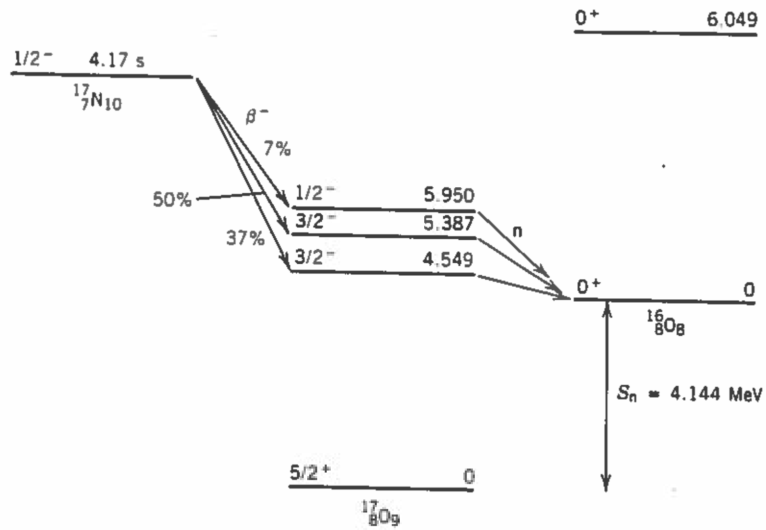

Figure 9.15 The β-delayed neutron decay of ^{17}N.

Assuming $E_x' = 0$ for ^{16}O, the three measured ^{17}N β-delayed neutron energies give excitation energies of 4.551, 5.388, and 5.950 MeV. Nuclear reactions can also be used to measure the energies of the ^{17}O excited states, and three states are found in reaction studies with the energies we have just calculated. If we were to consider the possibility to reach excited states in ^{16}O (that is, $E_x' \geq 6.049$ MeV, the first excited state in ^{16}O), then the lowest possible excitation in ^{17}O would be 10.6 MeV, which is greater than the Q value of the ^{17}N β decay (8.68 MeV). Excited states in ^{16}O are therefore not populated in this decay.

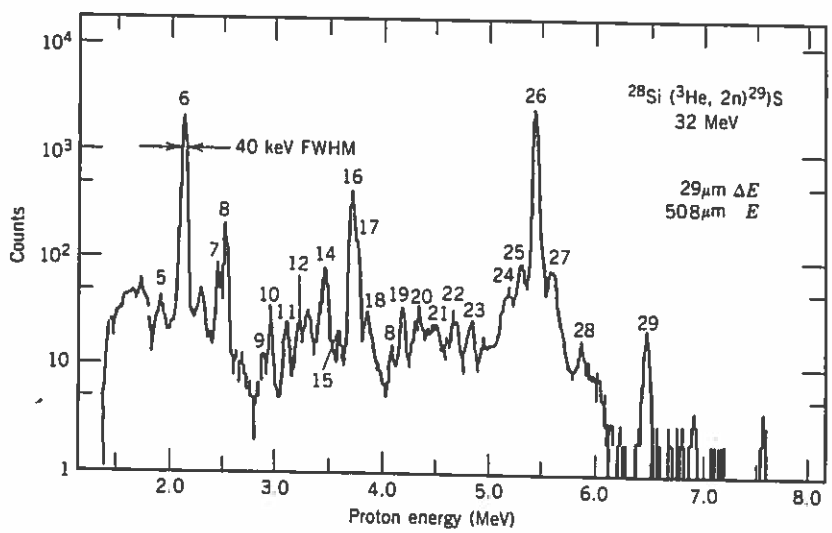

Figure 9.16 Protons emitted following the β decay of ^{29}S. The protons were observed using a $\Delta E \cdot E$ telescope of Si detectors. The numbers refer to specific proton decays of excited state of ^{29}P. Data from D. J. Vieira et al., *Phys. Rev. C* **19**, 177 (1979).

Figure 9.14 also shows the rate of neutron emission as a function of time, which gives the half-life of ^{17}N to be 4.17 s. This half-life is far too long for the decay to be a direct neutron emission process and it must therefore be a β-delayed emission process. The resulting decay is shown in Figure 9.15.

Proton emission will occur most easily from nuclei with an excess of protons, which is certainly the case for ^{29}S ($Z = 16$, $N = 13$). The activity is formed through the reaction $^{28}Si + {}^{3}He \rightarrow {}^{29}S + 2n$, which essentially adds two protons and removes a neutron from the stable initial nucleus ($Z = 14$, $N = 14$). The

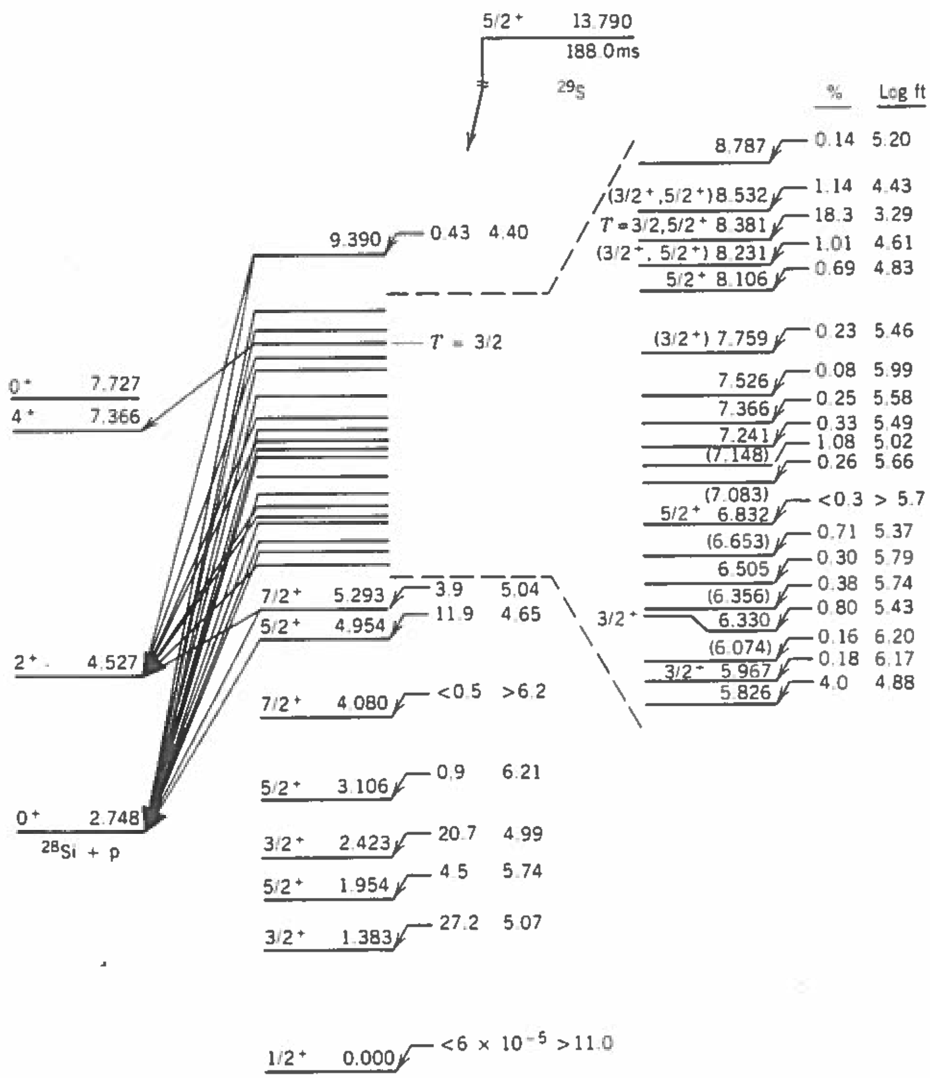

Figure 9.17 Excited states of ^{29}P deduced from the β-delayed proton decay of ^{29}S. The *ft* values are deduced from the intensity of the observed protons. Note the strong decay branch (small *ft* value) in the decay to the state at 8.381 MeV, which is the analog state of the ^{29}S ground state.

precursor ^{29}S decays by β^+ emission to states in the emitter ^{29}P, which then emits protons leading to final states in ^{28}Si. Figure 9.16 shows the observed proton spectrum, and Figure 9.17 illustrates the assignment of these proton groups to known initial and final states in ^{29}P and ^{28}Si. Many of the arguments for placing these decays proceed indirectly; for example, the energy difference between the 0^+ ground state and 2^+ first excited state in ^{28}Si is known to be 1.778 MeV, and thus two proton groups differing in energy by 1.778 MeV can be assumed to lead from the same state in the emitter to these two different final states in the daughter (groups 16 and 26, 18 and 27, 22 and 29). The analog state is associated with the strong groups 16 and 26; its log ft value of 3.29 is characteristic of superallowed decays, as expected for this strongly favored transition.

As we go to heavier nuclei, the density of excited states in the emitter becomes so large that the spacing between levels is smaller than the energy resolution of the detector. When this occurs, it is no longer possible to make the above identification of decays from specific states in the emitter, and only broad, average features of the decay can be discussed (Figure 9.18).

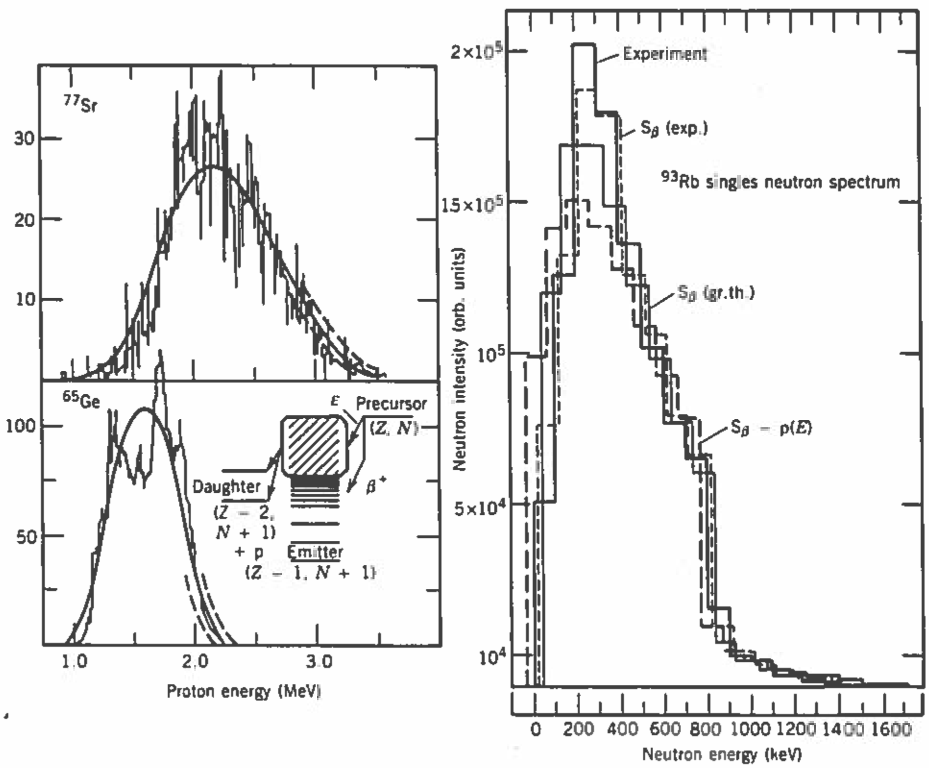

Figure 9.18 Proton (left) and neutron (right) emission following β decay in heavy nuclei. The spacing between excited states in the emitter is so small that we observe only a broad distribution, rather than the individual peaks of Figures 9.14 and 9.16. Attempts to fit the experimental data are based on statistical models, rather than on detailed calculations of individual nuclear states. Proton data from J. C. Hardy et al., *Phys. Lett. B* **63**, 27 (1976); neutron data from K.-L. Kratz et al., *Z. Phys. A* **306**, 239 (1982).