DELAYED-PROTON EMISSION FROM NEUTRON-DEFICIENT ISOTOPES OF XENON AND MERCURY

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1. INTRODUCTION

The heaviest element for which delayed-proton emission[1] has been reported is tellurium[2] (Z=52), and there is experimental evidence[3] pointing to the existence of delayed-proton emitters also in heavier elements (Xe-Ba). Here, we wish to report the results obtained until now at the ISOLDE facility[4] on delayed-proton-emitting isotopes of xenon (Z=54) and mercury (Z=80).

2. ENERGY SPECTRA AND INTENSITIES

Most of the experiments have been carried out with counter telescopes based on totally depleted silicon counters. In order to avoid the decay losses that occur when moving-tape or moving-disc collector systems are used, the samples were counted in the backward angle directly at the collection position (see captions to Fig. 1 and Fig. 3). The spectra of ^{181}Hg and ^{115}Xe are shown in Figs. 1 and 5.

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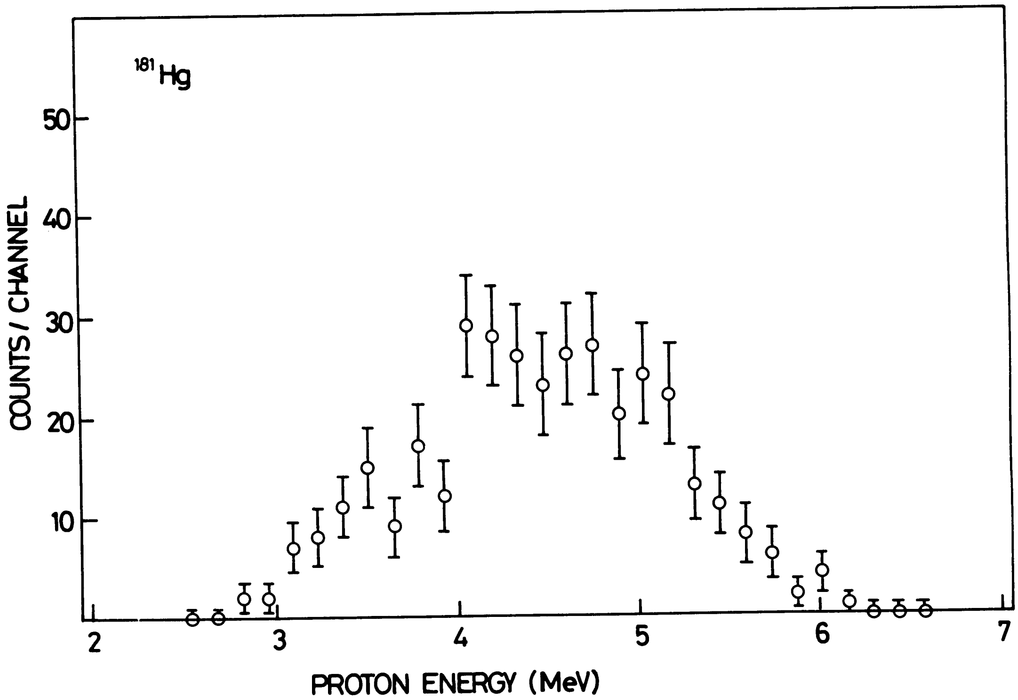


Fig. 1 : Delayed-proton spectrum of 3.6 sec ^{181}Hg measured with a counter telescope consisting of two totally depleted silicon counters, one 40 μ thick and 150 mm^2 in area, the other 400 μ thick and 450 mm^2 in area. The activity was collected on a thin foil placed directly in the beam of mass-separated radioactivity, and the counters were behind the foil to give a solid angle of 15% of 4π. Note that the dE/dx counter was chosen thick enough to stop all alphas; in addition to the dE/dx demand, it was required that more than 1 MeV was deposited in the back counter. The 50% cut-off of this system is at 2.2 MeV. For the xenon isotopes, where the proton spectrum extends further down and where there is no alpha problem, we used a 20 μ front counter. Here the cut-off was 1.5 MeV.

The absolute intensities of the proton branches of ^{181}Hg and ^{115,117}Xe were determined by absolute counting of gamma-rays from the long-lived daughter products accumulated on the collector foils. During the collection, the proton count rate was monitored to allow corrections for fluctuations in the intensity of the radioactive beam. The absolute gamma-ray intensities used were taken from elsewhere[5)]. For the mercury isotopes, the proton intensity was also determined relative to that of the well-known[6)] alpha intensities; the intensities given for ^{179,183}Hg were obtained on this basis. The main characteristics of the five proton emitters reported in the present work are summarized in Table 1.

Table 1

Delayed-proton emission from light mercury and xenon isotopes

Isotope	Half-life (sec)	p/alpha	p/dis
^{115}Xe	18 ± 4[a)]	-	$(3.4 \pm 0.6) \times 10^{-3}$
^{117}Xe	65 ± 6[b)]	-	$(2.9 \pm 0.6) \times 10^{-5}$
^{179}Hg	1.09 ± 0.04[c)]	$(2.7 \pm 0.5) \times 10^{-3}$	$\approx 1.4 \times 10^{-3}$
^{181}Hg	3.6 ± 0.3[c)]	$(4.2 \pm 0.6) \times 10^{-4}$	$(1.3 \pm 0.4) \times 10^{-4}$
^{183}Hg	8.8 ± 0.5[c)]	$(2.2 \pm 0.3) \times 10^{-5}$	$(2.7 \pm 0.6) \times 10^{-6}$

a) Determined from proton counting. A half-life of 19 ± 5 sec was found from beta counting. [The ISOLDE Collaboration, Phys. Letters 28 B, 415 (1969).]

b) The ISOLDE Collaboration, Phys. Letters 28 B, 415 (1969).

c) P.G. Hansen, H.L. Nielsen, K. Wilsky, M. Alpsten, M. Finger, A. Lindahl, R.A. Nauman and O.B. Nielsen, Nuclear Phys. A148, 249 (1970); P.G. Hansen, B. Jonson, J. Żylicz, M. Alpsten, Å. Appelqvist and G. Nyman, Nuclear Phys., in press.

It would be of interest to extend these investigations to proton emitters with low yields or low branching ratios. When carried out with counters, however, such experiments become very time-consuming, in particular because of the necessity of performing extensive background controls including mass settings away from the mass of interest. We have therefore recently begun experiments with the rotating-disc apparatus shown in Fig. 2. The apparatus should also be well suited for detecting fission fragments or long-range alpha particles. For protons, the detecting element is a 400 μ thick nuclear emulsion (Ilford K2). In the experiments, several masses are surveyed at the same time, and the half-life and an energy spectrum is also obtained. During the summer of 1970, exposures have been made for Xe and Cd. Until now, only the plates from the Cd exposure have been developed. There is an indication that previously unobserved ^{99}Cd may be a delayed-proton emitter.

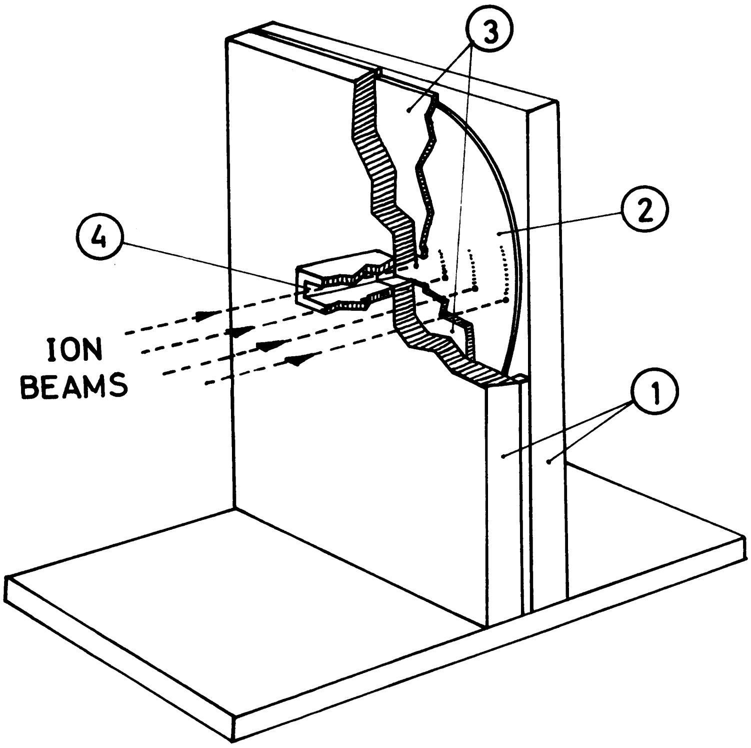


Fig. 2 : Rotating-disc apparatus used in the search for new, low-intensity proton emitters. The separated radioactive isotopes enter the apparatus through the slit (4) and are stopped on the rotating disc (2). Proton events are detected in Ilford K2 nuclear emulsions (3) facing the disc. The set-up is placed inside the collector chamber of the isotope separator shielded by 2 cm of lead (1).

3. COINCIDENCE EXPERIMENTS

For a detailed theoretical understanding of delayed-proton emission in heavy nuclei, it is of great importance to know which levels in the daughter isotope are being fed. Prompted in part by a calculation (Section 4) which showed that the ^{115}Xe protons should be abundantly in coincidence with gamma-rays, we have performed a series of proton-gamma coincidence measurements with the apparatus shown in Fig. 3. The results for ^{115}Xe are shown in Fig. 4; at 3 MeV proton energy the protons are (63 ± 10)% in coincidence with a 709 keV gamma-ray known[7] to proceed between the first excited state and the ground state of ^{114}Te. The ^{117}Xe protons go largely to the ground state of ^{116}Te with a weak branch coincident with a 0.68 MeV gamma-ray. The ^{181}Hg proton spectrum populates predominantly the known 159 keV 2^+ level[6] of ^{180}Pt.

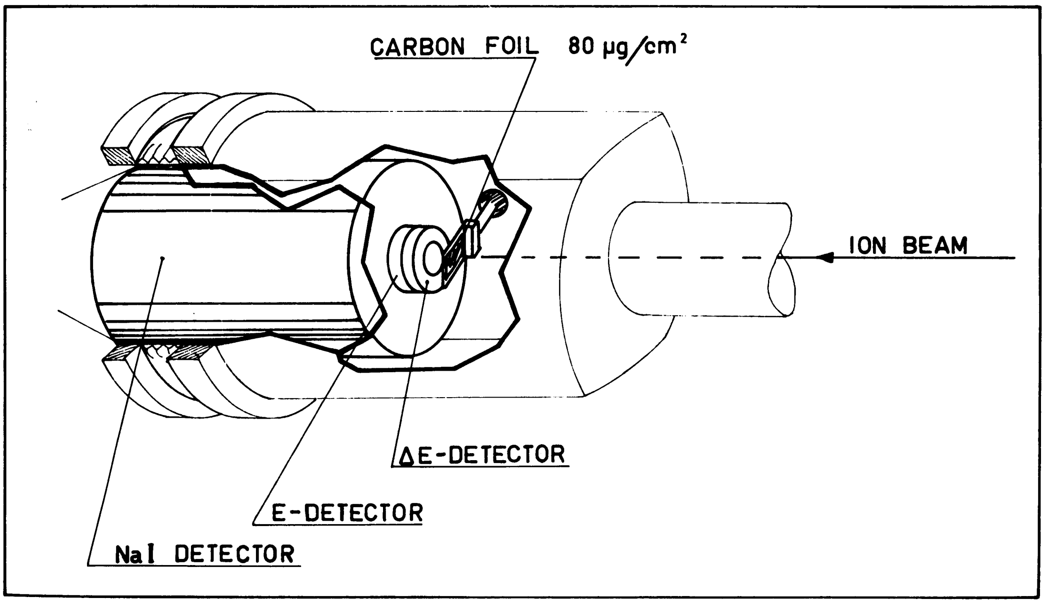


Fig. 3 : Coincidence set-up used for determining proton-gamma coincidences. Through an ion-optical transfer line[14] the radioactivity is focused on a 80 $\mu g/cm^2$ carbon foil placed in front of the counter telescope (see the caption for Fig. 1). Immediately behind this is placed a 3" NaI(Tl) crystal.

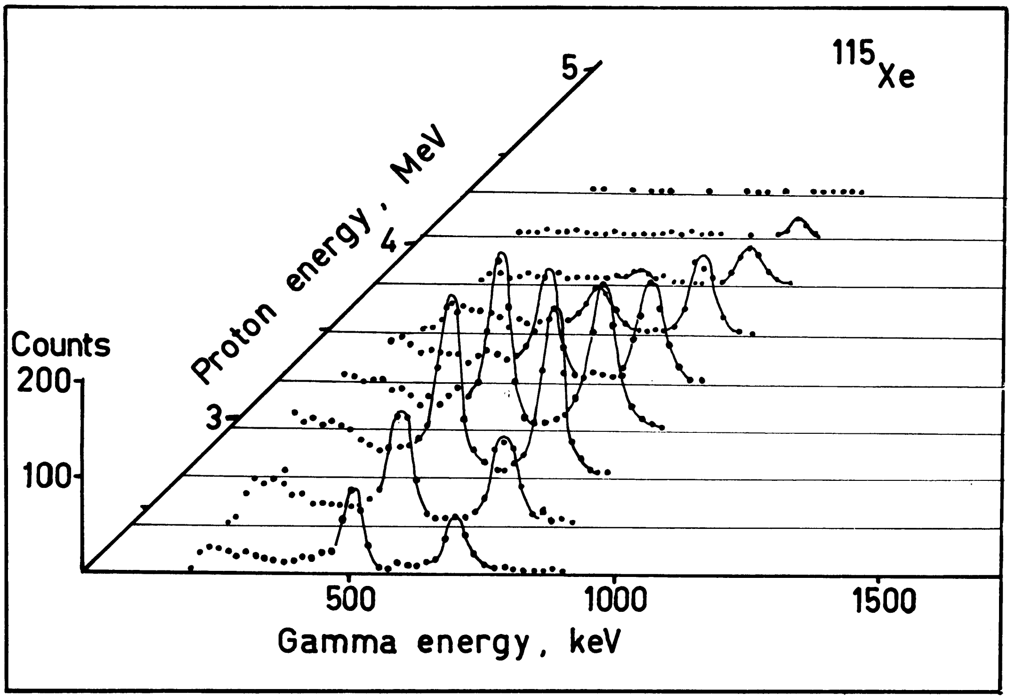
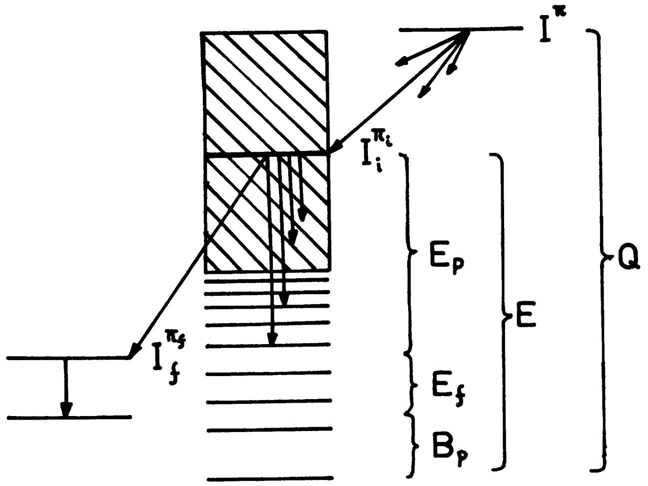


Fig. 4 : Two-dimensional spectrum of coincidence events between delayed protons and gamma-rays in the decay of ^{115}Xe. The gamma lines are annihilation radiation from positron decays, and the 0.71 MeV gamma-ray ($2^+ \rightarrow 0^+$) from ^{114}Te.

4. INTERPRETATION OF THE SPECTRA

Unlike the tellurium proton emitters, the proton spectra observed in the present work do not show well-developed fine structure (see also Fig. 1 of Ref. 9). This indicates that the spectra may be accounted for in the statistical model. A calculation similar to that performed by Karnaukhov et al.[8] has been carried out. With the energy, spin, and parity notation as given in the diagram below,



the energy spectrum of the protons may be written as

$$\mathcal{G}_p(E_p) = \sum_{f} \sum_{I_i,\pi_i} \omega_\beta(I,I_i) \cdot \mathcal{G}_\beta(E) \cdot \frac{\Gamma_p^{if}}{\Gamma^i} , \tag{1}$$

where $\omega_\beta(I,I_i)$ is a spin weight factor, and where the beta intensity $\mathcal{G}_\beta(E)$ to levels with the energy E is calculated from the model strength functions described by Damkjær et al.[9]:

$$\mathcal{G}_\beta(E) = f(Q - E,Z) / \int_C^Q f(Q - E,Z)\, dE . \tag{2}$$

The sum in Eq. (1) extends over all intermediate spins and parities in the compound nucleus, and over all final levels f. The compound nucleus expression for the average partial proton width is

$$\Gamma_p^{if}(E_p) = \frac{\sum_{j,\pi_i\pi_f} T_{\ell j}(E_p)}{2\pi\, \rho_i(E)} , \tag{3}$$

where $\rho_i(E)$ is the density of levels with spin I_i at the energy E, and where the sum over the penetrabilities includes only the proton waves corresponding to the parity $\pi_i \pi_f$. The average total width of the levels with spin I_i is

$$\Gamma^i = \Gamma^i_\gamma + \sum_f \Gamma^{if}_p(Ep) \quad . \tag{4}$$

Calculations have been carried out based on the level-density expression given by Newton[10], and with Cameron's empirical expression[11] for the average gamma widths. The proton penetrabilities have been taken from the optical-model calculations of Mani et al.[12].

The expression (3) for the partial proton width is probably the most interesting term in the calculation. It shows that delayed protons are emitted as the result of the competition between a dramatically increasing penetrability for sub-barrier protons and an almost equally strongly increasing level density function. The gamma widths vary relatively slowly with the excitation energy. It is for these reasons that the delayed-proton spectra cover a wide energy range.

The proton spectrum shown in Fig. 5 is calculated under the assumption that the initial spin of ^{115}Xe is $5/2^+$. The spectrum is seen to be dominated by an s-wave component to the first 2^+ level of ^{114}Te with a weaker d-wave branch of higher energy to the ground level. The intensity agrees fortuitously well with experiment. The main features of the calculation are confirmed not only by the high-energy (d-wave) tail observed in the singles spectrum (Fig. 5) but also by the coincidence experiment described in Section 3.

The calculations for ^{117}Xe were also carried out assuming a $5/2^+$ assignment. The result resembles that of Karnaukhov and co-workers[8]: the d-wave to the ground level now dominates and only a weak branch to the 2^+ level appears. This is in agreement with our coincidence experiment.

The ^{181}Hg spectrum can be fitted with a single s-wave component, whereas the ^{183}Hg spectrum seems to require a superposition of s and p components[9].

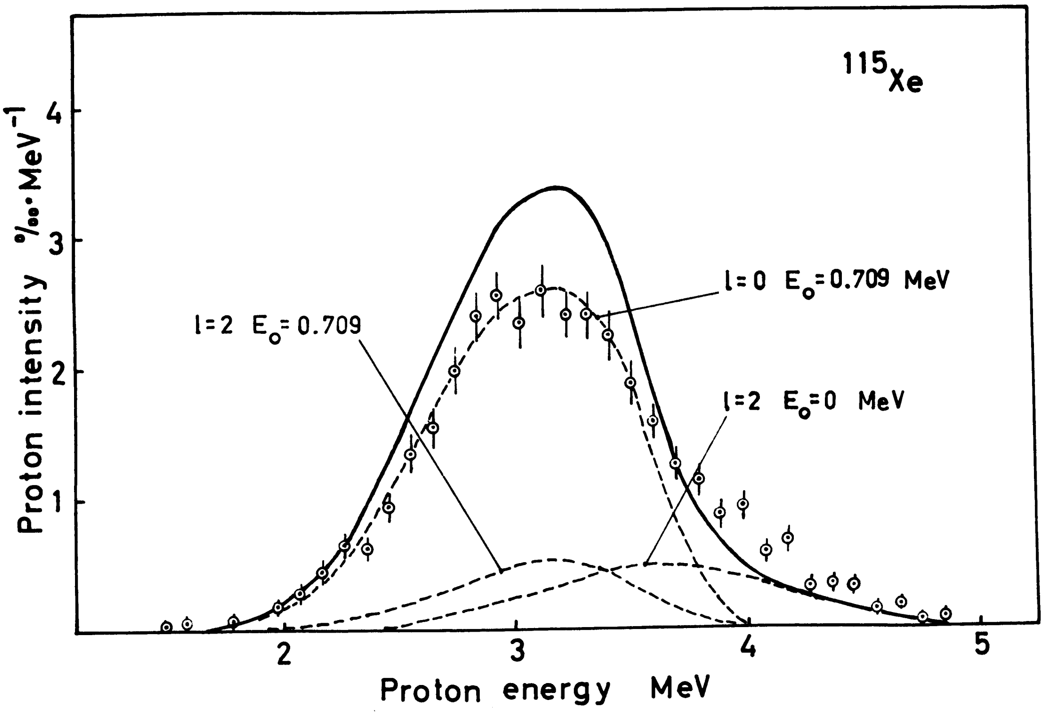


Fig. 5 : Delayed-proton spectrum of ^{115}Xe measured in the singles mode (see the caption for Fig. 1). The full-drawn curve is the calculated total spectrum (see text), while the dashed curves represent the individual components. The comparison is being made on an absolute scale.

5. CONCLUSION

Delayed proton spectroscopy is a promising tool for studying heavier nuclei. The main features of the calculation given in Section 4 are well supported, although further calculations and experiments are necessary. We believe that the approach taken here, in particular the use of slowly varying beta strength functions with a low-energy cut-off, should also be the key to calculations of delayed-neutron spectra and intensities.

It seems likely that delayed-proton spectra may be used to obtain nuclear level densities as a function of energy [see Eq. (3)]. In this connection it is interesting to note that until now we have failed to observe even-even proton precursors. This is mainly due to the lower Q value of the beta decay (because of the pair energy), but there should also be an effect of the higher level density in the odd-odd system. It should be interesting to compare the proton spectra of even- and odd-mass isotopes.

The use of delayed-proton spectra for determining spins and parities of the compound levels populated in beta decay was discussed in Ref. 9. In turn, this will provide information on the spin and parity of the initial level. Tentatively, we assign to $^{115,117}Xe$ the spin and parity $(5/2 \text{ or } 7/2)^+$, and to ^{181}Hg $3/2^-$ (Note that in this case we have established the absence of any appreciable branch to the 4^+ level in ^{180}Pt). The ground state of ^{183}Hg probably has even parity.

A further study of the fluctuations[8)] in the proton spectra might also be rewarding.

The authors are indebted to the CERN Nuclear Chemistry Group, in particular to Dr. A. Kjelberg for help and support. They wish to thank Dr. J.P. Bondorf for advice regarding the calculation of the proton widths.

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