dependent and independent terms.[7] The scattering terms may be either destructive or constructive. We point out only that in the pseudoscalar perturbation theory with pseudoscalar coupling,

$$4\pi\,\mathrm{Re}(s^{p*}s^{n})=\sigma^{p}=\sigma_{s}{}^{n};\quad \mathrm{Re}(\mathbf{S}^{p*}\cdot\mathbf{S}^{n})=0.$$

The interference is expected to be strongly constructive, in disagreement with the experimental result. The pseudovector coupling results, neglecting nuclear recoil, are

$$4\pi\,\mathrm{Re}(s^{p*}s^{n})=-\sigma^{n}\cos^{2}\theta=-\sigma^{n}\cos^{2}\theta,$$

$$4\pi\,\mathrm{Re}(\mathbf{S}^{p}\cdot\mathbf{S}^{n})=\sigma^{p}\sin^{2}\theta=\sigma^{n}\sin^{2}\theta,$$

$$2\int d\omega F(\Delta q)[\mathrm{Re}(s^{p*}s^{n})+\tfrac{1}{3}\mathrm{Re}(\mathbf{S}^{n*}\cdot\mathbf{S}^{n})]=-0.1\sigma^{p}=-0.1\sigma^{n}\approx-2.5\text{ mb}.$$

The net interference is destructive, but smaller than the experimentally observed interference.

[7] The charge exchange cross section is necessarily less than the cross section of π^{-} on p; the interference due to the charge exchange reaction is therefore at most 8 mb, and this only if all scattering of negative pions or protons were charge exchange.

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The Beta-Spectrum of RaD

G. M. INSCH, J. G. BALFOUR, AND S. C. CURRAN
Department of Natural Philosophy, University of Glasgow, Glasgow, Scotland
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The electronic radiations from a very thin source of RaD are analyzed by means of a proportional counter, operating as a 2π spectrometer. The β-rays of the continuum which coincide with the photoelectrons of highest energy form the tail on the pulse distribution which is analyzed to isolate the β-particles and to compare their spectrum with Fermi theory. The disintegration energy is found to be 64.5 ± 2.5 kev and the limiting energy of the β-rays$=18\pm2.5$ kev. The form of the spectrum agrees with the theoretical shape for an allowed transition and $E_0=18$ kev. The presence of a complex system of soft photoelectron peaks, probably emitted mostly in cascade, is deduced from the remarkable shape of the pulse spectrum at low energies (5 to 25 kev).

INTRODUCTION

THE unsatisfactory situation existing as late as 1949 in our understanding of the decay of RaD has been well summarized by Feather.[1] Isolation of the continuous β-spectrum had not been achieved and the rather large number of low intensity γ-rays detected (energies 7.3, 16.1, 23.2, 31.3, 37, 42.6, 46.7 kev) did not readily suggest a unique system of levels. Feather, however, points out two significant groupings of quantum energies. Very recent work by Cranberg,[2] Frilley *et al.*,[3] and Butt and Brodie[4] has extended knowledge of the decay, but they have not been concerned with the main objective of the present work, which was the examination of the β-spectrum. Most observers[5,6] agree that the β-rays are very soft, but even the limiting energy has not been well defined, estimates ranging from $\sim$15 to $\sim$40 kev.

The proportional tube spectrometer is clearly suited to the study of the soft radiations of RaD and has been employed in examining the L x-rays and soft γ-rays.[7] Early work on the particles proved somewhat difficult, mainly on account of difficulties in preparing gaseous or solid sources effectively free of RaE and RaF, both of which contributed very large disturbing pulses. More recently, however, relatively clean sources ($\sim$97 percent) have been separated following the method used by Cranberg[2] and this has greatly assisted in the successful application of the instrument. It has been found possible, by direct examination of the particles emitted from a thin source ($\sim$20 μg of chloride) mounted on thin foils (Nylon $\sim$50 μg/cm^2 and aluminium $\sim$1.6 mg/cm^2), to separate the β-rays from the relatively very intense and complex system of photoelectron lines of low energy. The separation was sufficiently good to permit comparison of the shape of the spectrum with Fermi theory. The tube with source at an aperture in the cathode constitutes a spectrometer of 2π acceptance angle.

APPARATUS

The proportional counter, 1.4 inches in diameter and 8 inches in fully operating length[8] was enclosed in a cylindrical vessel C, Fig. 1, into which the thin source could be slipped. The vessel was filled to a pressure of one atmosphere and the mixture (ethylene+16 cm of argon) was such that the efficiency of the L x-rays of RaE from the source was <5 percent. The spectrometer was thus rendered responsive chiefly to photoelectrons and β-rays, but it was, of course, sensitive to the very soft M x-radiations. It integrated the ionizing events

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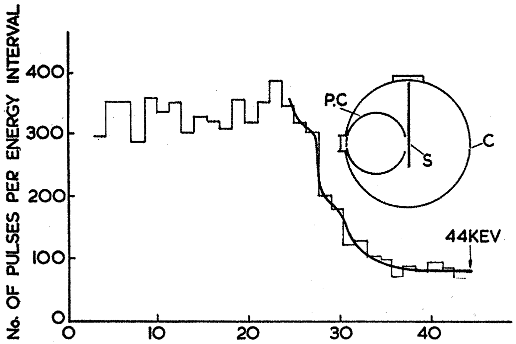

FIG. 1. Pulse spectrum shape between ∼4 and 40 kev using source of counting rate 2.5×10^4 c/min mounted on aluminum, 1.6 mg/cm². The counter is shown in the inset. The source S is at an aperture in the proportional tube spectrometer $P.C.$

which occurred within ∼10 μsec of each other. The counting rate was usually between 2×10^4 and 3×10^4 c/min. Calibration was achieved with fluorescence x-rays of Cu $K\alpha$ of energy 8.04 kev, the amplifier gain being increased by a factor of 4. The output pulses from the amplifier were analyzed by means of the cathode-ray tube and moving film technique.

RESULTS

The total range of the pulse spectrum was covered in two overlapping parts, from ∼4 to 40 kev, Fig. 1, and from 33 to beyond 80 kev. This region is shown separately in Fig. 2, and the final end point occurs at 62±2.5 kev. This value was verified by critical examination of the spectrum shape between 50 and 70 kev with improved statistical data.

The shape of the distribution is very remarkable, but it has been confirmed in several different experimental arrangements of counter and source. The nearly flat plateau between 4 and 26 kev shows definitely significant peaks around 10 and 23 kev. Independent work in this department, using scintillation spectrometers, confirms these results and suggests that the form of the curve arises from the emission of homogeneous photoelectrons of various energies, produced by internal conversion of soft γ-rays in the L and M shells of RaE, which are frequently emitted in cascade so that the pulse spectrum is produced mainly by different combinations of β-rays and photoelectrons. The presence of the associated β-rays is largely responsible for the nearly complete failure to resolve the many groups. We do not propose to discuss further this part of the curve.

Beyond the main plateau two plateaus of shorter length are clearly observed. These terminate at energies of nearly 30 kev and about 44 kev and are ascribed to the presence of the two well-established lines in the photoelectric spectrum (L and M shell conversion of the hardest γ-ray, energy 46.7 kev). The energies are close to the expected values if some allowance is made for energy loss of the photoelectrons in the source and the possibility of simultaneous detection of M x-radiations in the case of the second. The smooth drop of the curve above each plateau suggests the presence of β-particles of the continuum since these can be detected simultaneously if the life of the excitation level at 46.7 kev does not exceed 10 μsec. Four combinations of β-particle and photoelectron e^- are possible: (a) β and e^- backward, neither detected; (b) β forward into counter, e^- back, β alone detected; (c) e^- forward, β back, e^- alone detected; (d) β and e^- forward, both detected as a single ionizing event.

Case (b) gives rise to β-rays which are merged in the general distribution at low energies. Case (c) gives a tendency to peak at about 30 and 44 kev, while (d) is chiefly responsible for tails at energies above the peaks. We expect, therefore, that close examination of the shape of the curve from around 44 kev to 62 kev will give a clear picture of the β-spectrum associated with

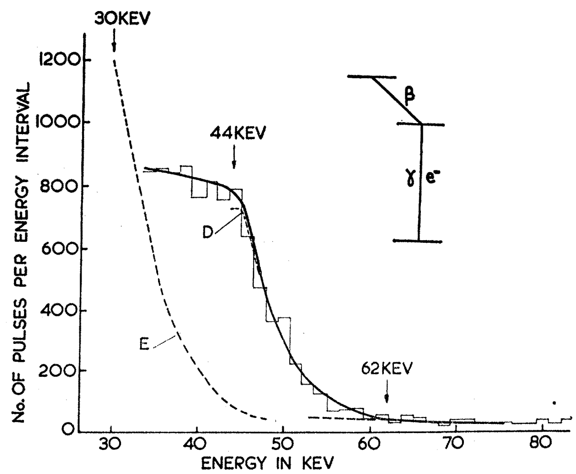

FIG. 2. Curve D shows modification of end of spectrum obtained by using curve E which represents the combination of photoelectrons, ∼30 kev in energy, with β-rays.

the level at 46.7 kev. This part of the curve must necessarily represent the β-distribution closely.

ANALYSIS OF THE β-SPECTRUM

A theoretical Fermi distribution $F(Z=83$, allowed) for an energy limit E_0 of 18 kev was evaluated. This value of E_0 followed from the facts that the over-all end-point of Fig. 2 occurs at 62 kev and the photoelectron peak due to M-shell conversion at 44 kev. The curves of Fig. 3 indicate the method of using F. Thus curve P, centered at 44 kev, and representing the form that a homogeneous group of electrons of this energy would take as experimentally analyzed by the tube (based on observations with γ-rays of energy 46.7 kev) was constructed so that the areas under P and F (not shown) were equal. Using P and F (and weighting properly in accordance with their shapes), curve A was drawn to represent the distribution observed by recording simultaneously any one electron of group P

and any β-particle of group F. Now in the spectrometer, P and A, which enclose the same areas, correspond to cases (c) and (d) above. They combine to produce the pulse distribution S of Fig. 3, which is then the derived curve which can be used for comparison with the results shown in Fig. 2 to check the extent of the agreement of our results with Fermi theory.

In Fig. 2, therefore, a curve D (dashed line) is drawn coinciding exactly with the observed distribution from 62 to (62–14), i.e., 48 kev, and below this energy differing from the experimental curve by an amount corresponding to the tail of the curve increased in the ratio $\frac{3}{2}$ (the heights of the 30- and 44-kev plateaus are as $\frac{3}{2}$).

The final test of agreement between theory and experiment is obtained by checking how well the modified experimental curve D above 44 kev fits the corresponding part of the derived curve S. The comparison

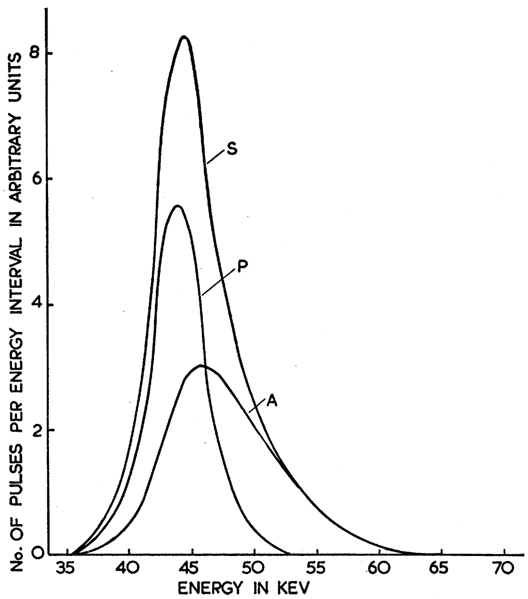

FIG. 3. Illustration of the method of deriving the curve S from curves P and A. Curve P represents photoelectrons alone, curve A photoelectrons+β-rays, and S the composite curve.

is shown in Fig. 4 and the close fitting of the two curves is very satisfactory. The agreement appears to confirm that the region of the observed spectrum above 44 kev corresponds to the combination of β-rays of limiting energy 18 kev with photoelectrons. It is somewhat unfortunate that the photopeak is not really accurately defined (sometimes the x-rays are associated) as this would give additional accuracy to E_0, but the limiting energy would appear to be stated within fairly conservative limits by:

$$E_0 = 18 \pm 2.5 \text{ kev}.$$

CONCLUSIONS

It appears that the disintegration energy of RaD is 64.5±2.5 kev and that the main mode of decay consists of the emission of β-rays of limiting energy $E_0 = 18$ kev

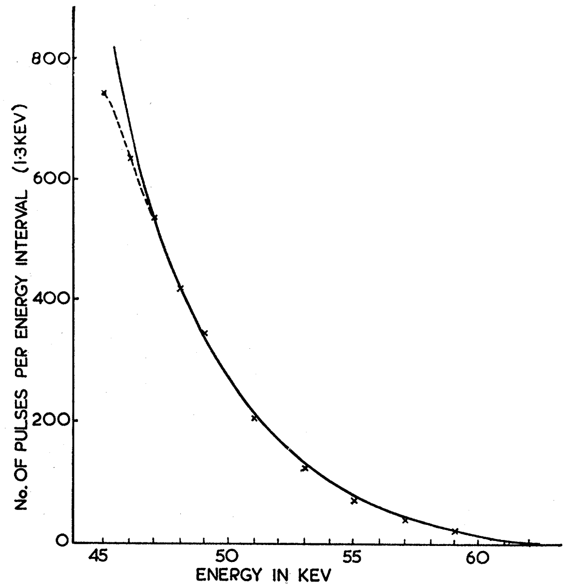

FIG. 4. Comparison of the derived curve S with the experimental results. The experimental points are shown by crosses.

leaving the RaE nucleus excited to 46.7 kev. This value of E_0 gives $\log ft = 5.5$, which definitely classifies the transition as allowed unfavored[9] rather than first forbidden which follows from previous data[10] on E_0.

Although direct de-excitation to the ground state occurs, by internal conversion in the L and M shells, frequently cascade processes of internal conversion take place. The lack of resolution of the corresponding peaks in the lower energy part of the pulse spectrum, Fig. 1, arises partly from the complexity of these photoelectron radiations, and the presence of Auger electrons, but mainly it is due to the accompanying β-rays which smooth out the distribution. It is difficult to make an accurate assessment of the probability of direct de-excitation because of this smoothing. The average energy of the observed pulses is 18 kev, but this figure is defined almost entirely by the photoelectrons and not by the β-rays.

Beta-transitions to levels of RaE other than that at 46.7 kev, if not entirely negligible, would appear to be of rather low intensity, and this is particularly true of the ground to ground transitions of energy 64.5 kev in view of the success of our analysis which assumes its absence.

Finally, it is noteworthy that β-emission of such low energy in a heavy nucleus should apparently correspond rather closely with Fermi theory and gratifying to find that the rather radical modifications of the process which have been suggested[11,12] do not seem to have any justification in fact, at least in this particular case.

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