EXPERIMENTAL NUCLEONICS

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EXPERIMENT 2

Relative Beta Measurements; Backscattering and Self-absorption

The most usual purpose of a radiation measurement is to determine the disintegration rate or the "strength" of a sample. Frequently only relative values are needed; these, however, are proportional to the true counting rates, provided that all measurements can be made under identical conditions. This situation is not always attainable, however, because of variations in the chemical or physical nature of the sources. A knowledge of some corrections and precautions is therefore necessary even for the relative measurements.

RELATION BETWEEN DISINTEGRATION RATE AND COUNTING RATE

THE IDEAL ARRANGEMENT; GEOMETRY AND COUNTER EFFICIENCY

An "ideal source" is infinitely thin, so that no radiation is absorbed in the source itself. It is supported by an infinitely thin backing, at a large distance from all solid matter which could scatter the radiation. In the ideal arrangement, the counter window is infinitely thin and the space between source and counter is evacuated. In this case, the measured counting rate m_0 is related to the disintegration rate D ($\equiv$ number of beta particles emitted; a simple decay is assumed here) by the equation

$$m_0 = D \frac{\Omega}{4\pi} \epsilon_\beta f_M f_\tau \qquad (2.1)$$

The solid angle subtended by the sensitive volume of the counter is Ω; $D \frac{\Omega}{4\pi}$ is the number of particles reaching the counter. The intrinsic sen-

sitivity of the counter for beta particles is ϵ_β, normally very close to 100%. The factor f_M takes into account the apparent increase in counting rate due to multiple discharges (failure of the quenching mechanism). Finally, the counting rate is decreased by the factor $f_\tau = 1 - m_0\tau$ because of the dead time τ of the counter.

For practical purposes, it is advantageous to lump together all the above factors except f_τ. The product

$$E = \frac{\Omega}{4\pi}\,\epsilon_\beta f_M \tag{2.2}$$

may be called the corrected efficiency.[1] Its absolute value is determined by counting a source of known strength (for the preparation of a calibrated source, see Experiment 3). In most applications, only relative values of E must be known; they are determined with the aid of a standard source whose strength either is constant (e.g., uranium) or decreases at a slow, known rate (e.g., RaE in equilibrium with RaD, $T_{1/2} = 22$ y).

Relative values of E must be known for two reasons.

Variation of solid angle. If sources of widely differing strength are measured, it may be advantageous to vary the distance between source and counter in order not to overload the counter. One may attempt to determine the influence of changing distance by calculation. For a point source at a distance d from the counter window (radius r), one obtains (Figure 2.1):

$$\frac{\Omega}{4\pi} = \frac{1}{2}\,(1 - \cos\alpha) = \frac{1}{2}\left(1 - \frac{d}{\sqrt{d^2 + r^2}}\right) \tag{2.3}$$

For extended sources, more complicated formulas can be derived.[1,2] It is questionable, however, whether the sensitive volume of the counter should be assumed to be defined by the window rather than by a plane located somewhat behind the window. Certainly the efficiency for detecting particles passing obliquely near the edge is very low.* It is strongly recommended, therefore, that one determine the relative corrected efficiencies E, and *not* use a calculated solid angle for comparative measurements at different distances.

Variation of efficiency in time. It is found that, generally, the efficiency E varies with time. This is most probably due to variations in f_M. They can be caused by various effects. Since the alcohol is decomposed

* A better definition of the solid angle may be obtained by absorbing these particles in a diaphragm of aperture somewhat smaller than the window diameter.[2a]

by the discharges, the characteristic of the counter shifts with its use. The starting voltage is lowered, the plateau shortened, and its slope increased because of the increasing probability of multiple discharges. A counter with a sloping plateau is, obviously, quite sensitive to voltage fluctuations. Many counters exhibit, in addition to aging phenomena, a dependence on temperature which is not yet fully understood. For accurately reproducible measurements, thermostats have been used.

The procedure is therefore to determine the values of E from day to day (or at shorter intervals) and to correct all measurements to an

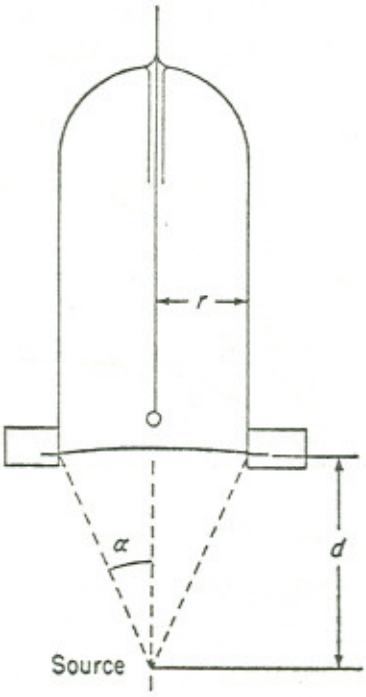

Fig. 2.1. Solid angle of end window counter.

$$\Omega = 2\pi(1 - \cos\alpha)$$

arbitrarily chosen value of E. In this way variations of E are compensated. One should not get a false feeling of security, however, and apply these corrections irrespective of their magnitude. If the variations are more than about 10%, their source must be investigated and eliminated (possibilities: bad counter, erratic operation of the scaling circuit or recorder, nonreproducible geometry).

BACKSCATTERING

If a backing of thickness d is placed behind the source, some particles emitted originally in a direction away from the counter are scattered back (multiple Rutherford scattering). Under otherwise ideal conditions, the counting rate is larger than the value given in equation 2.1 by the backscattering factor f_B.

$$m_1 = DEf_\tau f_B \tag{2.4}$$

f_B increasing with increasing thickness of the backing. It reaches a saturation value, theoretically, if the thickness is equal to half the range R of the beta particles. Practically, the maximum backscattering is obtained already for $d = 0.2R$. The dependence on the energy of the radiation and on the atomic number of the backing is shown in Figure 2.2. The factor f_B increases faster with increasing backing thickness, the lower the energy of the radiation, and the higher the atomic number. This behavior reflects the dependence of the Coulomb scattering on the energy and the atomic number Z. The saturation values are found to be independent of the energy between 0.3 and 2.3 Mev. This is

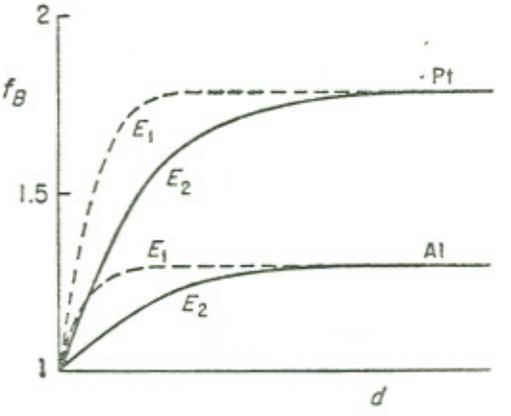

Fig. 2.2. Backscattering factor f_B as function of the surface density, d (mass per unit area), of Al and Pt backings for two different beta energies ($E_2 > E_1$), schematic.

explained by the fact that for increasing energy, the decrease in scattering cross section of the nuclei of the backing is compensated by the increase in number of nuclei encountered by the electrons (because of the increase in range). The dependence of the saturation backscattering factor

Table 2.1

Saturation Backscattering Factors

Backing	Z	f_B^S		
		(a)[1]	(a)[3]	(b)[3]
Lucite	—	1.15	—	—
Cardboard	—	1.19	—	—
Al	13	1.29	1.20	1.33
Fe	26	—	—	1.59
Cu	29	1.48	1.43	—
Ag–Pd	46–47	1.66	1.59	1.83
Pt	78	1.78	—	—
Pb	82	—	1.74	2.05

Source: Burtt,[1] Glendenin and Solomon.[3]

f_B^s on Z is given in Table 2.1. The values in (a) are obtained by mounting the source on a thin film and placing the different backings behind it. If thin sources are deposited directly on the metal backings, one finds the backscattering factors listed under (b), which are somewhat higher. The difference must be due to the microscopic roughness of the metal surfaces. For electrons emitted from the small cavities, smaller scattering angles are necessary in order to reach the counter. Although in most applications the values in (b) are used, the backscattering factors (a) will be determined in this experiment because of the difficulties involved in the preparation of suitable sources for the measurement of the values in (b).

It has also been noted that the backscattering factors for positrons are appreciably smaller than those for electrons.[4] This may be expected because the relativistic Coulomb scattering cross section is smaller for positrons.

Since it is not practical, in routine work, to prepare sources with negligible backing, and because of the dependence of f_B on the thickness for thin backings, it seems that reproducible results are best obtained by using a thick backing for which f_B^s is constant.

ABSORPTION AND SCATTERING IN THE COUNTER WINDOW AND IN AIR

The counting rate as given in equation 2.4 is reduced by the absorption of the radiation in the counter window and in the air path (factor f_W),

$$m_2 = DEf_\tau f_B f_W \tag{2.5}$$

To determine f_W, absorbers (e.g., aluminum foils) are placed in the path of the particles and an absorption curve is measured. The absorption is found to be essentially exponential,

$$n(x) = n(0)e^{-\mu x} \tag{2.6}$$

(after correction for dead time). Here x is the thickness of the absorber (in cm) and μ the absorption coefficient (cm^{-1}). It is advantageous, however, to measure the mass per unit area d (surface density) of the absorber rather than its thickness. Since $d = \rho x$, the exponent becomes $\mu x = \left(\frac{\mu}{\rho}\right)d$, where $\frac{\mu}{\rho}$ is the mass absorption coefficient (in cm^2/g). This quantity is nearly the same for mica, air, and aluminum. The absorption curve, then, can be written as a function of the total absorber (window + air + aluminum foils):

$$n(d_W + d_{air} + d) = n(d_W + d_{air})e^{-\frac{\mu}{\rho}d} \tag{2.7}$$

The semilogarithmic plot, a straight line, can be extrapolated easily to zero thickness (Figure 2.3). One obtains, then, the intensity at zero total absorber and the absorption factor

$$f_W = \frac{n\,(d_W + d_{air})}{n(0)} = e^{-\frac{\mu}{\rho}(dW + d_{air})} \tag{2.8}$$

NOTE: It is rather common practice not to distinguish rigorously between the linear absorption coefficient and the mass absorption coefficient. Thus the symbol μ is also used for the "absorption coefficient in cm^2/g" and the "thickness" of an absorber may be given in g/cm^2. The terms will be used in this way in most of the following experiments.

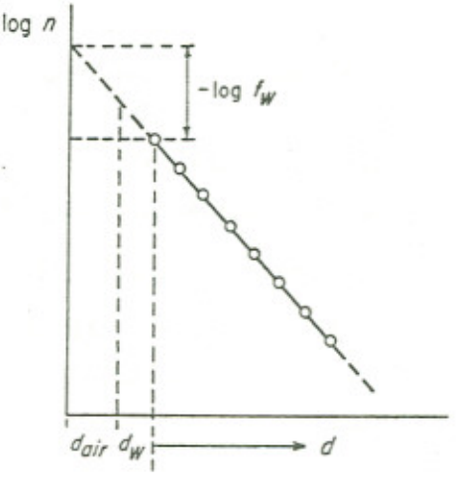

Fig. 2.3. Absorption curve. Abscissa = total absorber ($d_{air} + d_W + d$). ○ = measured points.

The procedure outlined above is exactly valid for the determination of the absorption in the counter window, because the absorbers, placed in front of the counter, simply act like a thicker window. The procedure is not accurate for evaluating the influence of the air because of scattering. The correct method would be to place several absorbers at equal distances between source and counter so as to simulate the scattering—together with the absorption—by the air. In practice, however, the simple procedure illustrated in Figure 2.3 is sufficiently accurate for most purposes. (For P^{32} and a source-counter distance of 5 cm, air scattering has been found to *increase* the counting rate by 2%.[1] For shorter distances the effect is smaller.)

It should be emphasized that the absorbers must be placed close to the counter and under no circumstances closer to the source than to the counter. If a source is covered with a thin absorber, one may observe, instead of a decrease in counting rate, an increase. This is easily explained by the threefold influence of the absorber. (a) It

absorbs the lowest-energy beta particles, (b) scatters some particles *out* of their path, which without absorber would have reached the counter, and (c) scatters some particles *into* a direction toward the counter which originally would not have reached the counter. If the absorber is very close to the source, the gain due to (c) can overcompensate the loss due to (a) and (b). Obviously, no absorption coefficient can be measured in this way. For the same reason, it is difficult to correct for the influence of the cover foil customarily placed over a sample. Its thickness may be added to the window and air only if the source is close to the counter so that scattering is negligible compared to absorption.

INFLUENCE OF HOUSING AND SUPPORT

If housing and support are lined with low Z material, no influence on the counting rate is found except for backscattering from the base (for sources mounted on thin backings). If, however, material of higher Z is near the source, it produces a considerable increase in counting rate by scattering.

SELF-ABSORPTION IN THE SOURCE[1–3,5]

If the source is not infinitely thin, the counting rate will be different from that given in equation 2.5 by a factor f_s because of absorption and scattering of the radiation in the source itself. The dependence of f_s on the thickness t of the sample can be calculated in a crude way by assuming an exponential absorption with an absorption coefficient μ independent of the depth in which the particles are emitted. If the total number of counts registered for a *thin* source of the same strength is m_2, then the counts due to a layer of thickness dx would be

$$dm = m_2 \frac{dx}{t}$$

if there were no absorption. The absorbing layer x reduces this by $e^{\mu x}$. The total intensity measured is

$$m = \int dm = \int_0^t m_2 \frac{dx}{t} e^{-\mu x} = \frac{m_2}{\mu t}(1 - e^{-\mu t}), \tag{2.9}$$

i.e.,

$$f_s = \frac{m}{m_2} = \frac{1}{\mu t}(1 - e^{-\mu t}). \tag{2.10}$$

From the discussion of backscattering and of scattering by an absorber close to the source, it is obvious that the assumption of similar behavior

of the radiations emitted by the different layers of the thick source is not strictly valid. It must be expected that the contribution of the front layers (toward the counter) is larger than assumed because of back-scattering caused by the deeper layers. Backscattering is the same for all layers only in the case where the source is mounted on a thick backing. The contribution from the layers slightly below the surface will be increased because of "scattering in" (see above). Under favorable circumstances (large counter-source distance) it has been observed that a small increase of the thickness of a source of constant activity leads to an *increase* in counting rate instead of a decrease (Figure

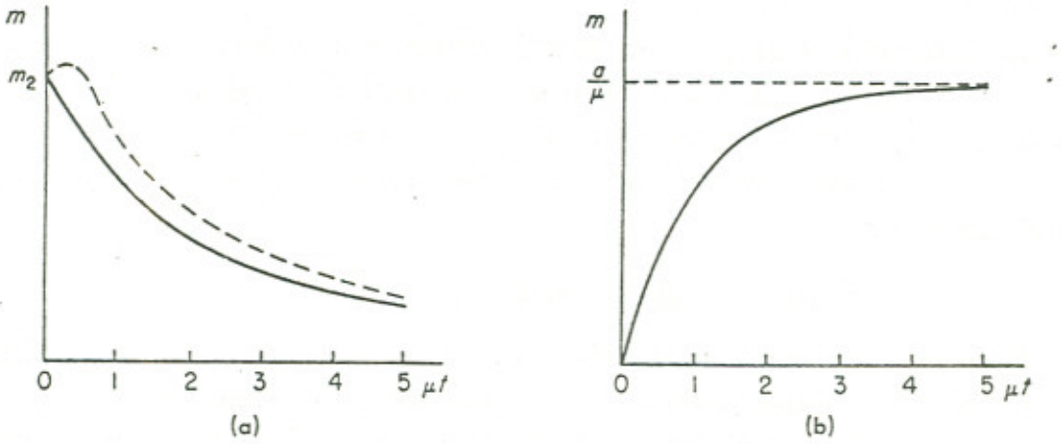

Fig. 2.4. Self-absorption curves. (a) Curve obtained by increasing the source thickness, keeping the total activity constant (dilution) ——— $m = \frac{m_2}{\mu t}(1 - e^{-\mu t})$, calculation, in agreement with measurement for small source-counter distance. - - - - - measurement for large source-counter distance, showing effect of scattering *in*. (b) Saturation curve obtained by increasing the source thickness keeping the measured specific activity a constant. Scattering effect neglected. $m = \frac{a}{\mu}(1 - e^{-\mu t})$.

2.4a). It is advisable, therefore, to measure the self-absorption factor as a function of t for the arrangement used. This can be done either by diluting a source of given activity with inactive material or by adding more material of the same measured specific activity a. The activity of a source of thickness t would be $m_2 = at$ (without absorption) and the measured counting rate is approximately

$$m = \frac{a}{\mu}(1 - e^{-\mu t}) \qquad (2.11)$$

This is a familiar saturation type of curve (Figure 2.4b).

Limiting cases. For thick sources, the activity measured (m in equation 2.11) is directly proportional to the specific activity a. This allows

very simple measurements of relative activities, provided the sources are of uniform specific activity.

For thin sources, $\mu t < 0.1$, equation 2.10 can be developed.

$$f_s \cong \frac{1}{\mu t}\left\{1 - \left[1 - \mu t + \frac{(\mu t)^2}{2} - \cdots\right]\right\} \cong 1 - \frac{\mu t}{2} \cong e^{-\frac{\mu t}{2}} \qquad (2.12)$$

The self-absorption, therefore, can be taken into account, approximately, together with the absorption in counter window, air, and cover foil, by simply adding half the source thickness (in mass/unit area) to these absorbers. The procedure is not accurate because the effective mass absorption coefficient $\frac{\mu}{\rho}$ (for self-absorption) is different from the mass absorption coefficient (for external absorption) in aluminum, which is used for these corrections. The difference arises from variations in Z (of source and external absorber) and in position relative to the counter.

SUMMARY

The counting rate m is connected with the disintegration rate D by

$$m = DEf_\tau f_B f_W f_S, \qquad (2.13)$$

with

E = corrected efficiency
f_τ = correction factor for counter dead time
f_B = correction factor for backscattering
f_W = correction factor for absorption in window, air (and cover foil)
f_S = correction factor for self-absorption in the source

For absolute measurements, E is determined with the aid of a standard whose disintegration rate is known from a previous calibration (cf. Experiments 3, 5); f_τ is determined as in Experiment 1; f_B is either taken from Table 2.1—for thick backing—or determined experimentally; f_W is obtained by extrapolating an Al-absorption curve to zero absorber with the reservations made concerning scattering in air and in the cover foil; and f_S is measured by a separate experiment or, for thin sources close to the counter, approximated together with f_W.

It must be emphasized again, in view of the inaccuracies in the determination of the various correction factors, that very accurate, absolute and relative, results can be obtained only by measuring different samples under conditions as closely identical as possible.

Experimental Nucleonics
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EXPERIMENT 6

Measurement of Source Strength by Comparison with UX_2; Determination of the Partial Half Life for Beta Decay of K^{40}

DECAY OF K^{40} [1-7]

Only a small fraction of the large number of radioactive isotopes known today (about 700) are found in nature. Unstable nuclei present in the earth's crust either must have a half life of the order of or greater than the age of the earth (2–3 $\times$ 10^9 years) or must be daughter products in equilibrium with a long-lived radioelement.

In addition to the members of the radioactive series (see Experiment 5), there are, dispersed through the periodic system, some isolated cases of naturally radioactive isotopes (Table 6.1). The long half lives of the

Table 6.1

Isotopes	$T_{1/2}$	Radiations
K^{40}	1.6×10^9y*[4,5,7]	β^-, γ, K
Rb^{87}	6×10^{10}	β^-, γ, e^-
Sm^{152}	3×10^{11}	α
Lu^{176}	2.4×10^{10}	β^-, γ, K
Re^{187}	4×10^{12}	β^-

* Not corrected for electron capture.

beta emitters are explained by great differences in angular momentum $I\hbar$ between initial and final nucleus (e.g., K^{40}: $I = 4$, Ca^{40}: $I = 0$ and Rb^{87}: $I = 3/2$, Sr^{87}: $I = 9/2$). A beta transition involving a large change in angular momentum is highly forbidden by selection rules.

The most important of the radioisotopes of Table 6.1 is probably K^{40} because of the high abundance of the element, the rather short half life, and the energetic radiations emitted. The heat developed by its decay has an appreciable influence on the temperature balance of the earth's crust.

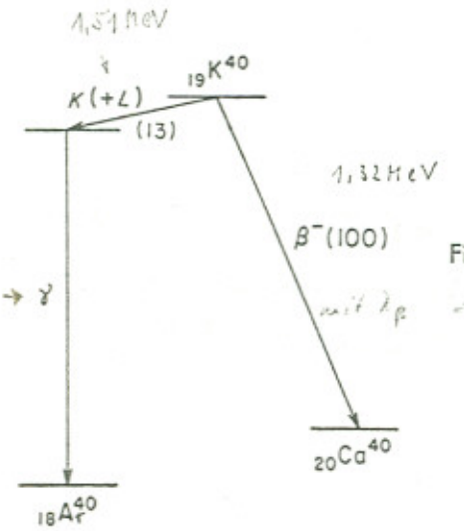

Fig. 6.1. Decay scheme of K^{40}.

Both neighbors of $_{19}K^{40}$($_{20}Ca^{40}$ and $_{18}A^{40}$) are stable. Dual decay, therefore, is possible. The transition $K^{40} \rightarrow Ca^{40} + \beta^- + \bar{\nu}$ seems to be the main mode of disintegration. Its decay constant λ_β and the corresponding partial half life $T_\beta = \dfrac{0.693}{\lambda_\beta}$ will be determined in this experiment. The maximum energy of the beta spectrum is 1.36 Mev.[1,2] In addition, a gamma ray of 1.46 Mev, having an intensity of about 13% of that of the beta radiation, has been observed. Since its energy is higher than that of the upper limit of the beta-ray spectrum, it cannot be in cascade with a soft partial beta spectrum, and must be ascribed to electron capture leaving the resulting A^{40} in an excited state. No indication of K capture to the ground state of A^{40} has been found, and no positrons have been observed. The total decay constant is the sum of the partial decay constants for β^- emission and electron capture:

$$\lambda = \lambda_\beta + \lambda_c \tag{6.1}$$

If only K capture to the excited state of A^{40} occurs, $\lambda_c = 0.13\lambda_\beta$, $\lambda = 1.13\lambda_\beta$, and the true half life is

$$T_{1/2} = \frac{T_\beta \lambda_\beta}{\lambda} = \frac{T_\beta}{1.13} \tag{6.2}$$