Ionization *vs* Energy Relation for Fission Fragments*

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(Received December 27, 1955)

The ionization *vs* energy relation has been measured for fission fragments stopped in nitrogen, neon, argon, and argon plus CO_2 (3%). The fission fragments were obtained from thermal-neutron-induced fission of U^{235}. Results of these measurements are consistent with the nuclear recoil effect and show that the ionization produced is not simply proportional to the fragment energy.

SINCE fission fragments are very massive and have, immediately after formation, roughly twenty electrons stripped from their atoms, the effective charge of these fragments is considerably higher than that of most particles studied in physics. Furthermore, the electron capture and loss process as the fragments are slowed results in an effective charge which decreases to zero as the fragment energy decreases. This greater mass and variable effective charge of fission fragments results in an energy loss process which is considerably more complex than, and, in some respects, basically different from, that for lighter particles such as protons and alpha particles. A study has been made of the ionization *vs* energy relation for fission fragments stopped in nitrogen, neon, argon, and argon plus CO_2 (3%). The fission fragments were obtained from the thermal-neutron-induced fission of U^{235}. Results of these measurements are consistent with the nuclear recoil effect previously discussed by Knipp and Ling[1] and Ozeroff[2] and show that the ionization produced is not simply proportional to the fragment energy.

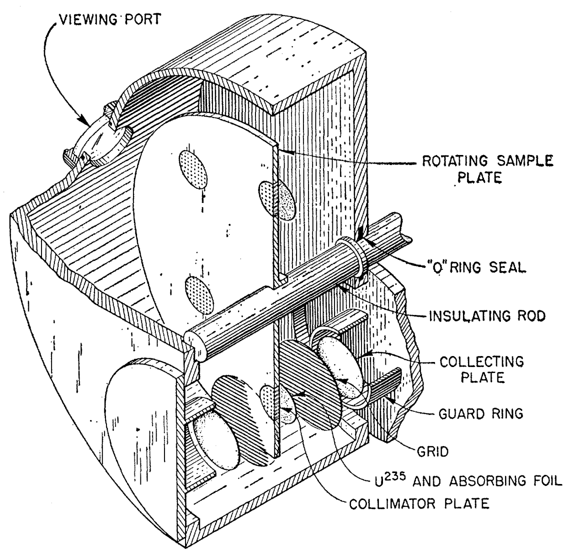

FIG. 1. Simplified diagram of double ionization chamber. The fragments whose pulse heights were measured entered the right side of the chamber directly; the coincident fragments passed first through the collimator and then into the left side of the chamber, giving a coincidence pulse. This allowed effective collimation of the fragments whose pulse heights were measured without requiring passage through the collimator. Rotation of the center plate containing the various slowing foils permitted ionization measurements to be made with the same filling of the chamber.

For these measurements thin aluminum and nickel foils of various thicknesses were used to slow the fragments to various energies. In each case the velocity distribution of the slowed fragments was determined from a time-of-flight measurement,[3] and the median energy of each of the two (light and heavy) fragment groups was calculated using the median velocity and mass of each group. The foils used in slowing the fragments together with the median light- and heavy-fragment energies are listed in Table I.

In a separate set of measurements, the ionization (pulse-height) distribution for each group was determined by using electron collection in a double, back-to-back, gridded ionization chamber and the same slowing foils. A simplified diagram of the chamber is shown in Fig. 1. Fragment pulse heights were compared with alpha-particle pulse heights, the alpha-particle energies being accurately known. Careful tests were made for such effects as recombination, negative-ion formation, and diffusion; these effects were in all cases either eliminated or minimized and taken into account. A complete account of the experimental details of these

TABLE I. Absorbing foils and fragment energies.

Foil material	Foil thickness (mg/cm²)	Median heavy-fragment energy (Mev)	Median light-fragment energy (Mev)
...	0	66.87	98.86
Nickel	1.1	41.48	67.69
Aluminum	1.1	29.78	59.83
Aluminum	1.8	17.45	40.50
Aluminum	2.5	...	22.40

* Work performed under the auspices of the U. S. Atomic Energy Commission.
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[1] J. K. Knipp and R. C. Ling, Phys. Rev. 82, 30 (1951).
[2] J. Ozeroff, U. S. Atomic Energy Commission Report AECD-2973, 1950 (unpublished).
[3] R. B. Leachman and H. W. Schmitt, Phys. Rev. 96, 1366 (1954).

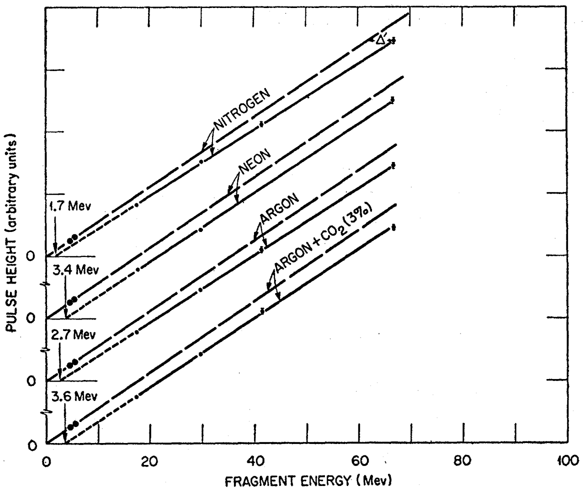

FIG. 2. Ionization *vs* energy for median heavy fragment. The data were fitted arbitrarily to a straight line by the method of least squares; the extrapolation of the straight line to $I=0$ is dotted. The value of Δ is given for each gas. The dashed line passing through the origin gives ionization *vs* energy for alpha particles. The quantity Δ' is displayed for nitrogen.

ionization measurements is being prepared for publication elsewhere.

Graphs of ionization *vs* energy for the heavy-fragment group are given in Fig. 2, and similar graphs for the light-fragment group are given in Fig. 3. In each case two alpha-particle points with a linear plot[4] from the origin to higher energies are given for comparison. It can be seen that the results are consistent with the theory that toward the end of the range of fission fragments, energy loss by non-ionizing processes becomes increasingly important. That this energy appears only quite inefficiently in a measurement of ionization gives rise to the concept of "ionization defect."

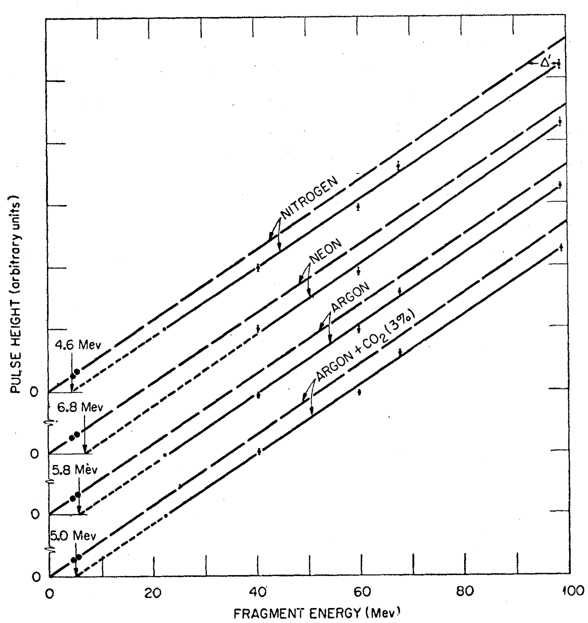

FIG. 3. Ionization *vs* energy for median light fragment. See caption for Fig. 2. Ionization (pulse-height) units are the same as those of Fig. 2.

[4] J. A. De Juren and H. Rosenwasser, Phys. Rev. **93**, 831 (1954).

For unslowed fragments Knipp and Ling[1] have defined the ionization defect Δ (see Fig. 2) in terms of the equation

$$E=wI+\Delta, \tag{1}$$

where E is the fragment energy, I is the ionization (number of ion pairs formed by particles stopped in the gas), and w is the energy loss per ion pair for high-velocity fragments. They have calculated Δ by assuming that for high velocities w depends almost entirely on the nature of the gas and is largely independent of the mass, charge, and velocity of the particles. The result is that Δ is of the order of five Mev and is slightly smaller for the light fragment than for the heavy fragment. An ionization defect Δ' (see Figs. 2 and 3) for fission fragments stopped in argon plus CO_2 (3%) has been determined[5] by comparing the ionization distributions of Brunton and Hanna[6] with the measured velocity distributions. For this, w was assumed to be equal to w_α, the energy loss per ion pair for alpha particles. By analogy with (1),

$$\Delta'=E-w_\alpha I. \tag{2}$$

The results are $\Delta'=5.7$ Mev for the light fragment and $\Delta'=6.7$ Mev for the heavy fragment. The average energy losses per ion pair $\bar{w}$ for full-energy fragments relative to w_α obtained from these results are $\bar{w}=1.06w_\alpha$ for the light fragment and $\bar{w}=1.11w_\alpha$ for the heavy fragment.

The values of Δ, Δ', and $\bar{w}/w_\alpha$ obtained from the present measurements are summarized in Table II. The relative values of Δ' inferred from Table II are qualitatively in agreement with those obtained from the less detailed measurements of Herwig and Miller.[7]

TABLE II. Results of measurements. Values of Δ, Δ', and $\bar{w}/w_\alpha$ are given for each gas. Uncertainties are standard deviations based on an assumed linear fit of the data.

Gas	Fragment group	Δ(Mev)	Δ'(Mev)	$\bar{w}/w_\alpha$
Argon plus CO_2 (3%)	Heavy	3.6±0.5	6.3±0.5	1.10±0.02
	Light	4.9±0.7	6.5±0.8	1.07±0.02
Argon	Heavy	2.7±0.5	5.5±0.5	1.09±0.02
	Light	5.8±0.7	5.1±0.8	1.05±0.02
Nitrogen	Heavy	1.7±0.5	5.3±0.5	1.09±0.02
	Light	4.6±0.7	6.3±0.8	1.07±0.02
Neon	Heavy	3.4±0.7	4.8±0.7	1.08±0.02
	Light	6.8±1.0	4.3±1.0	1.05±0.02

[5] R. B. Leachman, Phys. Rev. **87**, 444 (1952).
[6] D. C. Brunton and G. C. Hanna, Can. J. Research **A28**, 190 (1950).
[7] L. O. Herwig and G. H. Miller, Phys. Rev. **95**, 413 (1954).

The absolute values of Δ' and $\bar{w}/w_\alpha$ for argon plus CO_2 (3%) given in Table II agree with the earlier determination[5] based on the ionization measurements of Brunton and Hanna.

Note added in proof.—Note from Table II that for each gas, the defects Δ and Δ' are approximately the same for light fragments. Consequently, the value of w for these high-velocity particles is very nearly the same as that for alpha particles. This is in accord with the expectation[1] that w is insensitive to the mass and charge of fast particles. In the case of heavy fragments, however, the results show that Δ' is greater than Δ for each gas; thus for heavy fragments we have $w > w_\alpha$. It therefor appears[8] that at the velocities used in the light-fragment measurements no appreciable energy is lost in nuclear recoils; while at the generally lower velocities of the heavy fragments, the energy lost in nuclear recoils is significant and increases with decreasing velocity. The importance of nuclear collisions even at these velocities, $v \lesssim 2v_0$, where $v_0 = e^2/\hbar$, is a consequence[9] of the large nuclear charge of fission fragments.

[8] Suggested by J. Lindhard (private communication, 1955).
[9] N. Bohr, Kgl. Danske Videnskab. Selskab, Mat. fys. Medd **18**, No. 8 (1948).

PHYSICAL REVIEW VOLUME 102, NUMBER 1 APRIL 1, 1956

Time-Dependent Directional Correlation of 1.1-hr Pb^{204}†

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(Received December 16, 1955)

A study is made of an effect attributable to the interaction of the electric quadrupole moment of the 0.27 μsec level of Pb^{204} with the crystalline electric field in metallic, polycrystalline, thallium in which 68-min Pb^{204} is produced by $(p,2n)$ reaction. The directional anisotropy in the rate of delayed coincidences between the γ ray preceding the 0.27 μsec state and the γ rays following the state is observed as a function of the delay time. Although some discrepancy between the observed function and theory is found, the time dependence suggests a coupling frequency $eQ(\partial^2V/\partial z^2)/h$ of 12 Mc/sec. Measurements of the directional correlation between the two gamma rays in prompt coincidence following the 0.27 μsec state supports the assignment, by Krohn and Raboy, of spin 4 to that state and of some mixing of $M3$ with the dominantly $E2$, 371-kev gamma ray. Evidence of prompt γ rays of several energies, following K-capture in 12-hr Bi^{204}, is also found.

INTRODUCTION

It has been shown by Abragam and Pound[1] that the interaction of the nuclear quadrupole moment with the gradient of a static electric field results in a periodic attenuation of the coefficients of the directional correlation function of two successively emitted nuclear radiations, provided that the interacting field has an axis of at least threefold symmetry. The result is particularly simple in a source composed of a large number of randomly oriented microcrystals, where it takes the form

$$W(\theta,t) = 1 + \sum_\nu G_\nu(\omega_0 t) A_\nu P_\nu(\cos\theta). \qquad (1)$$

The coefficients A_ν are those appropriate to the decay scheme in the absence of a disturbance and the forms of the time-dependent attenuation functions $G_\nu(\omega_0 t)$ are determined by the spin of the intermediate state. The dimensionless parameter $\omega_0 t$ is proportional to the product of the time t, measured from the first decay, and the strength ω_0 of the quadrupole interaction.

Such an effect is observable if the period characteristic of the interaction is not much longer than the half-life of the disturbed intermediate state. On the other hand, the period of the interaction must be long compared with the minimum resolving time attainable in order that the structure of the attenuation function be well resolved. Present instrumental techniques do not allow a resolving time, with energy selection, less than about 5 millimicroseconds, so that a half-life of at least 50 millimicroseconds is essential. The magnitude of ω_0 determining the period of the attenuation function, $G(\omega_0 t)$, is not known *a priori*, but may be estimated from values of electric quadrupole interactions of stable nuclei in various compounds observed by magnetic and pure quadrupole resonance.

The known nuclei suited to such studies are few. Lead-204 has a level of half-life of 0.27 microsecond, that could allow good resolution of an attenuation function. However, having a closed proton shell and an even number of neutrons, its quadrupole moment is expected to be small and, therefore, the interaction with an extranuclear field gradient might be too weak to exhibit a complete period of the attenuation function, even in the relatively long half-life.

An experiment of this kind in 48-min Cd^{111} has

† Supported in part by the joint program of Office of Naval Research and the U. S. Atomic Energy Commission.
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[1] A. Abragam and R. V. Pound, Phys. Rev. **92**, 943 (1953).