Ionization Defects of Fission Fragments*

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THE mean total kinetic energy of fission fragments produced from U^{235} by thermal neutrons is still a quantity of considerable uncertainty. Estimates[1] based on ionization yields are appreciably less than the only direct (calorimetric) measurement.[2] We wish to show that there is evidence that about 2.5 Mev for the average light fragment and about 4.2 Mev for the average heavy fragment escape detection in the usual ionization experiments. These ionization defects occur because the light fragment loses about 5 Mev, and the heavy fragment about 8 Mev, to recoiling gas atoms, which themselves have a reduced ionization efficiency because they in turn produce recoil atoms, etc.

Double-chamber ionization data[3] give a distribution in ratio of ionization of pairs of fragments which is broader than the distribution in ratio of energies obtained from data on masses.[4] The difference in the distributions is somewhat reduced when the dispersion arising from neutron recoil and instrumental errors are taken into account. The remaining discrepancy is attributed to a variation in ionization yield with fragment mass. For the most probable fission asymmetry, the energy to ionization ratio of the average light fragment is found to be approximately 3.7 percent less than for the average heavy fragment.[5]

The ionization defect Δ of a heavy particle of energy E that is stopped in a gas is given by

$$\Delta=\int_0^E dE\lambda(E)\int_0^{E_m'} dE'k(E,E')\chi'(E'), \tag{1}$$

where $\lambda=[1+(b^e/b^r)]^{-1}$ is a function of the energy determined by the ratio b^e/b^r of the stopping cross sections for loss of energy to excitation and ionization and to atomic recoil, respectively, and

$$k(E,E')=\sigma(E,E')E'\bigg/\int_0^{E_m'} dE'\sigma(E,E')E'.$$

Here $\sigma(E,E')$ is the cross section per unit energy range for the production of a recoil atom of energy E'; E_m' is the maximum energy transferred to an atom and $\chi'(E')$ is $1-(\omega^e I'/E')$, where I' is the number of ion pairs resulting from a gas atom of energy E' and ω^e is the energy loss per ion pair of an atom the energy of which is very high. We have

$$d(E'\chi')/dE'=\lambda'\int_0^{E'} dE''k'(E',E'')\chi'(E''),\quad \chi'(0)=1, \tag{2}$$

in which primed quantities are similarly defined for a gas atom in its own gas.

Reasonable estimates for the ratios of stopping cross sections for low velocities can be made from the analysis of the ionization by recoil particles from alpha-decay.[6] Atomic scattering is approximately spherically symmetrical in the center of gravity system below particle velocities of the order of

$$\left[2m\left(\frac{M+M'}{MM'}\right)ZZ'(Z^{\frac{2}{3}}+Z'^{\frac{2}{3}})^{\frac{1}{2}}\right]^{\frac{1}{2}}\frac{e^2}{t}$$

and very nearly coulomb with minor screening above this velocity.[7] Correspondingly, $k(E,E')$ is $2E'/E_m'^2$ and

$$\left\{2E'\ln\left[\frac{2M'}{M+M'}\frac{E}{ZZ'\epsilon_0(Z^{\frac{2}{3}}+Z'^{\frac{2}{3}})^{\frac{1}{2}}}\right]\right\}^{-1}$$

(except outside the screening radius, where it is zero), respectively. Ratios of stopping cross sections for intermediate and high velocities can be estimated by well-known methods.

In this manner it is possible to make a crude calculation of the behavior of the solution of (2). It is found, for instance, that an ionization defect $\Delta'\approx 0.8$ Mev for a very energetic argon particle in argon is not unreasonable, and that $\chi'=0.5$ at about 350 kev. Numerical integration of (1) leads to 0.94 and 0.975 as probable values of the ionization efficiencies in argon gas of the heavy and light fission fragments from U^{235} by thermal neutrons, respectively. The ratio of efficiencies is 0.964. The remarkable agreement with that found from the analysis of the fragment pair distributions must be regarded as largely accidental, because of the approximate nature of both considerations.

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[1] 156 Mev by Brunton and Hanna, Can. J. Research **A28**, 190 (1950); 162 Mev by Jentschke, Zeits. F. Physik **120**, 165 (1943); about 155 Mev, when corrected for foil losses, by Flammersfeld, Jensen, and Gentner, Zeits. f. Physik **120**, 450 (1943).

[2] 165±8 Mev by Henderson, Phys. Rev. **58**, 774 (1940).

[3] D. C. Brunton and G. C. Hanna, reference 1; M. Deutsch and M. Ramsey, MDDC 945 (1946); W. Jentsche, reference 1; Flammersfeld, Jensen, and Gentner, reference 1.

[4] Plutonium Project Report, Rev. Mod. Phys. **18**, 513 (1946).

[5] R. B. Leachman, Phys. Rev. **79**, 197 (1950). Details of this analysis and other considerations will be presented in papers submitted to the Physical Review.

[6] Knipp, Leachman, and Ling, Phys. Rev. **80**, 478 (1950).

[7] N. Bohr, D. Kgl. Danske Vidensk. Selskab, Mat.-fys. Medd. **15**, No. 8 (1948).

Nuclear Spins of the 2.62-Mev and 3.20-Mev Excited States of Thorium *D*

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APPROXIMATELY 70 percent of the beta-disintegrations of ThC'' are followed by two gamma-rays of energy 0.58 and 2.62 Mev; these involve the three energy states 0, 2.62, and 3.20 Mev of ThD. By comparison of the measured internal conversion coefficients with the calculations of Hulme *et al.*[1] and by consideration of the degree of forbiddenness of the beta-spectra, Oppenheimer[2] and Arnoult[3] have assigned spins 0, 2, 3 to these levels. Martin and Richardson[4] on the basis of their recent measurements of internal conversion coefficients and the theoretical calculations of Rose *et al.*[5] have decided that the spins of these levels are 0, 1, 3. Bell and Elliott[6] after an unsuccessful search for the 3.20-Mev cross-over transition, have concluded that the spin of the 3.20-Mev level could be either 3 or 4.

Since the angular correlation function for two successive gamma-rays is very sensitive to the spin changes and multipolarities involved,[7,8] a determination of this function provides an independent approach to the problem. For this purpose we have used a coincidence circuit of resolving time 5×10^{-9} sec., similar to that constructed by Bell and Petch,[9] with two anthracene scintillation counters to investigate the angular correlation of successive gamma-rays resulting from the decay of ThC''. The coincidences observed were almost all due to the 0.58- and 2.62-Mev gamma-rays. Counts for ten-minute periods were taken alternately at the 90° position and at a chosen θ-position until at least 10,000 coincidences had been recorded at each. This procedure was carried out in 15° steps from $\theta=90°$ to 180°. Chance coincidences, obtained directly by introducing a delay of 5×10^{-8} sec. into one channel preceding the mixing stage of the circuit, were subtracted from the number of observed coincidences. The apparatus, when tested on the Co^{60} gamma-rays, gave a correlation function which conformed very closely to the published results of Brady and Deutsch.[10]

Figure 1 records the results of a series of experiments planned to obtain the correlation function for the 0.58- and 2.62-Mev gamma-rays from ThD. A complete set of points (series A) was recorded with an instrumental angular resolution of 12°, using sources of initial strength of about 0.3 mc of thorium active deposit on thin aluminum foil packed into a thin wall brass or Bakelite capsule of inside diameter 2 mm. To obtain better resolution and better statistics the measurements were repeated (series B) with an instrumental resolution of 7°, using a 1.5-mc source of radiothorium in equilibrium with its products sealed in a platinum capsule of diameter 5 mm enclosed in a brass container. In both series the front surfaces of the anthracene crystals were covered with 2 mm of lead. Since, according to Arnoult and Oppenheimer, the weak 0.27-Mev gamma is also in cascade with the 2.62-Mev radiation, series B was repeated with 4 mm of lead over each