Average Number of Neutrons per Fission for Several Heavy-Element Nuclides*

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The relative average number of neutrons per fission, $\bar{\nu}$, of several spontaneous fissioning nuclides has been measured by making use of the coincidence between fission events and neutrons detected in a LiI(Eu) crystal.

I. INTRODUCTION

Since the total energy of fission is divided between the kinetic energy of the fragments and the energy lost during neutron and prompt gamma emission, it has been of interest in understanding the fission process to measure these several effects independently.

Determination of the average number of neutrons per fission, $\bar{\nu}$, depends ultimately on determining the number of neutrons coming from a sample, and all the problems usually associated with absolute neutron counting are encountered. In addition, those neutrons not connected with fission must be excluded or determined accurately.

To avoid absolute standardization of a neutron source, $\bar{\nu}$ for the spontaneous fission of Cf^{252} and Cm^{244} was determined relative to a Bureau of Standards Ra-Be neutron source,[1–3] and all other numbers were determined relative to one or the other of these values.

II. EXPERIMENTAL

A. Counting Equipment

The neutron counter consisted of a europium-activated lithium-iodide crystal mounted on a photomultiplier, and the fission counter was of the close parallel-plate type. The neutron pulse was shaped, put through a variable delay unit, and finally tested for coincidence with the pulse from the fission counter. The fission pulse was treated in much the same manner. The neutron and fission single events and the neutron-fission coincidences were recorded on separate scalers.

Under normal operating conditions, the delay equipment was adjusted so that the fission pulse was delayed between 1 and 2 μsec and was about 5 μsec long. The neutron pulse was kept as short as possible, or about 0.5 μsec. The neutron detector was very insensitive to gamma radiation and since a very small fraction of fission associated gamma occurs between 1 and 10 μsec, delaying the fission pulse assures that observed coincidences are with neutrons and not with gamma radiation. To increase the probability of neutron detection, at these late times, the counter was surrounded with about 6 inches of paraffin which served as a neutron moderator. To check chance-coincidence background, the delays were reversed so that the recorded coincident events were those which were with neutrons which were detected before the fission event.

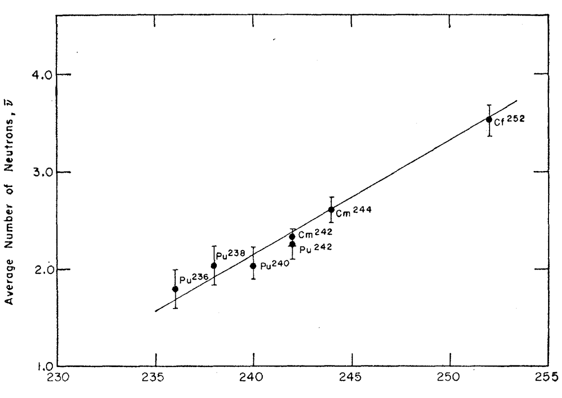

Fig. 1. Plot of $\bar{\nu}$ *vs* A, the mass number of a fissioning nuclide.

B. Results

Table I is a compilation of the data obtained from several runs. Relative $\bar{\nu}$ is the average number of neutrons per fission times the neutron counter efficiency, ϵ. As long as ϵ is very small compared to 1, $\epsilon\bar{\nu}=c/f$, where c/f is the ratio of coincidence events to fission events measured during the same time interval. The accuracy limits indicated in this table are standard deviations of the total number of events observed. Each sample was reprepared and repurified at least once during the course of the experiments to insure against errors from impurities. The sum of all corrections to $\bar{\nu}$, including those arising from chance coincidence, background, and isotopic and chemical contamination, is less than 2.5% in each case.

Table I. Values of $\bar{\nu}$ for several heavy-element nuclides.

Nuclide	Relative $\bar{\nu}\times10^2$	$\bar{\nu}$
Cf^{252}	0.703±0.011	3.52±0.16
Cm^{244}	0.521±0.008	2.61±0.13
Cm^{242}	0.464±0.006	2.33±0.11
Pu^{242}	0.451±0.024	2.32±0.16
Pu^{240}	0.418±0.014	2.09±0.11
Pu^{238}	0.409±0.022	2.04±0.13
Pu^{236}	0.38 ±0.040	1.89±0.20

* This work was performed under the auspices of the U. S. Atomic Energy Commission.
[1] J. A. DeJuren (private communication).
[2] Higgins, Crane, and Gunn, Phys. Rev. **99**, 183 (1955).
[3] Crane, Higgins, and Thompson, Phys. Rev. **97**, 242 (1955).

The $\bar{\nu}$ values for the various nuclides calculated from the relative $\bar{\nu}$'s in Table I are based on values for Cf^{252} and Cm^{244} of 3.53 ± 0.15 and 2.60 ± 0.12, respectively.[2–3] All these values are on the average about 7% lower than those determined by Hicks *et al.*,[4,5] who used the $\bar{\nu}$ value[6] of Pu^{240} to determine the counting efficiency of their neutron detector. This discrepancy arises from the difference in neutron counting standardization, and since Pu^{240} was determined relative to the $\bar{\nu}$ for the thermal fission of U^{235}, the discrepancy indicates a difference in the Bureau of Standards neutron source measurement and the U^{235} $\bar{\nu}$ measurement.

Figure 1 is a graphic presentation of these data, and it is interesting to note the regular variation of $\bar{\nu}$ with mass number.

[4] Hicks, Ise, and Pyle, Phys. Rev. **98**, 1521 (1955).
[5] Hicks, Ise, and Pyle (to be published).
[6] Diven, Taschek, Terrel, and Martin (to be published).

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Neutron and Proton Densities in Nuclei*

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A semiempirical investigation of neutron and proton densities in nuclei is made. Experimental values are assumed for the nuclear radius, binding energy, surface energy, surface thickness, and symmetry energy. It is found that the neutron and proton densities extend to approximately the same radius; these results do not depend sensitively on the input data. The nuclear potential extends $\sim 0.7\times10^{-13}$ cm further than the material radius. An estimate of $\lesssim 100A$ Mev is given for nuclear compressibility.

I. INTRODUCTION

THE excellent experiments on electron scattering[1] and on mu-meson spectroscopy[2] indicate for the charge distribution a surface thickness of $2.2-2.5\times10^{-13}$ cm and an "equivalent" radius of $1.2A^{1/3}\times10^{-13}$ cm. (An "equivalent" radius is the radius of a uniform distribution which leads to the same energy for the $2p\rightarrow1s$ transition in mu-mesonic atoms. The point where the charge density falls to half its central density is more like $1.1A^{1/3}\times10^{-13}$ cm.) Other experiments[3] which depend upon the nuclear charge distribution do not appear to be in disagreement with these results. Experiments which measure the nuclear potential,[3] however, quite generally lead to larger values for the radius. Attempts to measure the neutron distribution[3] (as opposed to the charge distribution) are hopeful, but as yet inconclusive.

In a previous paper,[4] density distributions in nuclei were calculated neglecting the Coulomb potential. Assuming experimental values for the nuclear radius, binding energy, surface energy, and surface thickness, the calculations yielded the following conclusions: (1) The nuclear potential (at half-maximum) extends $\sim 0.7\times10^{-13}$ cm beyond the nuclear density. (2) The nuclear compressibility is estimated to be $\lesssim 100A$ Mev.

The present investigation is designed to examine effects arising from the Coulomb potential. The primary effect of the Coulomb potential is to increase the number of neutrons relative to protons, through beta decay. The variation in the potential through the nucleus is also of consequence in *tending* to increase the relative number of protons at the surface.

Johnson and Teller[5] have proposed that the distribution of protons in the nucleus may lie within the neutron distribution by as much as 1/3 to 1/2 of the nuclear surface thickness. Their arguments are based on two consequences of the Coulomb potential: (1) Owing to the larger number of neutrons than protons, the neutrons have, on the average, greater kinetic energy and will extend further than the protons. (2) The Coulomb potential forms a barrier which inhibits penetration of the proton wave functions into the forbidden region. The effectiveness of these arguments depends upon the approximate equality of the nuclear potential for both neutrons and protons.

There are also factors which tend to counter the Johnson-Teller effect. The nuclear symmetry energy tends to resist separation of neutrons and protons, and the decrease in the Coulomb potential toward the edge of the nucleus tends to move protons closer to the surface. The present investigation indicates that the

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[1] R. Hofstadter *et al.*, Phys. Rev. **95**, 512 (1954). For analyses of the data, see Yennie, Ravenhall, and Wilson, Phys. Rev. **95**, 500 (1954); D. G. Ravenhall and D. R. Yennie, Phys. Rev. **76**, 239 (1954). See also reference 3.
[2] V. F. Fitch and J. Rainwater, Phys. Rev. **92**, 801 (1953). For analyses of the data, see L. N. Cooper and E. M. Henley, Phys. Rev. **92**, 789; D. L. Hill and K. W. Ford, Phys. Rev. **94**, 1617 (1954). See also reference 3.
[3] An excellent summary and analysis of the experiments on nuclear density and potential distribution is given by K. W. Ford and D. L. Hill, Ann. Rev. Nuc. Sci. **5** (1955). Further references to original literature will be found there.
[4] R. A. Berg and L. Wilets, Phys. Rev. **101**, 201 (1956), henceforth referred to as I.
[5] M. H. Johnson and E. Teller, Phys. Rev. **93**, 357 (1954).