Nuclear Models and Nuclear Fission*

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The hindrance to spontaneous fission by the odd nucleon in the fissioning nucleus may be explained as due to the pairing energy of the odd nucleon at the saddle-point deformation.

TO explain systematic features in nuclear spectroscopy, a number of nuclear models have been used with remarkable success. However, as more of the fine details are brought to the fore, simple models become inadequate and more complicated ones have to be developed. Eventually, one has to look into the individual nucleonic interactions as the final resort to explain all the features of nuclear spectroscopy. The successful treatment by Kisslinger and Sorensen[1] of the low-energy properties of nuclei by considering pairing and long-range interactions is an important step along this direction.

A similar situation exists in nuclear fission. While a few salient features may be explained in terms of simple models, the adequacy of these models is in doubt as experimental data accumulate. It seems that one is again forced to look into the individual nucleonic interactions for the complete solution. The success of the Kisslinger and Sorensen treatment indicates that the pairing and long-range interactions may be considered in a similar manner for a nucleus with very large deformation such as the saddle-point deformation in fission. One immediate consequence is that there is to be an even-odd effect of the energy at the saddle point just as the even-odd variation of nuclear mass at the ground state.

There is actually an even-odd effect in fission, and we may try to explain it on the basis of the above discussion. It is known that[2,3] the addition of an odd nucleon to an even-even nuclide hinders the rate of spontaneous fission; the lifetime becomes longer by a factor of about 10^3. The addition of an odd neutron and an odd proton (thus making the fissioning nuclide an odd-odd type) prolongs the lifetime by a factor of about 10^5. If this is to be attributed to a higher fission barrier, the increase in barrier energy is about 0.4 and 0.7 Mev, respectively. To explain the hindrance factor Seaborg[2] has considered a possible change of nuclear radius due to the addition of an odd nucleon; on the other hand, Newton[4] and Wheeler[5] have used the unified model of Bohr and Mottelson. According to the previous discussion, the pairing energy manifests itself in both the ground state and the saddle-point deformation of the fissioning nucleus. Thus the addition of an odd nucleon to an even-even nucleus raises the ground-state energy by δ_A, where A is the mass number of the fissioning nucleus; it also raises the saddle-point energy by $\delta_A{}^S$, the value of which we do not know. If $\delta_A{}^S$ is greater than δ_A by about 0.4 Mev, then we have the desired explanation of the increase of the fission barrier energy. Furthermore, the additivity of energy explains the hindrance factor due to an odd neutron plus an odd proton. The value of $\delta_A{}^S-\delta_A$ probably may be estimated as follows: Consider a continuous deformation process starting from the undeformed compound nucleus (odd-A type), passing through the saddle point, and eventually ending at two separate daughter nuclei (one even-even type and the other even-odd type). The corresponding change of the pairing energy is from δ_A to $\delta_A{}^S$ and then to $\delta_{A/2}$, the latter corresponding to the pairing energy of a daughter nucleus with the mass number reduced by one-half. This value $\delta_{A/2}$ is a minimum estimate; for an odd-A fissioning nucleus may be divided into an odd-odd nucleus plus an odd-A nucleus and the total pairing energy in the last stage is $3\delta_{A/2}$. According to the Fermi mass formula[6] in which δ_A equals $0.036/A^{\frac{3}{4}}$ amu, the value of $\delta_{A/2}-\delta_A$ may be calculated and turns out to be about 0.4 Mev. It is likely that $\delta_A{}^S-\delta_A$ is of the same order of magnitude as the difference of pairing energies between the initial and final stages, the minimum estimate of which is 0.4 Mev. Therefore, the difference in pairing energy is of the right order of magnitude to account for the hindrance factor.

That there is an even-odd effect for the saddle-point energy has been discussed by Swiatecki[7] on an empirical basis. In an effort to establish systematics of fission thresholds, he found that the empirical saddle-point mass, obtained by adding the experimental fission threshold energy to the ground-state mass, as a function of Z^2/A, actually splits into three curves corresponding to the odd-odd, odd-A, and even-even nuclear types with spacing $\delta_A{}^S=1.2$ mmu. He took the value of δ_A for ground-state masses of fissionable nuclei to be 0.77 mmu. The difference $\delta_A{}^S-\delta_A$ is thus 0.40 Mev, exactly

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the amount necessary to account for the hindrance factor. In fact, Swiatecki has pointed out that the fission threshold energies deduced from spontaneous fission lifetimes are consistent with the systematics established in induced fission.

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Decay of I^{134}

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The decay properties of 53-min I^{134} have been investigated with scintillation techniques as part of a program for the systematic study of xenon energy levels. Energies (and intensities) of the gamma rays determined from the single-crystal and coincidence studies are 0.135 (3.2), 0.18, 0.23, 0.27, 0.32, 0.39 (7.2), 0.41 (0.6), 0.43 (2.9), 0.51 (0.9), 0.54 (8.4), 0.61 (19), 0.69 (7.3), 0.75 (1.3), 0.77 (6.0), 0.848 (100), 0.864 (4.6), 0.890 (74), 0.96 (2.0), 1.00 (4.7), 1.07 (18), 1.15 (10), 1.28 (1.4), 1.34 (1.5), 1.46 (3.7), 1.49 (1.0), 1.62 (4.9), and 1.79 (4.9) Mev. There are two gamma rays at each energy of 0.89 and 1.07 Mev. The single-crystal spectra were corrected experimentally for gamma-ray summing. Gamma coincidence spectra were measured by gating at energies of 0.135, 0.41, 0.61, 0.85, 0.89, 1.00, 1.07, 1.15, 1.46, 1.62, and 1.79 Mev in the gamma-ray spectrum. Beta-ray spectra were measured in coincidence with gamma rays at 0.85, 1.00, 1.07, 1.15, 1.46, 1.62, and 1.79 Mev. These measurements and the single-crystal data disclosed beta rays with end-point energies of 2.41, 2.21, 1.68, 1.49, 1.25, and 1.05 Mev. In a three-crystal "beta-gamma-gamma" experiment the 2.41-Mev beta-ray group was shown to populate a level in Xe^{134} at 1.74 Mev; therefore, the energy difference between the ground states of I^{134} and Xe^{134} is 4.15 ± 0.06 Mev.

A decay scheme is proposed with energy levels (and spins) in Xe^{134} at 0.85 (2+), 1.62 (2+), 1.74 (4+), 1.92, 2.34, 2.43, 2.48, 2.64, 2.88, 3.11, 3.30, and 3.41 Mev. A collective nature of the low-lying levels is suggested in that the 1.62- and 1.74-Mev states appear to be members of a "vibrational" doublet at about twice the energy of the first excited state.

The half-life of I^{134} was redetermined as 52.8 ± 0.3 min.

I. INTRODUCTION

In recent years there have been a number of attempts to systematize and explain the low-lying levels of even-even nuclei in the medium-weight ($A=40$–140) region. Although a large quantity of experimental information has been accumulated, in only a few cases have the levels of more than two or three nuclides of the same Z been thoroughly investigated. The even xenon isotopes show promise for a systematic study of thos sort, since their excited states are abundantly populated by beta-decay from iodine nuclides of convenient half-life. In addition to the earlier work[1] on xenon nuclides with $A=126$, 128, 130, and 132, recent research at this laboratory[2–4] has been performed on the decay of I^{130}, I^{132}, and I^{136}. With this report of the results of experiments on levels in Xe^{134} from the decay of I^{134}, the even xenon isotopes form one of the largest sets of well-characterized energy levels of a given family. The nuclide Xe^{134} is of great interest since its heavier near-neighbor Xe^{136} is a closed-shell nuclide, but one which exhibits a surprising "vibrational" behavior. The low-lying levels of its lighter, near-neighbor Xe^{132} also appear to have a collective nature. As will be seen, Xe^{134} seems to possess a similar level structure with a doublet of 2+ and 4+ character at an energy of approximately twice that of the first 2+ state.

Abelson[5] found a new 54-min iodine activity among the products of uranium fission, and demonstrated that it was the daughter of a tellurium isotope with a 43-min half-life. Katcoff, Miskel, and Stanley[6] assigned the 54-min period to I^{134} by fission-fragment range measurements.

The first detailed investigation of the radiations from I^{134} was reported by McKeown and Katcoff.[7] The gamma-ray spectrum obtained by these investigators showed an intense gamma ray at 0.86 Mev, which was interpreted as the de-excitation of the first excited state of Xe^{134}. Additional gamma rays were found at 0.120, 0.200, 1.10, and 1.78 Mev. The most energetic beta component was found to have an energy of 2.5 ± 0.2 Mev, and to be in coincidence with the intense 0.86-

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