Deviations from Mayer's Scheme for Filling Nuclear Shells and the Interaction of Levels

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THERE are nuclei which do not fit into Mayer's scheme for the filling of shells [1]. These deviations can be explained by making the following assumptions: between similar nucleons which are in neighboring orbital angular momentum quantum number levels and have the same spin orientation with respect to the orbit-namely that for which the total angular momentum j is the largest possible- there exists a strong interaction, leading to the weakening of the coupling between nucleons in the level with the lower angular momentum. The coupling of a pair of nucleons in this level may become weaker than the coupling of a pair of nucleons in higher levels. This phenomenon may be considered as the extraction of a nucleon from the filled level of lower l and the coupling of it to one of the odd nucleons of the higher level.

Consider the first nucleus which deviates from the scheme, ${}_{11}Na^{23}$. The particles in this nucleus are in the following states: $1s_{1/2}\ 2p_{3/2}\ 2p_{1/2}\ 3d_{5/2}$. The $2p_{3/2}$ and $3d_{5/2}$ levels satisfy the conditions given above. In the $3d_{5/2}$ level of ${}_{11}Na^{23}$ there are not less than two particles. They cause a weakening of the coupling between the particles in the $p_{3/2}$ level, resulting in the extraction of a particle from the filled $p_{3/2}$ and the coupling of it to the particles in the $d_{5/2}$ level. The Na nucleus will have the following structure: $1s^{(2)}_{1/2}\ 2p^{(3)}_{3/2}\ 2d^{(2)}_{1/2}\ 3d^{(4)}_{5/2}$. The magnitude of the magnetic moment corroborates the fact that ${}_{11}Na^{23}$ is in a $p_{3/2}$ state. In shell IV, ${}_{25}Mn^{55}$ is an exception to the scheme. The following levels enter into the state of the nucleus: $1s_{1/2}\ 2p_{3/2}\ 2p_{1/2}\ 3d_{5/2}\ 3d_{3/2}\ 2s_{1/2}\ 4f_{7/2}$. The $3d_{5/2}$ and $4f_{7/2}$ levels satisfy our conditions. The $4f_{7/2}$ of ${}_{25}Mn^{55}$ has to be filled by at least two particles; they weaken the coupling between the nucleons in the $3d_{5/2}$ level. As a result, a particle is extracted from the full $3d_{5/2}$ level and is coupled with the particles in the $4f_{7/2}$ level. Thus ${}_{25}Mn^{55}$ has the following structure:

$$1s^{(2)}_{1/2}2p^{(4)}_{3/2}2p^{(2)}_{1/2}3d^{(5)}_{5/2}3d^{(4)}_{3/2}\,2s^{(2)}_{1/2}4f^{(6)}_{7/2}.$$

The magnitude of the magnetic moment corroborates the $d_{5/2}$ state of Mn^{55}.

The existence of an unfilled $d_{5/2}$ level together with a filled $d_{3/2}$ level is not inconsistent with spin-orbit coupling, which requires that the $d_{3/2}$ level be filled after the $d_{5/2}$ level is completely full. This requirement is fulfilled when there are no particles in the $4f_{7/2}$ level. With the presence of nucleons in the $4f_{7/2}$ level, however, the energy of a particle in the $d_{5/2}$ level becomes greater than in the $d_{3/2}$ level. These considerations carry over to other appropriate levels also. Especially interesting is the manifestation of this level interaction in shell IV. Here our conditions are satisfied by the $4f_{7/2}$ and $5g_{9/2}$ levels. However, the level interaction does not lead to a nucleus with a ground state spin 7/2, but the excited states have isomers with this spin. The existence of spin 7/2 in the excited states of nuclei with number of particles between 39-49 is difficult to explain in the ordinary shell structure theory. In ${}_{34}Se^{79}$ the state with spin 7/2 is the ground state. In shell V our conditions are satisfied by the $4g_{9/2}$ and $6h_{11/2}$ levels; as spins of 9/2 do not occur here, we conclude that the extraction of particles from the $g_{9/2}$ level does not occur. The appropriate levels of shell VI are the $6g_{11/2}$ and $7i_{13/2}$ levels. There are few nuclei with unknown spins in this region, and investigating them is difficult.

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[1] M. I. Korsunskii, Usp. Fiz. Nauk 52, 1 (1954)

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The Fission of Heavy Nuclei by Slow Mesons

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IN this letter, there are briefly described the results of work during 1950-1952 on fission of heavy nuclei as a result of interaction with slow π^- mesons. The results are presented in reports of RIAN (Radium Institute of the Academy of Sciences, USSR)[1-5]. A detailed account of this work will be published in JETP.

Thick layer photographic plates with nuclei of uranium, lead and wolfram introduced into the photo-sensitive layer were irradiated by slow π^- mesons. After development the plates were examined under a microscope. Upon examination of the plates, there were observed shatterings of nuclei by the mesons, with the formation of stars in cases of fission. Events were considered as fission if at the end of the meson trace, there were observed two approximately oppositely directed traces of multiple charge particles of the type of fragments resulting from uranium fission by slow neutrons. Cases of fission were observed resulting from capture of slow π^- mesons by nuclei of uranium, lead and wolfram*.

As it turned out, the probability of fission of wolfram as a result of capture of slow π^- mesons is very small[7]. Basic investigations were made of the interaction between slow π^- mesons and uranium nuclei. There were observed 356 cases of such fission, from the examination of which it was possible to draw certain conclusions concerning the mechanism of interaction between slow mesons and these nuclei.

1. When slow π^- mesons are captured by nuclei of elements located at the end of the periodic system, nuclear fission takes place with a certain probability. The probability of fission is greatest for uranium. The numerical value of the probability of fission for uranium nuclei, computed on the basis of our experimental data, depends on the assumed distribution of the uranium nuclei introduced into the emulsion. In the case of uniform distribution among all the elements entering into the emulsion, the numerical value of the probability is 0.87 ± 0.27. At non-uniform distribution, when the entire quantity of uranium is distributed only in the gelatin of the emulsion and does not enter into the crystals of AgBr**, the value of the probability becomes equal to 0.42 ± 0.15, i.e., about one half of the cases of capture of slow mesons result in fission.

2. For interaction between slow π^- mesons, the distribution according to their track lengths of the single fragments in the resulting fission exhibits a sharp maximum (Fig. 1) which indicates a considerable number of cases of fission into fragments of approximately equal mass.

3. The average combined track of pairs of fragments for fission by slow π^- mesons (23.7 μ) agrees well, within the experimental error, with the average combined track (24 μ) of fragments resulting from fission of uranium by slow neutrons. This shows that the energy formed at the expense of the rest mass of the captured π^- meson is not converted into kinetic energy of the fragments.

4. Besides the cases of uranium nuclear fission which appear to be binary, in ten cases out of a hundred the fission is accompanied by the emission of a light charged particle. A special investigation of the nature of these particles showed that they are in most cases protons. Their angular distribution with respect to the line of fission is shown in Fig. 2. These data indicate that the process of fission by capture of slow π^- mesons differs sharply from the process of fission caused by slow neutrons and that the former process corresponds rather to division of nuclei into fast particles.

5. All these presented facts do not contradict the following assumptions concerning the mechanism of the process. A slow π^- meson captured in one of the meson orbits of the uranium atom interacts with a pair of nucleons (np) or (pp)[9] to which it imparts the energy of its rest mass and its charge; as a result, there are obtained two fast particles with energies approximately 70 mev each. Fast particles of such energy in passing through the nucleus may expel from the nucleus, as a result of collisions, one or two nucleons and then emerge (if the energy is sufficient) leaving the nucleus in a highly excited state. The excited nucleus must lose the excitation energy by the evaporation of the nucleons and undergo fission at some stage of the excitation.

The fact that the probability of fission is less than one indicates that in some cases the excitation energy is basically expended only for the evaporation of the nucleons.

6. On the basis of the proposed interaction mechanism, it is possible to explain the binary fission as fission with emission of neutrons (primary or secondary), the fission with emission of charged particles differing from binary fission only in that in this case together with neutrons there are emitted also the primary or the secondary proton. The relatively large number of protons accompanying fission at energies above 20 mev tends to confirm our view that the significant portion of the protons observed in the fission process is related to the knocked out particles and not to evaporation. The observed, nearly isotropic, angular distribution of the emitted protons with respect to the line of flight of the fragments naturally follows from the above.

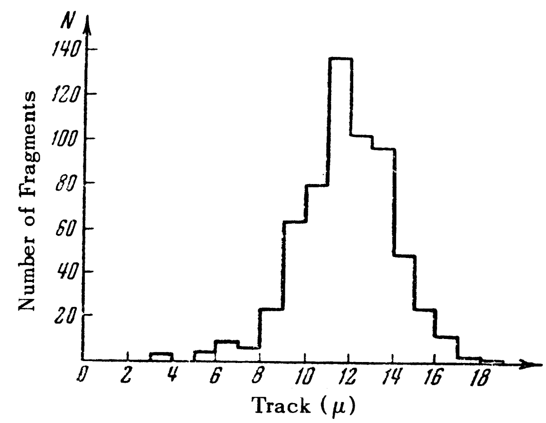

FIG. 1. The distribution of tracks of single fragments in uranium nuclear fission by slow π^- mesons.

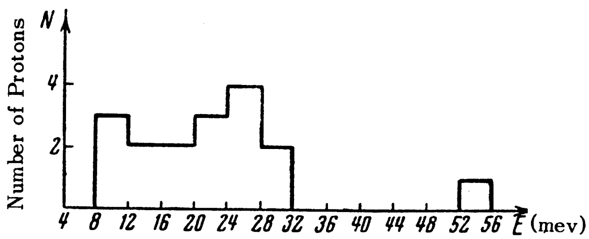

FIG. 2. Distribution by energy of protons emitted in the process of fission of uranium nuclei by slow π^- mesons.

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* The first report was completed in March, 1950. Almost simultaneously and independently of us, fission of uranium with capture of π^- mesons was discovered by Frank and Belovitskii [Report FIAN (Institute of Physics, Academy of Sciences, USSR)]. The first communication concerning fission of uranium by slow π^- mesons appeared in October, 1951, in the work of Al-Salam[6].

** Experimental proof of such unequal distribution is contained in the work of Lozhkin and Shamov[8].

1 N. A. Perfilov and N. S. Ivanova, Report RIAN, March, 1950

2 N. A. Perfilov and N. S. Ivanova, Report RIAN, October, 1950

3 N. S. Ivanova and N. A. Perfilov, Report RIAN, June, 1951

4 D. V. Viktorov, N. S. Ivanova and N. A. Perfilov, Report RIAN, January, 1952

5 N. S. Ivanova and N. A. Perfilov, Report RIAN, June, 1952

6 S. G. Al-Salam, Phys. Rev. **84**, 254 (1951)

7 N. A. Perfilov, Report RIAN, June, 1953

8 O. V. Lozhkim and V. Shamov, Report RIAN, January, 1954

9 S. Tamor, Phys. Rev. **77**, 412 (1950)

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The Probability of Uranium Nuclear Fission by its Absorption of Slow Π^- Mesons[1]

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THE first determinations of the probability of fission of the uranium nucleus by the capture of π^- mesons were carried out in our laboratory in 1951. Perfilov and Ivanova, and Perfilov and the authors[2,3], with the use of thick-layered emulsions, came to the conclusion that apparently practically every capture of a π^- meson by a uranium nucleus leads to fission of the latter. The same conclusion was reached later by Al-Salam[4], using a similar method.

The same method was adopted for the experiments being described. Nuclear plates were soaked in a 4% solution of $UO_2Na(C_2H_3O_2)_3$ and exposed to slow π^- mesons. Under microscopic examination of a given stage of the plate there were counted the number of times that a π^- meson stopped in the photo-layer, the number of cases of fission of uranium nuclei by π^- mesons, and the number of uranium nuclei (by means of the number of α-particle tracks arising from the natural radioactive decay of uranium). For the determination of the total number of cases of capture of π^- mesons by uranium nuclei, it is necessary to know first, how the uranium is distributed throughout the volume of the emulsion, and second, how the probability of capture of slow π^- mesons depends on the Z of the nucleus.

The distribution of uranium in the soaked emulsion was investigated in the following manner. The soaking of the emulsion in uranium salt was carried out and stirred in a special container in a