$$\Delta = \arccos \bar{\sigma}^{-1/2} - (\bar{\sigma} - 1)^{1/2} \bar{\sigma}^{-1}$$

for symmetric fission. Figure 3 illustrates the agreement between calculation and experimental data. The period of fission of U^{236}_{92} nuclei by capture of thermal neutrons, according to Ref. 8 $\sim 10^{-12}$ sec., which is, in fact, obtained from Eq. (1), if one assumes that the radius of the potential well for the excited level is 1.2 times greater than for the ground level (the energy difference of these levels $\sim$ 6 mev). This assumption is entirely acceptable, since the bottom of the well has parabolic shape. This assumption is equivalent to taking into account of the influence of the deformation of the nuclear surface on the probability of tunnel fission; this has been done in the case of α-decay in Ref. 9, where it was also shown that deformation of the nucleus very considerably increases the probability of the tunnel transition. Extension of these calculations to asymmetric fission shows that it is sufficient to take the relative deformation of the nucleus due to polarization by the captured neutron as equal to 0.5 in order to explain the difference in the periods of spontaneous and induced fissions. Deformations of this order of magnitude are entirely reasonable.[10] It is interesting to note that the influence of deformation on ln $(\omega/\bar{\omega})$ is so slight that on a logarithmic scale asymmetric fission (spontaneous as well as induced by thermal neutron capture) is represented by almost the same graph. Application of (1) to fission by fast particles, with energy of the order of 15 – 25 mev, is illustrated in Fig. 4 and shows good agreement with experiment.[11] In the calculations it was assumed that the kinetic energy of the (fast) particle causing fission is completely transferred into the energy of the fission fragments. Thus the hypothesis, put forward in Ref. 1, does in fact give a unified explanation of the basic regularities of asymmetric fission. An explanation of the fission threshold by slow neutrons in the nuclei Th^{232}_{90}, Pa^{231}_{91}, U^{238}_{92} can also be given from the point of view here set forth and does not require the assumption of a supra-tunnel mechanism of fission.[12]

[1] Ia. I. Frenkel, *Principles of the Theory of Atomic Nuclei*, Academy of Sciences Press, 1950, p. 159.

[2] H. Bethe, *Nuclear Physics*, Part II, GITTL, 1948, p. 184 (Russian translation).

[3] K. Way and E. Wigner, Phys. Rev. 73, 1318 (1948).

[4] E. Fermi, *Nuclear Physics*, IIL, 1950, p. 14. (Russian translation).

[5] Zh. Sigel, Usp. Fiz. Nauk 33, 1, 77 (1947).

[6] Ia. I. Frenkel, Izv. Akad. Nauk SSSR Fiz. Ser. 10, 415 (1946).

[7] G. T. Seaborg, Phys. Rev., 85, 157 (1952).

[8] R. R. Wilson, Phys. Rev. 72, 98 (1947).

[9] L. A. Sliv and L. K. Peker, Dokl. Akad. Nauk SSSR 99, 727 (1954).

[10] A. Bohr and B. R. Mottelson, Problems of Contemporary Physics, 9, p. 34, 1955. (Russian translation).

[11] A. Newton, Phys. Rev. 75, 17 (1949); R. W. Spence, BNL – C – 9, 1949.

[12] N. Bohr and J. A. Wheeler, Phys. Rev. 56, 426 (1939).

Translated by A. V. Bushkovitch
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Pion-proton Interactions at 1.4 BEV

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Eisberg et al.[1] have made a detailed study of the interaction of negative pions with protons at 1.37 bev. The analysis by Belen'kii and Nikishov[2] of $n-p$ collisions at 1.7 bev shows that a direct comparison of experimental results for multiple particle production with Fermi's[3] statistical theory in its original form leads to considerable divergence of theory and experiment. When, however, the statistical theory also allows for the formation of isobar states the discrepancy disappears, leaving a quite satisfactory agreement with experiment.

It is also of interest to compare with the statistical theory including isobar states the experimental data on the interaction of negative pions with protons. We shall use the notation N for nucleon, N' for isobar state and π for pion. The important cases here are those which give the following states as a result of pion-nucleon collisions: $N\pi$ – elastic scattering; $N'\pi$, $N\pi\pi$ – the production of one secondary meson; $N'\pi\pi$, $N\pi\pi\pi$ – the production of two secondary mesons. The statistical weights of these states are calculated as in Refs. 2 and 4. For brevity we shall write $N'\pi\pi \equiv 2N'$ etc.

After correcting for identity, spin and isotopic spin conservation, the relative statistical weights of processes $1N$, $2N$, $1N'$, $2N'$, $3N$ and $3N'$ (in %) are, respectively, 21, 30, 29, 13, 6 and 1. The last process can thus be neglected. Furthermore,

Table 1

Charged reaction products	Milburn's results with $R=1.3\times10^{-13}$ cm	Including isobars		Experi-ment
		$R=1.3\cdot10^{-13}$ cm	$R=1.4\cdot10^{-13}$ cm	
$(\pi^-+p)_{el}$	0.32	0.16	0.15	0.11
$(\pi^-+p)_{inel}$	0.29	0.29	0.29	0.35
$\pi^++\pi^-$	0.36	0.50	0.50	0.50
$\pi^++2\pi^-+p$	0.03	0.05	0.06	0.04

TABLE 2

Number of secondary pions	Experi-ment	By Fermi's theory with $R=1.4\times10^{-13}$cm	Including isobars with $R=1.4\times10^{-13}$cm
0	12	22	16
1	71	65	67
2	24	20	24

these weights are subdivided according to charge states.

It follows from the calculation that the observed interactions comprise approximately 78% of the total number of interactions. The remaining interactions give only neutral particles. These are reactions leading to the states (n 0), (n 00) and (n 000).

Let us compare these results with experiment and with the calculations which neglect isobars. We shall first compare our calculation with the calculation in Ref. 1 which neglects isobar states and with the experimental data of Table VIII of Ref. 4. This table gives the distribution of the observed charged products of $\pi^- - p$ collisions. $(\pi^- - p)_{el}$ denotes instances in which the observed secondary particles satisfy energy and momentum conservation laws; $(\pi^- - p)_{inel}$ denotes instances when these laws are not satisfied so that neutral undetected particles are also involved. We reproduce a part of this table supplemented by two columns containing our results (Table 1).

We note that the calculation is not compared with all elastic collisions but only with the incoherent portion of them, since Fermi's theory involves only the latter.[1,4]

It is also possible to compare the number of instances with different pion multiplicities. Here, however, the experimental results are much less definite. Eisberg observed 147 interactions. Of these 95 were inelastic; the 52 elastic collisions are subdivided into 40 coherent and 12 incoherent cases. Thus there were noted 107 collisions resulting in charged products, which are those of interest to us. Furthermore, the 95 observed inelastic collisions are subdivided (with considerable indeterminacy) into 71 with the creation of one secondary meson and 24 with the creation of two secondary mesons. This subdivision is compared with the calculations by Fermi's theory neglecting isobars and by formulas which raise the multiplicity considerably (the mesons are considered extreme relativistic particles). The results are given in Table IV of Ref. 1. We again copy a portion of this table and add a column containing the results of our calculations, which are more precise and also allow for isobars (Table 2).

The agreement is seen to be satisfactory.

Finally, we shall compare the meson and nucleon momentum distributions in the center of mass system for the reactions (p −0) and (n +−). In calculating the momentum distribution for the $N\pi$ process we assume that an isobaric state decays isotropically in its own reference system. In addition, we assume that the width of an isobar level is zero. We thus obtain the graphs of Figs. 1 and 2.

It is evident that allowance for the width of an isobar level would result in still better agreement of the calculation with experimental data. Thus the results for $\pi^- - p$ interactions are in satisfactory agreement with the statistical theory when

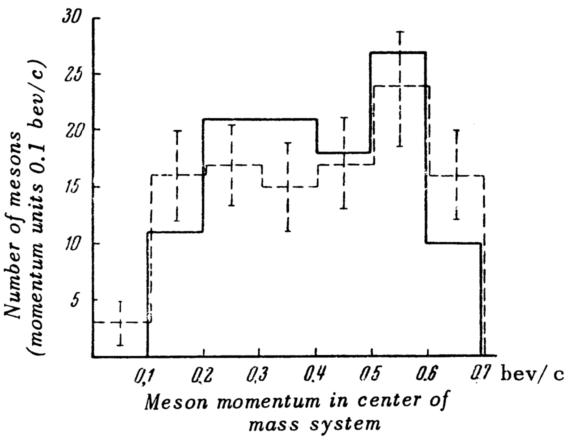

FIG. 1. Meson momentum distribution in the center of mass system for the reactions ($p-0$) and ($n+-$). Dashed line – Eisberg et al, experimental distribution; solid line– distribution according to the statistical theory including isobars.

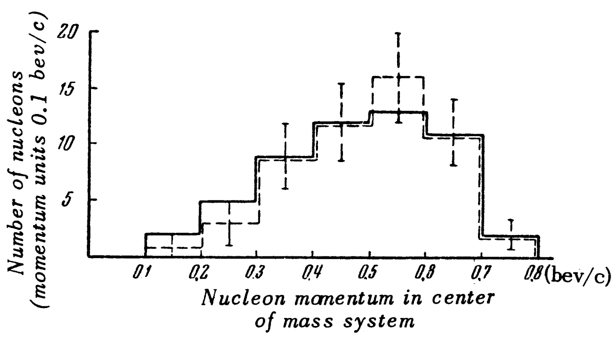

FIG. 2. Nucleon momentum distribution in the center of mass system for the reactions ($p-0$) and ($n+-$). Dashed line– Eisberg et al., experimental distribution; solid line– distribution according to the statistical theory including isobar states.

it includes isobar states.

We also note that according to the above calculation the meson momentum distribution is in contradiction with the statistical theory when isobar states are neglected, but is not in contradiction with the assumption that particle creation can only take place through isobaric states. However, the marked spread of Q (isobar decay energy) can be interpreted as being due to the fact that a considerable part is played by creation without immediate isobaric states.

In conclusion I wihh to express my gratitude to Professor S. Z. Belen'kii for interesting discussions and for his continued interest.

[1] L. M. Eisberg et al., Phys. Rev. 97, 797 (1955).

[2] S. Z. Belen'kii and A. I. Nikishov, J. Exptl. Theoret. Phys. (U.S.S.R.) 28, 744 (1955); Soviet Phys. JETP 1, 593 (1955).

[3] E. Fermi, Phys. Rev. 92, 452 (1953).

[4] R. H. Milburn, Rev. Mod. Phys. 27, 1 (1955).

[5] W. B. Fowler et al., Phys. Rev. 95, 1026 (1954).

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On the Interaction between Nucleon and Antinucleon

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WE investigate by means of the "old" Tamm method the interaction between nucleon and antinucleon. The Schrödinger equation for the wave functional of the system has the form:

$$(H_0+H')\Psi = W\Psi, \tag{1}$$

where W is an eigenvalue of the total energy of the system. Let us expand Ψ in a series of eigenfunctions of H_0 :

$$\Psi = \sum_{\lambda, m, n} a_\lambda^{mn}\psi_\lambda^{mn}. \tag{1a}$$

Here m is the number of mesons in a free state, n is the number of nucleon pairs, λ denotes momenta, spins and isotopic spins of the particles, a_λ^{mn} is the probability amplitude of finding the system in the state(λ, m,n). From Eq. (1), we obtain an integral equation for the amplitude a_λ^{mn}

$$[W-E_\lambda^{mn}]\,a_\lambda^{mn} = \sum_{q=n-1}^{n+1}\ \sum_{p=m\pm1}\ \sum_{\mu}\langle\lambda mn\,|\,H'\,|\,\mu pq\rangle\, a_\mu^{pq}. \tag{1b}$$

From this equation it is possible to obtain an equation for the amplitude a_λ^{01} corresponding to the state in which only a nucleon and an antinucleon are present. We have

$$[W-E_\lambda^{01}]\,a_\lambda^{01} = \sum_{\mu}[\langle\lambda 01\,|\,H'\,|\,\mu 11\rangle\, a_\mu^{11} + \langle\lambda 01\,|\,H'\,|\,\mu 10\rangle\, a_\mu^{10} + \langle\lambda 01\,|\,H'\,|\,\mu 12\rangle\, a_\mu^{12}]. \tag{2}$$