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Further Investigation of the Radioactivity of Sb^{124}*

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The shape of the highest energy beta-ray group in Sb^{124} is found to have a forbidden shape that is characteristic of a once-forbidden transition involving a change of two units of angular momentum and a change of parity. As a consequence, the end points of the three highest energy groups are changed somewhat to 2.291 ± 0.005, 1.69 ± 0.01, and 0.95 ± 0.03 Mev. A high resolution measurement of photo-electrons confirms the existence of the 0.607-, 0.653-, and 0.730-Mev gamma-rays. The internal conversion of the 0.607-Mev gamma-ray was studied. The character of the radiation and relation of the parity assignments to possible predictions of the nuclear shell model are discussed. A search for possible positron or K-capture transitions to Sn^{124} gave no indication of the existence of such radiation.

I. INTRODUCTION

With the availability from Oak Ridge of sources having high specific activities, it seemed desirable to reinvestigate certain aspects of the Sb^{124} (60-day) disintegration.

In particular, it was suspected that the highest energy negatron group, with an end point previously reported[1] as 2.37 Mev might, if studied in greater detail, exhibit a forbidden spectrum shape. Such a shape might be expected from the high comparative half-life ($ft \sim 10^{10}$) associated with the transition. Previous investigations[1, 2] probably should not have been expected to distinguish a forbidden shape because of insufficient intensity in the region near the end point.

Since the general experimental techniques are now somewhat improved over those used earlier, an attempt was also made to check on the gamma-rays previously reported at 0.608, 0.654, and 0.732 Mev with better resolution and reliability.

Since Sb^{124} lies between stable Te^{124} and the relatively stable[3] Sn^{124}, there exists the possibility that the negatron emission might be in competition with positron emission or K-capture. A search was made, therefore, for positrons and for the Auger electrons which would be expected if any appreciable amount of the decay goes by K-capture.

The internal conversion of the 0.607-Mev gamma-ray was also studied.

II. EXPERIMENTAL METHOD

The measurements were carried out in the 40-cm radius of curvature, shaped magnetic field spectrometer.[4] Accurate magnetic field measurements were facilitated by a continuous comparison with a standard Helmholtz field by means of a rotating coil, balance arrangement.[5]

For the beta-spectra measurements, the resolution was 0.5 percent. For the gamma-ray determinations, this was increased to 0.85 percent (for a 0.6-Mev gamma-ray) because of the energy degeneration of the photo-electrons emerging from the finite thickness of the Pb radiator.

The beta-source was prepared by spreading, with the aid of insulin, $SbCl_3$ on a backing[6] of 0.02 mg/cm^2 LC600. The source was 0.6 cm wide, 2.5 cm high, and had an average thickness of 0.5 mg/cm^2. Very rapid drying of the deposit close under an infra-red lamp seemed to give the best uniformity. The source was maintained at ground potential by means of two small tabs of 0.18-mg/cm^2 aluminum, contiguous to the deposit.

For the gamma-ray measurements, the activity was deposited in a copper box with walls just sufficiently thick to stop all the primary beta-radiation. The photo-electrons were then ejected from a 5.6-mg/cm^2 Pb radiator which had been deposited on the 0.4×2.5-cm front face of the box, by thermal evaporation in vacuum.

III. RESULTS

The momentum distribution of the beta-rays of Sb^{124} is shown in Fig. 1. The open circles represent the data obtained in one run of the present investigation. The closed circles represent the data obtained earlier by Cook and Langer,[1] adjusted to the same intensity by a factor of 22.8. The inset shows the results of a study of the internal conversion of the 0.607-Mev gamma-ray obtained with a source which was 7.2 times as intense.

It is clear that the present investigation yields much more detailed information in the high energy region and, in general, joins quite well with the earlier data.

Figure 2 shows a conventional Fermi plot of the data in the high energy region. The values for the Coulomb factor, F, were taken from a set of curves prepared by relativistic calculation.[7] It is evident that the points do

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[1] C. S. Cook and L. M. Langer, Phys. Rev. **73**, 1149 (1948).

[2] Kern, Zaffarano, and Mitchell, Phys. Rev. **73**, 1142 (1948). This paper contains a complete list of references to earlier work.

[3] Sn^{124} has recently been reported to decay by double beta emission with a half-life of 6×10^{15} years. E. L. Fireman, Phys. Rev. **75**, *323 (1949)*.

[4] L. M. Langer and C. S. Cook, Rev. Sci. Inst. **19**, 257 (1948).

[5] L. M. Langer and F. R. Scott, Rev. Sci. Inst. **21**, 522 (1950).

[6] L. M. Langer, Rev. Sci. Inst. **20**, 216 (1949).

[7] S. A. Moszkowski (private communication).

not lie on a straight line; the highest energy group does *not* have a spectrum shape of the form associated with an allowed transition. The maximum energy, obtained by extrapolation of the curve, is $W_0=5.485\ mc^2$ or $E_0=2.291\pm0.005$ Mev.

Figure 3 shows the results of two attempts to fit the data with forbidden Fermi plots based on the two unique factors for once- and twice-forbidden transitions.[8, 9] The factor $a\propto[(W^2-1)+(W_0-W)^2]$ is characteristic of once-forbidden transitions involving a change of two units of angular momentum and a parity change. The factor

$$c\propto[3(W^2-1)^2+3(W_0-W)^4+10(W^2-1)(W_0-W)^2]$$

is unique for a twice-forbidden transition involving a spin change of three units and no change of parity. It is clear that the once-forbidden factor gives a very satisfactory fit at high energy. A correction factor based on a general $(W_0-W)^2$ dependence,[9] presumably applicable to most twice-forbidden transitions with spin change other than 3, was also tried and found not to fit the data.

Figure 4 shows the conventional and once-forbidden Fermi plots of the data. The broken lines indicate the results of the first two subtractions based on the assumption that the highest energy group is satisfied by the factor, *a*, and that the next inner group has the allowed shape.[10] It is easily seen how, in the absence of detailed information very close to the end point, the conventional plot $(C=1)$ might be interpreted to be a straight line extrapolating, as shown, to the higher end point reported earlier.[1, 2] The forbidden shape of the highest energy group not only lowers the value of its own end point but also affects somewhat the values of the maximum energies attributed to the next two inner groups. We now determine these as 1.69 ± 0.01 and 0.95 ± 0.03 Mev.

The present data, which are concentrated in the high

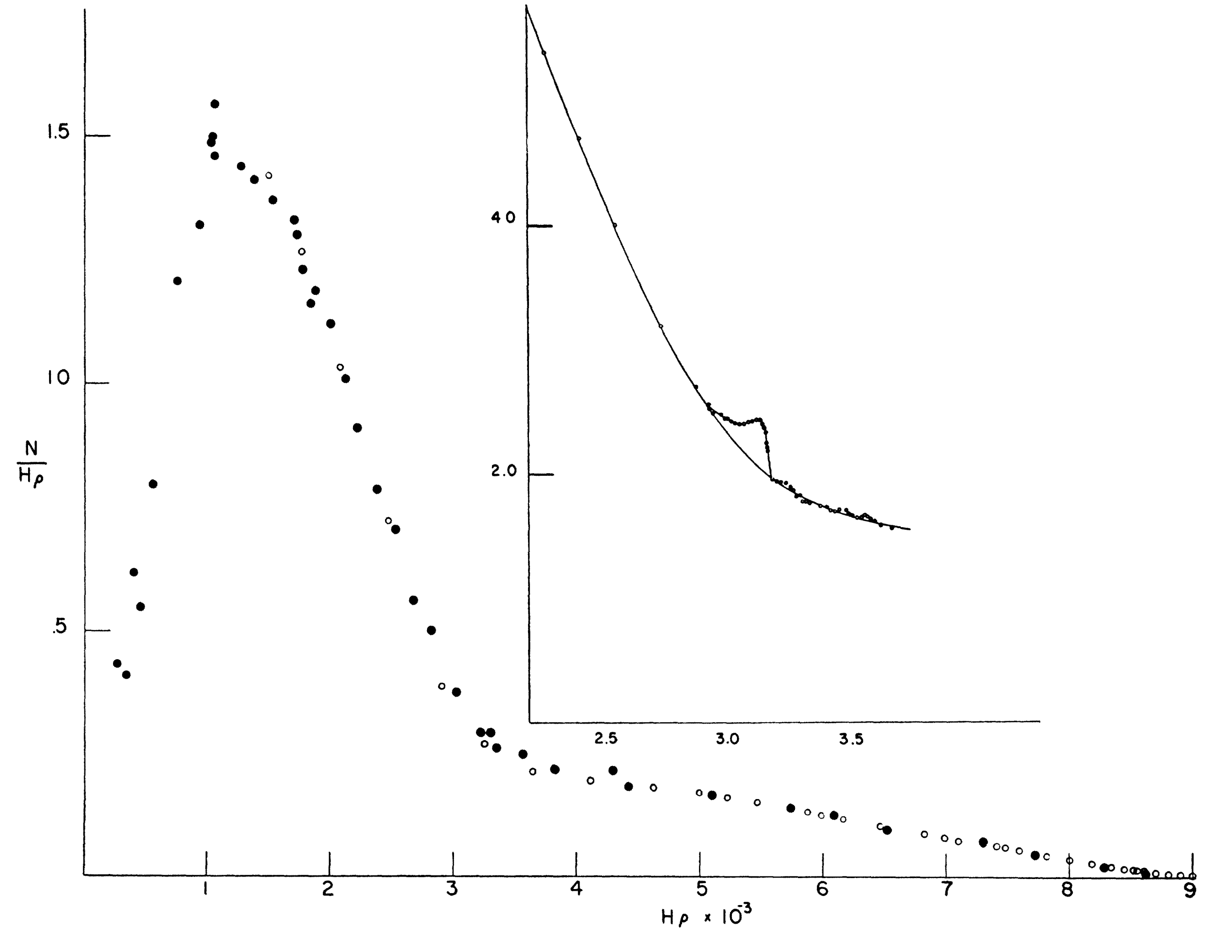

FIG. 1. Momentum distribution of the Sb^{124} negatrons. Closed circles represent the earlier data of Cook and Langer. The inset shows the internal conversion of the 0.607-Mev gamma-ray.

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[8] L. M. Langer and H. C. Price, Jr., Phys. Rev. **76**, 641 (1949).

[9] E. J. Konopinski, Rev. Mod. Phys. **15**, 209 (1943).

[10] The *ft*-values for some of the inner groups are sufficiently high so that one might very well expect additional forbidden spectrum shapes. Unfortunately, inaccuracies introduced in making such subtractions would mask the possible existence of any forbidden shape.

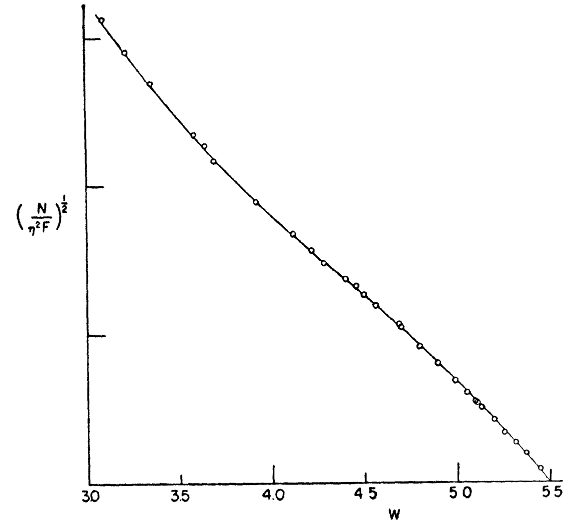

FIG. 2. Conventional Fermi plot of the Sb^{124} beta-distribution in the high energy region.

energy region, do not warrant further subtractions for the determination of lower energy groups. Furthermore, since the low energy spectra previously reported as having end points at 0.68 and 0.50 Mev are so much more intense, the determination of their maximum energies is negligibly affected by the new interpretation of the data.

Figure 5 is a plot of the photo-electron spectrum of the lower energy gamma-rays. The use of the thin radiator of only 5.6 mg/cm^2 of Pb yields much better resolution of these closely spaced lines than was obtained earlier. The photo lines corresponding to gamma-rays of 0.607, 0.653, and 0.730 Mev are now definitely resolved. As was suggested earlier, the *K*-line for the 0.730-Mev gamma-ray is superposed on the *L*-line of the 0.653-Mev gamma.

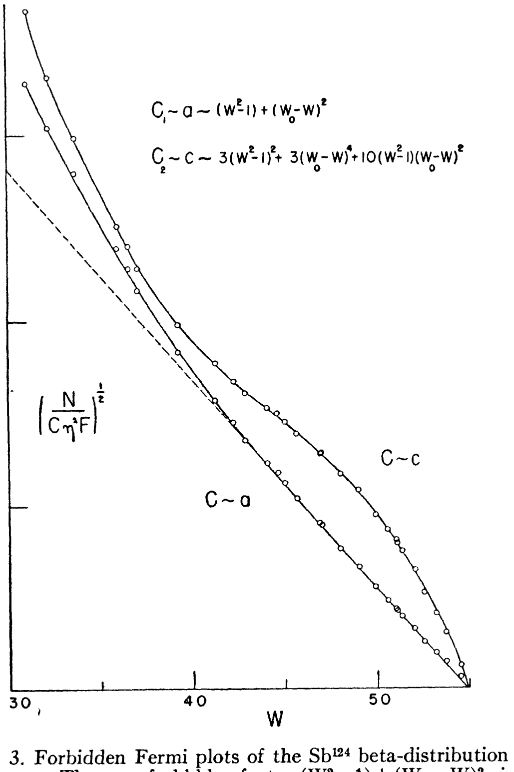

FIG. 3. Forbidden Fermi plots of the Sb^{124} beta-distribution at high energy. The once-forbidden factor $(W^2-1)+(W_0-W)^2$ gives a very good fit.

Inasmuch as the five beta-groups (2.29, 1.69, 0.95, 0.68, and 0.50 Mev) and the six gamma-rays (2.04, 1.71, 0.730, 0.653, 0.607, and 0.121 Mev) are difficult to fit into a unique energy level scheme, a search was made to determine whether any of the observed gammas might be associated with positron or *K*-capture transitions to Sn^{124}. A search was also made for the possible existence of a higher energy beta-transition directly to the ground state of Te^{124}. This is based on the assumption that the 2.29-Mev transition is to an excited state.[11] For these purposes, a beta-source was employed with seven times the intensity of a normal source. No measurable number of negatrons was observed with energies above 2.29 Mev. No positrons were detected. The very few Auger electrons observed could be attributed to a small amount of internal conversion of gamma-radiation and certainly was not indicative of any appreciable amount of *K*-capture. The search for Auger electrons was made with a counter having a 1.5-μg/cm^2 zapon window. Under the same experimental conditions, an appreciable intensity of Auger electrons was detected at 7 kev in Ga^{66}.

The same strong source was also used to study the weak internal conversion of the 0.607-Mev gamma-ray (Fig. 1).

IV. CONCLUSIONS

The 2.29-Mev beta-ray group is found to have a spectral shape different from that which is characteristic of an allowed transition. The data appear to be satisfied by the forbidden factor that is unique for a once-forbidden transition involving a change of two units of angular momentum and a change of parity. With this interpretation, the values of the end points of the three highest energy beta-groups are now changed to 2.291±0.005, 1.69±0.01, and 0.95±0.03 Mev.

A high resolution check on the closely spaced photolines definitely indicates gamma-rays with energies of 0.607, 0.653, and 0.730 Mev.

Since the 0.607-Mev gamma-ray corresponds exactly to the difference between the 2.29- and 1.69-Mev beta-groups, and the 0.730-Mev gamma-ray fits the difference between the 1.69- and 0.95-Mev groups, one is tempted to construct a level scheme on this basis. The high relative intensity of 0.607-Mev gamma-ray, how-

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[11] Coincidence experiments are not capable of answering this question because of the extremely small relative number of electrons with energy higher than that of the 1.69-Mev group. See E. T. Jurney and A. C. G. Mitchell, Phys. Rev. **73**, 1152 (1948).

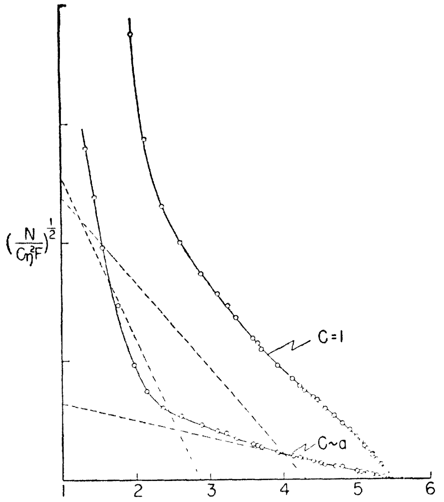


FIG. 4. Conventional and once-forbidden Fermi plots of the Sb^{124} data. The broken curves indicate the results of the first two subtractions. The extrapolation of the $C=1$ curve indicates how the incorrect maximum energy may be obtained in the absence of significant data near the end point.

ever, and the absence of any other gamma-ray of comparable intensity which could "feed" it, strongly suggests that the gamma-quanta of this energy must, for the most part, follow the 2.29-Mev beta-transition.[2] Unfortunately, the level scheme for the $\mathrm{Sb}^{124}-\mathrm{Te}^{124}$ disintegration remains somewhat ambiguous.

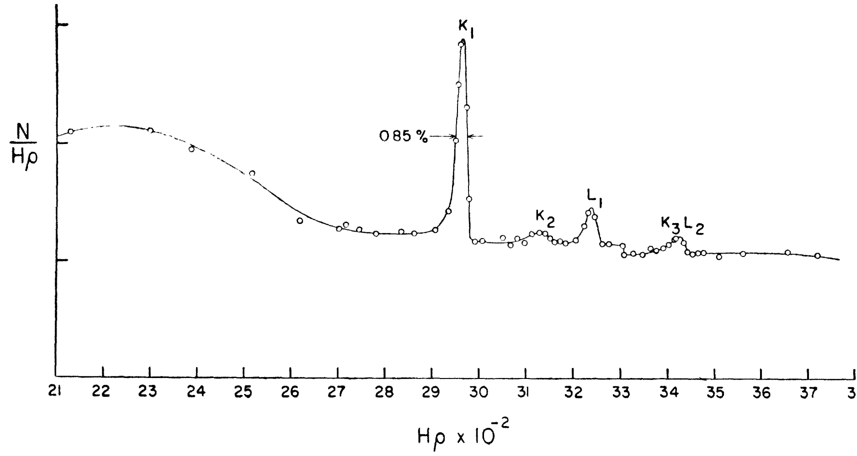
On the basis of the nuclear shell model[12] (extended to two odd nucleons), one might, at first glance, expect the ground state of Sb^{124} to arise from the combination of a $1g_{7/2}$ positron with a $1h_{11/2}$ neutron. Presumably, the resultant state should then have *odd* parity. Since the 2.29-Mev beta-transition is once forbidden, the product state in Te^{124} would then have *even* parity. Since the ground state of Te^{124} (which contains an even number of neutrons and protons) is expected to have *even* parity, the unobserved 2.9-Mev direct transition would be at least thrice forbidden. Under these conditions, the gamma-ray transition from the excited state in Te^{124} would involve no change of parity and could have a spin change as low as unity. This would be consistent with the classification of the radiation as magnetic dipole.

On the other hand, the amount of internal conversion is quite small. If one assumes that the 0.607-Mev gamma-transiton simply follows all beta-groups (neglecting the small amount associated with the 2.04-Mev gamma-ray) then the internal conversion coefficient (as determined by the ratio of the relative areas under the K-line and under the total beta-distribution) is 1.6×10^{-3}. This value is much too low for *magnetic* dipole radiation and is, in fact, in very good agreement with the theoretical value predicted for *electric* dipole radiation.[13]

If the 0.607-Mev gamma-ray is indeed *electric* dipole and does follow the 2.29-Mev beta-group, then the excited state in Te^{124} must have *odd* parity. Then, from the once-forbidden shape of the 2.29-Mev beta-group, one must conclude that the ground state of Sb^{124} has *even* parity and a spin of 3, contrary to the prediction based on the naive extension of the shell model to two odd nucleons.

It appears, however, that the beginning of the shell for the 51st proton is quite irregular.[14] The $2d_{5/2}$ and $1g_{7/2}$ states have approximately the same energy and either one might lie lower than the other and sometimes does. Furthermore, because of the preferential filling of the orbits by pairs, the $1h_{11/2}$ state, which has approximately the same energy as the $3S_{1/2}$, is suppressed, and one might therefore expect the 73rd neutron to be a $3S_{1/2}$. The combination of a $2d_{5/2}$ proton with a $3S_{1/2}$ neutron might be expected[15] to give a state with *even*

FIG. 5. Photo-electron distribution resulting from the 0.607, 0.653, and 0.730-Mev gamma-rays of Sb^{124}. A 5.6-mg/cm² Pb radiator was used.



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[12] M. G. Mayer, Phys. Rev. **75**, 1969 (1949).

[13] M. E. Rose *et al.* (tables, privately distributed).

[14] M. G. Mayer, Phys. Rev. **78**, 16 (1950).

[15] L. W. Nordheim, Phys. Rev. **78**, 294 (1950).

parity with spin of 3. Such an *even* parity state with spin of 3 could undergo a once-forbidden transition to an excited state of Te^{124} having *odd* parity and spin 1. This is then consistent with an electric dipole transition to the *even*, spin zero, ground state of Te^{124}. The direct 2.9-Mev transition is not observed since it is then twice forbidden.†

The absence of positron emission or K-capture is interpreted in either of two ways. If the ground state of Sn^{124} lies higher than that of Sb^{124} then one should not expect K-capture to take place. Furthermore, if this is so, then one should expect the twice forbidden single negatron emission from Sn^{124} to Sb^{124} to out-compete the double beta-decay to Te^{124}. It is, however, possible that the ground state of Sn^{124} does lie lower than that of Sb^{124}. In this case, the absence of positron emission or K-capture may be explained by the fact that the transition from the ground state of Sb^{124} to that of Sn^{124} is twice forbidden and is therefore out-competed by the negatron emission to Te^{124}.

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† *Note added in proof:* According to the empirical rules pointed out by Professor Nordheim, one would also obtain a state of even parity and spin 3 by combining a $g_{7/2}$ proton with the $S_{1/2}$ neutron. Since the measured spin of the nearby SB^{123} is 7/2, this is perhaps a better assignment.

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Relation between π- and μ-Meson Production Spectra in the Atmosphere*

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A method of obtaining the parent π-meson spectrum from the μ-meson spectrum is presented and the relation of the two spectra is discussed. It is concluded that the μ-meson spectrum must be rather smooth even if the parent spectrum is not.

I. ENERGY DISTRIBUTION OF μ-MESONS FROM THE DECAY IN FLIGHT OF π-MESONS

THE experimental information available suggests that all μ-mesons observed in cosmic rays arise from the decay of π-mesons. This note investigates the relationship between the production spectra of π- and μ-mesons.

Consider a π-meson (mass m_π) moving with velocity βc. Let U_π be its total energy divided by $m_\pi c^2$, p_π its momentum divided by $m_\pi c$. Let U_μ be the total energy of the μ-meson (mass m_μ) arising from its decay divided by $m_\mu c^2$, p_μ its momentum divided by $m_\mu c$. Let $U_{\mu0}$ and $p_{\mu0}$ be the corresponding values for a μ-meson arising from the decay of a π-meson at rest. On the assumption that the π-meson disintegrates into a μ-meson and a massless neutrino, conservation of energy and momentum gives:

$$U_{\mu0}=\tfrac{1}{2}[(m_\pi/m_\mu)+(m_\mu/m_\pi)], \tag{1a}$$

$$p_{\mu0}=\tfrac{1}{2}[(m_\pi/m_\mu)-(m_\mu/m_\pi)]. \tag{1b}$$

Let x be the cosine of the angle between the directions of motion of the π-meson and μ-meson as measured in the rest frame of the π-meson. Lorentz transformations yield:

$$U_\mu=(U_{\mu0}+\beta p_{\mu0}x)/(1-\beta^2)^{\frac{1}{2}}=U_{\mu0}U_\pi+p_{\mu0}p_\pi x, \tag{2a}$$

$$(p_\mu)_{||}=p_{\mu0}U_\pi x+U_{\mu0}p_\pi, \tag{2b}$$

where $(p_\mu)_{||}$ is the component of p_μ parallel to the motion of the π-meson. It is evident on physical grounds, and it follows from Eqs. (2), that $(p_\mu)_{||}>0$ (i.e., that the angle of emission of the μ-meson is less than 90°) provided that $U_\pi>U_{\mu0}$. In what follows we shall always assume that $U_\pi>U_{\mu0}$ and $U_\mu>U_{\mu0}$. The limitation thus introduced is not serious; it excludes from consideration π-mesons of kinetic energy less than 5.5 Mev and μ-mesons of less than 4.17 Mev. Equations (2) then show that the energy and momentum of the μ-meson are in the intervals

$$U_{\mu0}U_\pi-p_{\mu0}p_\pi<U_\mu<U_{\mu0}U_\pi+p_{\mu0}p_\pi, \tag{3a}$$

$$U_{\mu0}p_\pi-p_{\mu0}U_\pi<p_\mu<U_{\mu0}p_\pi+p_{\mu0}U_\pi. \tag{3b}$$

The limits for U_μ are shown in Fig. 1 where we have taken $m_\pi/m_\mu=283/215$. All directions of emission must be equivalent in the rest frame. Hence the probability $F(U_\mu)dU_\mu$ that the μ-meson has energy U_μ in dU_μ is given, with the help of Eq. (2a), by:

$$F(U_\mu)dU_\mu=\tfrac{1}{2}dx=dU_\mu/2p_{\mu0}p_\pi. \tag{4}$$

Equation (4) shows that $F(U_\mu)$ is independent of U_μ, hence any energy in the interval (3a) is equally probable. The width of the energy band is $2p_{\mu0}p_\pi=0.56p_\pi$.

One sees that the energy spread of the decay mesons is not negligible. Thus, only if the parent π-meson spectrum is smooth, will the μ-meson production spectrum be closely similar to it. Irregularities in the parent spectrum are largely smoothed out in the decay process.

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