any amount of screening as it merely follows from the fact that the coefficient of $|\boldsymbol{\lambda}\cdot\hat{\mathbf{u}}|^2$ in (1) is negative.

If the cross section is written the form

$$d\sigma(\mathbf{s}_1,\mathbf{p}_1,\boldsymbol{\lambda},\mathbf{k})=Z^2\left(\frac{e^2}{\hbar c}\right)\left(\frac{e^2}{mc^2}\right)^2\frac{d\xi}{\epsilon_1^2}\frac{dk}{k}$$
$$\times\{A+B(2|\boldsymbol{\lambda}\cdot\hat{\mathbf{u}}|^2-1)+C(i\hat{k}\cdot\boldsymbol{\lambda}^*\times\boldsymbol{\lambda})\},$$

the ratio of the axes of the ellipse is given by

$$[B+(B^2+C^2)^{\frac{1}{2}}]/|C|, \qquad (4)$$

and the maximum polarization by

$$P=\frac{d\sigma_{\max}-d\sigma_{\min}}{d\sigma_{\max}+d\sigma_{\min}}=(B^2+C^2)^{\frac{1}{2}}/A. \qquad (5)$$

At the lower end of the spectrum, $k\ll\epsilon_1$, the radiation is linearly polarized perpendicular to the plane of emission, with $P=2u^2\xi^2\Gamma/(1+\Gamma-2u^2\xi^2\Gamma)$. The linear polarization, $P=B/A$, decreases with increasing k, while the circular polarization, $P=C/A$, increases. At the upper end of the spectrum, the radiation is circularly polarized to the degree $P=\hat{s}_1\cdot\hat{k}$.

In the upper part of the spectrum, the term containing the transverse spin directions [the last term in Eq. (1)] is very small. The same is true for emission angles close to $\theta=1/\epsilon_1$, for any energy of the quantum. In most cases, therefore, a transversely polarized electron will emit only linearly polarized radiation. The amount of circularly polarized radiation is practically proportional to the *longitudinal* component of the spin of the incident electron. The latter result supports the conclusion drawn from the calculations using purely longitudinally polarized electrons.[2] The largest amount of circularly polarized radiation from transversely polarized electrons occurs for emission angles close to $\theta=0.4(1/\epsilon_1)$ or $\theta=2.4(1/\epsilon_1)$, when $\mathbf{s}_1$ lies in the plane of emission and when k is close to $\epsilon_1/2$. This maximal circular polarization is quite small, however—at most 10%; the linear polarization is at the same time twice as big.

The cross section for pair production by a quantum $\mathbf{k}$, $\boldsymbol{\lambda}$, integrated over one of the produced particles, is obtained from (1) by the usual substitutions: $\epsilon_1\rightarrow-\epsilon_1$, $\mathbf{p}_1\rightarrow-\mathbf{p}_1$, $\mathbf{s}_1\rightarrow-\mathbf{s}_1$, and $d^3k\rightarrow d^3p_1$. The expressions for Γ are again given by Eqs. (2) and (3). The maximum polarization of the produced particle is close to longitudinal, especially when the particle is the faster one, or when θ is close to $1/\epsilon_1$. The probability of producing transversely polarized electrons is in general considerably smaller. However, in the special case when $\theta\approx0.4(1/\epsilon_1)$ or $\theta\approx2.4(1/\epsilon_1)$ and $\epsilon_1\approx\epsilon_2/2$, the spin of the electron is almost always transverse to the momentum, and the electron polarization may be as big as 25%.

The effect of the Coulomb correction on the polarization part of the cross sections is of the same order as for the unpolarized cross sections. The correction to P is, however, in general somewhat smaller, being only a few percent even for the heaviest elements. This is particularly the case for circular polarization. Most striking is perhaps the expression for the circular polarization in the case of no screening, when all angles have been integrated out. For bremsstrahlung this is

$$P(\mathbf{s}_1,\mathbf{p}_1)=\frac{\hat{s}_1\cdot\hat{p}_1k(\epsilon_1+\frac{1}{3}\epsilon_2)}{\epsilon_1^2+\epsilon_2^2-\frac{2}{3}\epsilon_1\epsilon_2}, \qquad (6)$$

which is independent of the Coulomb correction.

The detailed calculations will be published later.

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[1] T. D. Lee and C. N. Yang, Phys. Rev. **104**, 254 (1956); **105**, 1671 (1957); Frauenfelder, Bobone, von Goeler, Levine, Lewis, Peacock, Rossi, and De Pasquali, Phys. Rev. **106**, 386 (1957).

[2] K. W. McVoy and F. J. Dyson, Phys. Rev. **106**, 1360 (1957).

[3] H. A. Bethe and L. C. Maximon, Phys. Rev. **93**, 768 (1954); H. Olsen, Phys. Rev. **99**, 1335 (1955).

[4] Davies, Bethe, and Maximon, Phys. Rev. **93**, 788 (1954).

Scattering of Nucleons from Nuclei at High Energies*

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In the multiple-scattering approximation the scattering of a nucleon from a nucleus[1] may be written as

$$g_B(E,q)=\bar{M}(E,q)F(q), \qquad (1)$$

where $g_B(E,q)$ is the Born approximation to the scattering amplitude, $\bar{M}(E,q)$ is the two-nucleon scattering amplitude appropriately averaged over the spins of the target nucleons, and $F(q)$ is the so-called nuclear form factor. E and $\mathbf{q}$ are the incident kinetic energy and momentum transfer vector, respectively. The above equation represents a good approximation as E increases and q approaches zero. For small q, $\bar{M}(E,q)$ is a slowly varying function of q relative to $F(q)$, so that g_B has roughly the same dependence on q as $F(q)$, which leads to an optical model potential with spatial dependence like the charge distribution. On this basis, of course, it is easy to go from the Born approximation to the scattering amplitude, g_B, to the scattering amplitude g. Since the approximations involved are best for q small, it is most appropriate to confine our attention to forward scattering.

Unfortunately, the averaged two-nucleon amplitude $\bar{M}$ is not directly available from the two-nucleon scattering experiments, but must be calculated from phase shifts.[2] However, Bethe[1] has shown that at 310 Mev all phase shifts which fit the two-nucleon scattering data give essentially the same result for nucleon-nucleus scattering, in good agreement with experiment. In this Letter it will be shown that the phase shifts of reference 2 are in agreement with experiment from 90 Mev to 310 Mev. In particular, the scattering of nucleons from C^{12} has been explicitly calculated. Calculations have been made at three energies, *viz.*, $E=90$ Mev, 156 Mev, and 310 Mev, for the elastic scattering cross section and polarization at forward angles, the total cross section, and the total inelastic cross section. These calculations are performed as in reference 1 except that Coulomb corrections have been omitted. The results are given in Table I and show that the main features of the nucleon-nucleus interaction follow directly from the properties of the nucleon-nucleon interaction.

Moreover, since $\bar{M}(q)$ may be written as

$$\bar{M}(q)=(\alpha_1+i\alpha_2)+(\alpha_3+i\alpha_4)\sigma_n, \tag{2}$$

and $F(q)$ is real, then $g_B(q)$ may likewise be written as

$$g_B(q)=(\beta_1+i\beta_2)+(\beta_3+i\beta_4)\sigma_n, \tag{3}$$

and, therefore,

$$-3\left[\frac{d^2\beta_\nu}{dq^2}\Big/\beta_\nu\right]_{q=0}=\langle r^2\rangle_\nu=-3\left[\frac{d^2\alpha_\nu}{dq^2}\Big/\alpha_\nu\right]_{q=0}+\langle r^2\rangle_0$$
$$=\langle a^2\rangle_\nu+\langle r^2\rangle_0, \tag{4}$$

where $\langle r^2\rangle_0$ is the mean square nucleon-density radius and is here identified with the charge radius. Thus, without appeal to large-angle scattering, it is possible to calculate the deviation of the mean square optical-model radii from that of the charge distribution. The values of $\langle a^2\rangle_\nu$ calculated from the two-nucleon amplitude are given in Table I. It should be noted that, if the spin-dependent scattering amplitude is considered to arise from a "spin-orbit potential" of the Thomas type, then $\nu=3$, 4 refer to the imaginary and real parts of that potential, respectively.

TABLE I. Comparison of calculation and observation for high-energy nucleon-nucleus scattering. The elastic scattering cross section and polarization in the forward direction, the total cross section, and the inelastic cross section are given neglecting Coulomb effects. The experimental values are given in parentheses. In addition, the mean-square radii for the spin-independent and spin-dependent nucleon-nucleus interaction are given.

E	310 Mev	156 Mev	90 Mev
$\sigma_{el}(0°)$ (barns/sterad)	1.1 (1.0)[a]	1.1 ($\sim$1.2)	1.0 ($\sim$1.7)[b]
P (for small angles) % per degree	8.4 (8.4)[c]	4.0 (5.0)[d]	2.3 (2.1)[e]
σ_{tot} (barn)	0.30 (0.29)[e]	0.38 (0.31)[e]	0.51 (0.54)[e]
σ_{inel} (barn)	0.21 (0.20)[f]	0.22 (0.22)[f]	0.25 (0.23)[f]
$\langle a^2\rangle_1$ (10^{-26} cm^2)	8.8	5.6	4.1
$\langle a^2\rangle_2$ (10^{-26} cm^2)	1.8	2.3	3.3
$\langle a^2\rangle_3$ (10^{-26} cm^2)	3.9	10.1	13.5
$\langle a^2\rangle_4$ (10^{-26} cm^2)	3.3	5.3	6.2
$\langle r^2\rangle_0$ (10^{-26} cm^2)	5.8	5.8	5.8

[a] A. Ashmore, Nuovo cimento (to be published).
[b] R. Wilson *et al.*, Phil Mag. **47**, 1003 (1956).
[c] O. Chamberlain *et al.*, Phys. Rev. **102**, 1659 (1956).
[d] R. Alphonce *et al.*, Nuclear Phys. **3**, 185 (1957).
[e] A. E. Taylor, Repts. Progr. in Phys. **20**, 125 (1957).
[f] R. Voss and R. Wilson, Proc. Roy. Soc. (London) **A236**, 41 (1956).

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[1] H. A. Bethe, Ann. Phys. **3**, 190 (1958). The present calculations were undertaken in consequence of Professor Bethe's results. A complete set of references to the theory will be found in Professor Bethe's paper.

[2] J. L. Gammel and R. M. Thaler, Phys. Rev. **107**, 291, 1337 (1957).

Evidence Against the Reaction $K^+\rightarrow\mu^++\mu^0$†

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MARSHAK and Sudarshan[1] have recently remarked that if a neutral muon exists, it would be most evident from the decay reaction

$$K^+\rightarrow\mu^++\mu^0. \tag{1}$$

This reaction can most easily be distinguished from the normal $K_{\mu2}{}^+$ decay mode,

$$K^+\rightarrow\mu^++\nu, \tag{2}$$

by the difference of about 11 Mev in the kinetic energies of the charged muons emitted in the two reactions. (This assumes that the μ^0 has a mass which is close to that of the μ^+.) The purpose of this Letter is to point out that the present evidence is definitely in favor of the normal $K_{\mu2}{}^+$ mode and that there is no evidence as yet for the process $K^+\rightarrow\mu^++\mu^0$, unless one is willing to postulate that the mass of the μ^0 is very much smaller than that of the μ^+.

In the course of making a complete tabulation[2] of the data on the elementary particles, and, in particular, the new strange particles, we have at hand all the published material on the K^+ decay modes. There are four experiments[3–6] that have measured the ranges of secondaries from many K^+ decays in large nuclear emulsion stacks, and these contain practically all of the precise measurements on the ranges of the emitted charged muons. (A few μ^+ ranges have been measured in multiplate cloud chambers, but these are not nearly as accurate as those measured in emulsions.) In these four experiments, approximately 4000 K^+ decays were examined, and, among these, in 41 cases positively