As can be seen, a particle with spin 3/2 possesses dipole and quadrupole kinematic moments and, moreover, the Hamiltonian H possesses an unusual term of a dipole type which depends on the momentum.**

Averaging is carried out over the charge density. Therefore the normalization condition has the form

$$\int \Psi^* \rho \Psi (dr) = 1,$$

$\rho = \eta\alpha^0$ is the Hermitian charge density matrix. The matrix η which determines the invariant bilinear Hermite form $(\Phi^*\eta\Psi)$ is found in the form

$$\eta = -\gamma_0 B^{ii} + (2 - \sqrt{3})\, \gamma_i \gamma_0 \gamma_k B^{ik}.$$

Correspondingly,

$$\rho = -B^{ii} + (1 - \sqrt{3})\, \gamma_i \gamma_k B^{ik} / \sqrt{3} + \gamma_i \gamma_0 B^{i0} / \sqrt{3} + \gamma_0 \gamma_i B^{0i} / \sqrt{3}.$$

The mean value of the energy of a particle with spin 3/2 in an electromagnetic field will be determined by the formula:

$$E = \int \Psi^* \rho i \frac{\partial}{\partial x_0} \Psi (dr) = \int \Psi^* \rho H \Psi (dr).$$

Hence for a guarantee of the reality of E we have the condition of the quasi-hermiticity of the operator H:

$$\int \{(H\Phi)^* \rho \Psi - \Phi^* \rho H \Psi\} (dr) = 0. \qquad (6)$$

For the Hermitian (5), the condition (6) is satisfied by taking into account the additional conditions (2) and (3).

The value of the energy in the linear approximation relative to the small parameter aF_{nm} is represented in the following form (at the same time we transform to the Gaussian units):

$$E = \int \Psi^* (-B^{ii}) \Big\{ H_0 + \frac{2}{3}(2 + \sqrt{3}) \frac{\hbar e}{M^2 c^2} \times [R_E^{\mu\nu} E_\mu + R_H^{\mu\nu} H_\mu] \Big(p_\nu - \frac{e}{c} A_\nu\Big) - \frac{2}{3}(2 + \sqrt{3}) \frac{\hbar e^2}{M^2 c^3} [R_E^{\mu 0} E_\mu + R_H^{\mu 0} H_\mu] \varphi + \frac{2}{3}(2 + \sqrt{3}) \frac{\hbar^2 e}{M^2 c^2} \Big[Q_E^{\mu\nu} \frac{\partial E_\mu}{\partial x_\nu} + Q_H^{\mu\nu} \frac{\partial H_\mu}{\partial x_\nu} \Big] \Big\} \Psi (dr). \qquad (7)$$

Thus a contribution to the energy, in addition to terms of the Hamiltonian of the Dirac type H_0, is made by supplementary terms of the dipole type, which depend on the momentum, and on the quadrupole electric and magnetic moments. Averaging in Eq. (7) is carried out over $\Psi^* (-B^{ii}) \Psi$ – the charge density of free particles.

For comparison we note that particles with spins 0 and ½ do not possess kinematic moments while a particle with spin 1 possesses kinematic dipole moments, which do not make a direct contribution to the energy but, in spite of this, are said to be electromagnetic interactions[3-5].

I consider it my pleasant duty to express my thanks to Dozent S. V. Izmailov for pointing out the theme and for his constant interest in the work.

* The analysis is carried out in a system of units in which $\hbar = c = 1$. The metric tensor g^{ik} is chosen in the form

$$g^{00} = -g^{11} = -g^{22} = -g^{33} = 1, \quad g^{ik} = 0 \ (i \neq k).$$

* In the summation the Latin indices run, as above, over the values 0, 1, 2, 3, and the Greek over the values 1, 2, 3.

** Terms of such a type were first obtained by Darwin[2] in the non-relativistic approximation for particles with spin ½ in an electromagnetic field.

1 M. Petras, Czech. J. Phys. **5**, 160 (1955).
2 C. G. Darwin, Proc. Roy. Soc. (London) **118A**, 654 (1928).
3 H. Kemmer, Proc. Roy. Soc. (London) **173A**, 91 (1939).
4 V. L. Ginzburg, J. Exptl. Theoret. Phys. (U.S.S.R.) **12**, 425 (1942).
5 S. V. Izmailov, Uch. zap. Leningrad State Pedagogical Inst. **103**, 219 (1955).

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74

Experimental Comparison of the Energy Spectra of γ–Quanta from the Decay of π^0–Mesons Formed on Carbon and Lead Nuclei by 600 Mev Protons

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In experiments conducted up to the present time there has not been discovered any noticeable difference in the γ–spectra formed by light and heavy elements [1,2]. Since the energy and angular distributions are interelated, the conclusion was made,[3] from the similarity of the energy spectra, that the angular distributions of the γ–quanta formed by light and heavy elements are coincident. However, direct measurements of angular distribution of γ–quanta[4] have disclosed a considerable dependence on the mass number of the nuclei irradiated by 660 mev protons. The dependence of the angular distribution of γ–quanta on the mass number of the nuclei obtained in the work of Ref. 4 can be satisfactorily explained by the relative capacity of nuclei to protons and by accounting for absorption of mesons in the nucleus. Computations made for this case showed that the γ–spectra formed by light and heavy elements should differ significantly only in the region of low energies (ϵ_γ < 70 mev). The coincidence of γ–spectra in this energy region cannot be considered as a definitely established fact, inasmuch as at these energies the background of chance coincidences is high and the spectrometer efficiency is relatively low.

To obtain a more accurate comparison of γ–spectra formed in light and heavy nuclei, relative measurements were made in this study of the flow of γ–quanta in different regions of the γ–spectra resulting from the decay of mesons formed in carbon and lead by 600 mev protons at 0° observation angle with reference to the motion of the protons. Measurements were made with a 12 channel double coil magnetic spectrometer.

Targets of lead and graphite, placed inside the vacuum chamber of the accelerator were changed successively every minute. Simultaneously with the change of targets, the registration system of the spectrometer was automatically switched so that one group of electromechanical counters registered the spectrum of the paris formed on the graphite target and the other those formed on the lead target. The energy of the γ–quanta to be registered was selected by changing the field intensity in the gap of the spectrometer magnet. For control purposes, simultaneously with the measurements of the relative γ–flow in different regions of the γ–spectrum, measurements were also made of the full flow of quanta by means of a γ–telescope described in Ref. 4.

According to Ref. 4, the full output of γ–quanta at 0° is 3.6 ± 0.1 greater in lead nuclei than in carbon. Taking this ratio for the full γ–quanta outputs, the ratios of the differential outputs (on $d\omega d\omega\epsilon_\gamma$) for different γ–quanta energies, as obtained in this work, can be presented in table form (see below). Thus for γ–quanta in the region of low energy (ϵ_γ < 70 mev), there is observed a difference in the γ–spectra formed on the nuclei of carbon and lead. The difference between the γ–spectra is, apparently, connected with the previously discovered change in the angular distribution of π^0–mesons related to the interaction effect between the bombarding protons and the nucleons in the presence of strong meson absorption. Hard γ–quanta at 0° observation angle are formed basically by the decay of π^+ mesons, produced on the surface of the nucleus; which is highly screened from the bombarding protons by the rest of the nucleons in the nucleus. Soft γ–quanta are formed basically on the opposite nuclear surface which is freely irradiated by protons. For this reason, in the case of π^0–meson formation on heavy nuclei, when the effects of proton and meson interactions with the nuclei are considerable, there is observed a relative increase in soft γ–quanta in the spectrum.

ε_γ (mev)	$(d\sigma_{Pb}/d\sigma_C)$ 0°
30	6.4±0.4
52	4.9±0.15
90	4.15±0.15
144	3.5±0.1
222	3.3±0.1
303	3.2±0.1
348	3.1±0.1
379	3.6±0.2
472	4.1±0.3

To the extent that the effects connected with absorption of π^0–mesons and the slowing down of the bombarding protons in the nuclear substance substantially change the angular distribution of the mesons and decrease the full cross section of meson formation on heavy nuclei, it is natural to expect also a considerable difference in the energy distributions of mesons formed on light and heavy nuclei. This difference between the spectra must be due to the change of the meson absorption and scattering cross section with energy and also to the greater loss of energy by the bombarding protons in heavy nuclei.

On the other hand, it can be concluded, from the comparison of spectra in the energy region above 120 mev, that the energy distributions of π^0–mesons formed at 0°–angle on nuclei of carbon and lead do not exhibit any noticeable difference. More accurate data concerning spectra of π–mesons, formed on light and heavy nuclei, could be obtained by making relative measurements of differential cross sections of the formation of charged mesons. For a quantitative evaluation of the expected difference in the spectra of π–mesons, it is necessary to make computations by the method of probability trials to account for the deceleration of the protons and the absorption and scattering of π–mesons in the nuclei.

1 Kozodaiev, Tiapkin, Baiukov, Markov, and Prokoshkin, Izv. Akad. Nauk SSSR , Fiz. Ser. 19, 589 (1955).
2 Crowe, Panofsky, Phillips and Walker, Phys. Rev. 83, 893 (1951).
3 R. Hales and B.Moyer, Phys. Rev. 89, 1047 (1953).
4 Tiapkin, Kozodaiev and Prokoshkin, Dokl. Akad. Nauk SSSR, 100, 689 (1955).

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87

Production of Very Strong Magnetic Fields by Rapid Compression of Conducting Shells*

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FOR the practical realization of cyclic accelerators of charged particles to energies in excess of 10^{10} ev, it is necessary to learn to create very strong magnetic fields, in excess of 10^5 oe. At the indicated energies, both for electrons and for protons, the formula

$$V = 3 \cdot 10^4 \, RH, \qquad (1)$$

holds, where V is the energy of the accelerated particles, expressed in electron volts, R is the radius of curvature of the trajectory in meters, and H is the magnetic field intensity in oersteds. Consequently, in a cyclic accelerator for 10^{11} ev or 100 bev, with a directing magnetic field $H = 10^5$ oe, the radius of the largest orbit must be 30 m, whereas with $H = 10^6$ oe, it needs to be only 3 m. Thus only at fields exceeding 10^5 Oe is there hope of building 100 bev apparatus of not too huge dimensions. If we learn to create magnetic fields of intensities 10^7 to 10^8 oe, we may hope for the practical production of compact cyclic accelerators for energies exceeding even 100 bev.

The strongest magnetic fields have been obtained by passage of powerful current impulses of short duration through ironless electromagnets (P. L. Kapitza). By this impulsive method, fields of order 3×10^5 Oe have been obtained. Further increase of the field was limited by the mechanical strength of the electromagnet coils, which were ruptured by the interaction forces of the currents.

There occurs to us an alternative method of creating very strong magnetic fields: by the rapid compression of conducting shells or loops. By this method it is in principle possible to obtain magnetic fields considerably stronger than the largest attainable by the impulsive method.

Let us consider a conducting hollow sphere, placed in an external magnetic field H_0 created by any practicable method. If the source of external field H_0 is suddently shut off, the field inside the sphere, because of induced currents, will decay exponentially with relaxation time

$$\tau = \alpha \, (4\pi\sigma / c^2) \, R^2, \qquad (2)$$

where R is the radius of the sphere , σ is the conductivity in absolute units, c is the speed of light, and α is a numerical coefficient of order unity, determined by the form of the conductor. For a 10 cm copper sphere, the relaxation time according to (2) exceeds 1 sec.

Let us now suppose that the sphere, located in an external field H_0, is subjected to an intense hydrostatic pressure, so that the linear dimensions of the internal cavity decrease by a factor n in a time interval T much shorter than the relaxation time τ. In this case, during the time interval T the conducting material of the sphere may be considered as having practically infinite conductivity, and consequently the magnetic lines of force may be considered rigidly connected to the material ("frozen" magnetic field). Since in the process of compression the magnetic lines of force cannot cross the conducting wall of the sphere, the magnetic flux through the cross section of the sphere will remain constant, i.e.,

$$\Phi = \int_0^R H(r) \, 2\pi r \, dr = \text{const.} \qquad (3)$$

Consequently, for an initially uniform magnetic field we get $\pi R^2 H = \text{const}$, whence

$$H / H_0 = (R_0 / R)^2 = n^2, \qquad (4)$$

where R_0 and H_0 are the initial values of the inside radius of the sphere and of the magnetic field.

In the process of compression of the sphere, work will be performed against the ponderomotive