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IONIZATION LOSSES OF ULTRARELATIVISTIC BARYONS CALCULATED WITH THE AID OF QUANTUM CHROMODYNAMICS

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The total ionization loss ε and the slowing-down coefficients B are calculated as functions of the Lorentz factor γ for ultrarelativistic baryons of the octet $J^P = (1/2)^+$. The electromagnetic form factors of baryons are based on QCD calculations. The function $\varepsilon(\gamma)$ and the asymptotic levels of ε are analyzed for various baryons. The idea of an experiment for determining the charge radii of hyperons is discussed.

The new range of superhigh energies mastered by the experimental physics of hadrons (with hadron Lorentz factors $\gamma > 10^3$) and the availability of accelerated hadron beams have stimulated research on the interaction of ultrarelativistic baryons with substance. In particular, the total mean ionization loss ε of superhigh-energy mesons and baryons has been calculated in [1]. The charge radii r_0* of hyperons, which were taken as calculation parameters from certain quark models of hadrons, were probably defined in [1] with insufficient precision. Below we present the values of ε produced by calculations in which the electromagnetic structure of baryons is taken into account on the basis of quantum chromodynamics (QCD).

The total ionization loss of hadrons can be calculated by the formula

$$\varepsilon \equiv \left|\overline{\frac{dE_{\text{ion}}}{dx}}\right| \text{ (MeV cm}^2\text{ g}^{-1}) = 0.307\beta^{-2}Z_h^2 Z_t A_t^{-1} B(\gamma, Z_t), \tag{1}$$

where β is the velocity of the impinging hadron (in units of the light velocity), Z_h is its charge, Z_t and A_t are respectively the atomic number and mass number of the medium nuclei. The dimensionless slowing-down coefficient B depends on the characteristics of both the medium and the impinging hadron. It may be regarded as the sum

$$B = B_d + B_s, \tag{2}$$

where B_d and B_s correspond to the contributions of distant and short-range collisions, respectively. The data calculated in the same way as in [1] are listed in Table 1. The slowing-down coefficients B_d were calculated by a modified Bethe–Bloch formula incorporating several corrections [1]. When investigating the dependence $B(\gamma)$, it is fundamentally important that a correction for the effect of density be taken into account, because for condensed media it makes the function $B_d(\gamma)$ saturate at $\gamma \gg 1$. In the case of short-range collisions, the slowing-down coefficient B_s does not depend on the medium characteristics, being a function of the cross section of elastic scattering of the hadron by the electron, which depends on the squared hadron electric form factor G_E [2]. The magnetic form factor G_M is expressed in terms of G_E via the scaling relation $G_M = \mu G_E$, where μ is the hadron magnetic moment.

The dependencies of G_E on the square of the transferred 4-momentum q which were used in our calculations are given in Table 2. The calculations were performed for charged baryons of the octet $J^P =$

* In the formulas to follow, r_0 should be regarded as a dimensionless parameter, which numerically coincides with the r.m.s. hadron charge radius expressed in Fm.

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Table 1

Baryon		Lorentz factor γ						
		10	3.16×10^1	10^2	3.16×10^2	10^3	3.16×10^3	10^4
p	B_s	0.696	1.791	2.904	3.950	4.648	4.832	4.876
	B	11.56	12.73	13.84	14.89	15.59	15.77	15.82
	ε	1.727	1.791	2.048	2.202	2.306	2.333	2.339
Σ^+	B_s	0.697	1.794	2.913	3.979	4.796	5.040	5.091
	B	11.57	12.74	13.86	14.921	15.74	15.98	16.03
	ε	1.728	1.883	2.049	2.207	2.328	2.364	2.371
Σ^-	B_s	0.697	1.794	2.909	3.954	4.738	5.043	5.109
	B	11.57	12.74	13.85	14.90	15.68	15.98	16.05
	ε	1.728	1.883	2.049	2.203	2.319	2.364	2.374
Ξ^-	B_s	0.698	1.795	2.911	3.950	4.698	4.961	5.015
	B	11.57	12.74	13.85	14.89	15.64	15.90	15.96
	ε	1.728	1.884	2.049	2.203	2.313	2.352	2.360

Note: The values of B_s are given for $\Omega_{\min} = 10$; the values of ε are in MeV cm^2 g^{-1} and refer to aluminum.

Table 2

Baryon	Electric form factor $\lvert G_E \rvert$	r_0	$\tilde{r}_0$	$\widetilde{M}$
p	$0.73665e^{-3.1q^2} + 0.235e^{-0.772q^2}$ $+0.0267e^{-0.22q^2} + 0.00165e^{-0.052q^2}$	0.76	—	0.33
Σ^+	$0.8e^{-1.55q^2} + 0.23e^{-q^4} - 0.03$	0.54	0.57	0.27
Σ^-	$e^{-0.98q^2+0.04q^4}$	0.48	0.49	0.31
Ξ^-	$e^{-1.12q^2+0.035q^4}$	0.51	0.52	0.31

Note: The symbols $\tilde{r}_0$ and $\widetilde{M}$ denote respectively the charge radius r_0 (in Fm) and the model factor M calculated by the parametrization formulas (4) and (5).

$(1/2)^+$. The listed parametrizations of $G_E(q^2)$ were derived in [3]. The table also gives the values of the charge radii r_0 calculated by these parametrizations.

In the case of the proton, the parametrization correctly reproduces both the experimental data [4] and the QCD calculations carried out in the framework of perturbation theory [5]. For hyperons, no experimental data are available and the parametrizations reflect the data of QCD calculations on a grid [6]. The electric form factor G_E is treated in [3] as the Fourier image of the electric charge density distribution in the hadron, which restricts the applicability range of the parametrization to $q^2 \leqslant 4$ (GeV/s)^2 and $\gamma \leqslant 10^4$. In our

calculations of B_s the energy Q transferred to the electrons* was bounded from below by $Q_{\min} = 10$.

As seen in Table 1, the slowing-down coefficients B_s and B and the total ionization loss ε enter a plateau for $\gamma \geqslant 10^3$, tending to their asymptotic values. Along with the above-mentioned saturation of the function $B_d(\gamma)$, the function $B_s(\gamma)$ is also saturated, which is due to the influence of the electromagnetic form factors of hadrons [1, 7].

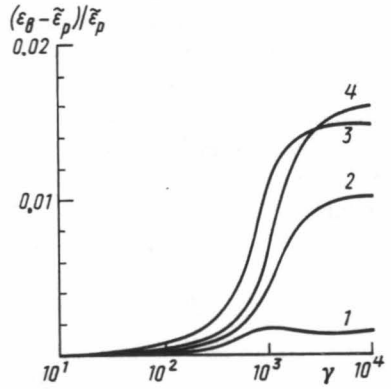

Fig. 1

Relative differences of total mean ionization losses for p (1), Ξ^- (2), Σ^+ (3), Σ^- (4) from proton ionization losses calculated by the dipolar formula.

The greatest difference in the values of ε is observed in the asymptotic region and does not exceed about 1.5% for baryons and about 0.5% for hyperons. The difference in the behavior of the function $\varepsilon(\gamma)$ is clearly seen in Fig. 1. For $\gamma \ll 10^3$, it is mainly determined by the difference in the masses and magnetic moments μ of the baryons, while for $\gamma \gg 10^3$ it depends on the charge radius r_0 and on μ. The smallest asymptotical ionization losses are observed for the proton, which has the greatest values of μ and r_0 among the octet baryons. Because the effects of r_0 and μ on ε are opposite (the slowing-down capability decreases with growing r_0), this fact demonstrates a decisive influence of the hadron charge radii on the asymptotic values of B. In Fig. 1 plotted as ordinates is the quantity $(\varepsilon_b - \tilde{\varepsilon}_p)/\tilde{\varepsilon}_p$, where ε_b are the baryon's total ionization loss and $\tilde{\varepsilon}_p$ is the same quantity for the proton whose electric form factor is described by the well-known dipolar formula (see, e. g., [8])

$$G_E(q^2) = [1 + q^2(\text{GeV/s})^2/0.71]^{-2}, \tag{3}$$

which yields much exaggerated values of G_E in comparison with the parametrization [3] for $q^2 > 10$ $(\text{GeV/s})^2$. As seen in Fig. 1, such high transferred momenta affect ε quite insignificantly (the difference does not exceed about 0.1%).

Following [1], we can write down the parametrization formula

$$M_b = M_p + 0.962(B_a^b - B_a^p) + 0.962\ln(r_0^b/r_0^p) - 3.05 \times 10^{-2}(\mu_b^2 - \mu_p^2), \tag{4}$$

which relates the asymptotic slowing-down coefficients B_a for some fixed medium with r_0, μ, and M, which is a model factor characterizing the compactness of electric charge distribution in the hadron [9] (the subscripts "p" and "b" refer to the proton and an arbitrary baryon, respectively).

It is of interest to find out to what extent the model factor concept is applicable for the parametrizations [3] which are not associated with simple "geometrical" models of electromagnetic form factors. Table 2 lists the model factors of baryons computed by Eq. (4), where the coefficient B_a^p was calculated with the aid of the dipolar formula (3), which corresponds to $M_p = 0.38$ [9] and $r_0^p = 0.8$. The average value of the model factor is 0.302 with a relative fluctuation of about 10%. The values of M calculated in this way are close to

* Q is expressed in units of doubled electron rest energy.

the model factor which corresponds to a Gaussian distribution of the lectric charge density ($M = 0.31$). It can be supposed that the model factors of the hadrons which belong to the same supermultiplet J^P must be close. If they are assumed to be equal in the baryon octet $J^P = (1/2)^+$ in question, then, according to (4), we have

$$r_0^b = r_0^p \exp\left[-(B_a^b - B_a^p) + 3.17 \times 10^{-2}(\mu_b^2 - \mu_p^2)\right]. \quad (5)$$

The charge radii calculated by (5) are given in Table 2. They are very close (within about 4%) to the "correct" values of r_0. This fact may be important for planning experiments for the determination of hyperon charge radii using the well-known proton charge radius r_0. Such experiments could be conducted along the lines discussed in [9]. It was proposed there to analyze the tracks of hard δ-electrons generated by ultrarelativistic hadrons in a liquid-hydrogen bubble chamber. It was shown in [9] that the investigation of the energy spectrum of such electrons allows one to obtain reliable estimates of B_s, B, and ε. In the superhigh energy range ($\gamma \gg 10^3$), in which $(B^b - B^p)$ tends to $(B_a^b - B_a^p)$, Eq. (5) can be used to determine the charge radius of any baryons (including unstable baryons, the hyperons), if during the experiment the chamber is alternately "irradiated" by beams of these baryons and proton beams.

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