The quadrupole effect in the elastic scattering of 1-GeV protons by *p*-shell nuclei

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We measured elastic scattering cross sections of protons ($E_p = 1$ GeV) on Be^9, B^{11}, C^{12}, C^{13}, nuclei. In the case of Be^9 and B^{11} nuclei, we found the filling of the diffraction minima to be a strong effect. The use of this effect is suggested for studying the shape of spherically asymmetric nuclei.

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In the general case nuclei with spin $I \geqslant 1$ are spherically asymmetric. Deformation of the nucleus is usually studied by spectroscopic techniques in which, as a rule, a determination is made of the electric quadrupole moment $Q_{\rm ch}$ which gives information

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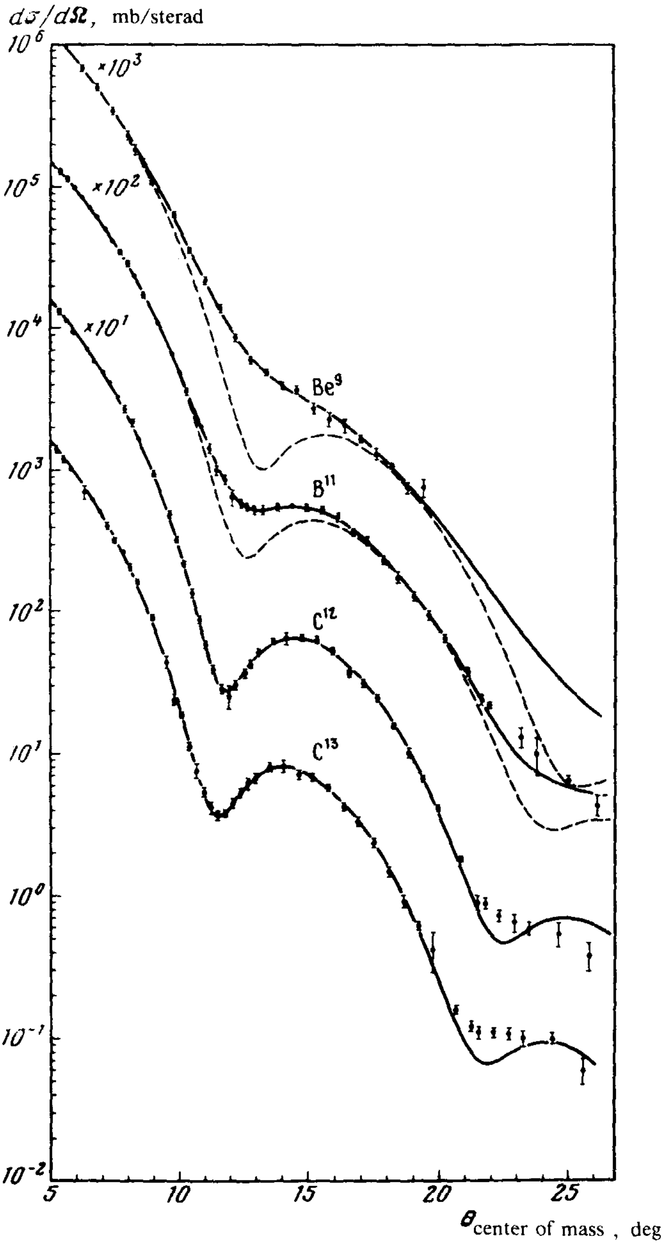

FIG. 1. Scattering cross sections for 1-GeV protons by Be^9, B^{11}, C^{12}, and C^{13} nuclei. Solid and dashed curves are calculated with and without taking the non-spherical component ρ_2 into account, respectively.

concerning the nonspherical component in the proton distribution. Electron scattering augment this information. Strongly interacting particles are necessary for studying the neutron component of atomic density. The scattering of 1-GeV protons is a good technique for studying nuclear density, including the protons and neutrons distribution.

In this work we report the results of measuring differential cross sections for the elastic scattering of 1-GeV protons by Be^9, B^{11}, B^{12}, C^{12}, and C^{13} nuclei (Fig. 1). The apparatus and measurement technique were described earlier.[1] Figure 1 shows clearly the effect of a strong filling in of the diffraction minima in the cross sections for proton scattering by Be^9 and B^{11} ($I = 3/2$) nuclei. A similar effect takes place in electron scattering, and is explained by the nonspherical charge density of the ground-state nucleus with spin $I \geqslant 1$.[2,3] A washed-out minimum was also observed during proton scattering by deuterons ($I = 1$).[4] We note, however, that in low-nucleon systems (H^2, He^3, and He^4) another interpretation is possible for this effect.[5] In our case (Be^9, B^{11}) the situation is more in hand in view of the well-defined filling of the minima; and also the fact that deep diffraction minima characteristic of scattering by spherical nuclei are observed in the cross sections at the nearby "reference" spherical nuclei C^{12} ($I = 0$) and C^{13} ($I = 1/2$).

The data were analyzed by applying the Glauber theory to scattering by non-

TABLE I. Quadrupole Moments Based on Electron[2,3] (Q_{ch}) and Proton (Q_{mass}) Scattering Data for Three Parameterizations of $\rho_2(r)$.

Form of parametrization	B^{11}			Be^9		
	Q_{ch}, Φ^2	Q_{mass}, Φ^2	Q_{mass}/Q_{ch}	Q_{ch}, Φ^2	Q_{mass}, Φ^2	Q_{mass}/Q_{ch}
$\tilde{\rho}_2 = \delta r^2 e^{-r^2/b^2}$	3.8(1)	6.3(1)	1.66(6)	5.5(1)	9.7(2)	1.75(4)
$\tilde{\rho}_2 = \delta \frac{\partial \tilde{\rho}_0}{\partial r}$	6.0(5)	8.1(2)	1.34(12)	6.4(3)	11.5(3)	1.79(7)
$\tilde{\rho}_2 = \delta r \frac{\partial \tilde{\rho}_0}{\partial r}$	10.5(2.6)	13.9(4)	1.32(33)	10.4(4,6)		
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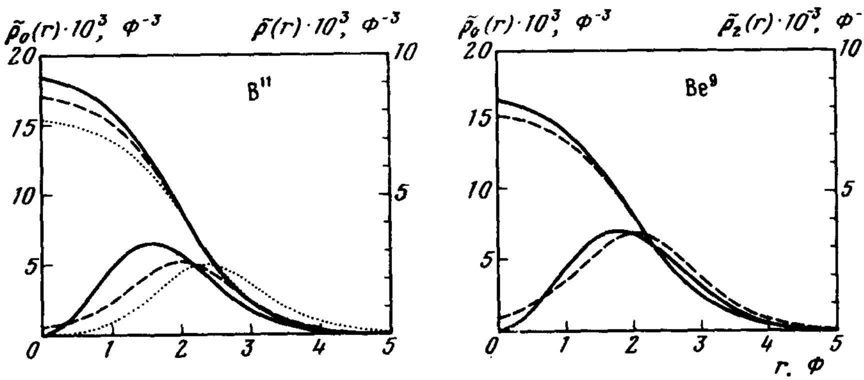

FIG. 2. Different density variants in terms of χ^2 for different parameterizations $\rho_2(r)$.

TABLE II. Nuclear Density Parameters Based on Proton Scattering Data.

	$\tilde{\rho}_0(r) = \rho_0 (1 + e^{\frac{r-R}{a}})^{-1}$				$\tilde{\rho}_2(r) = \delta\sqrt{\frac{4\pi}{5}}\frac{3}{2a_2^2}\frac{r^2}{\pi^{3/2}}e^{-\frac{r^2}{a_2^2}}$		
	R, Φ	a, Φ	ρ_0, Φ^{-3}	$\langle\tilde{r}^2\rangle^{1/2}$, Φ	a_2, Φ	δ	Q_{mass}, Φ^2
Be^9	2.021(16)	.589 (4)	.0157	2.68 (2)	1.855	312(7)	9.7 (2)
B^{11}	1.973 (9)	.529 (3)	.0182	2.49 (2)	1.690	.199 (4)	6.3(1)
C^{12}	2.123 (8)	.515 (3)	.0158	2.52 (1)	—	—	—
C^{13}	2.151 (12)	.519 (4)	.0152	2.55 (2)	—	—	—

spherical nuclei.[6] Thus, an approximation was used which is essentially equivalent to the approximation for a single inelastic transition.[7] Comparing calculations with experiment yields information concerning the nuclear density which has the form ($I = 3/2$) for a state with $M = 1$:

$$\tilde{\rho}(\mathbf{r}) = \tilde{\rho}_0(r) + \tilde{\rho}_2(r)\, Y_{20}(\mathbf{r}/r).$$

It has been found that the degree of filling of the minima is indirectly determined by the nonspherical density component $\tilde{\rho}_2(r)$, and its may serve as a measure of the deformation of the nucleus. A fundamental ambiguity in the analysis is associated with the choice of the parameterization $\tilde{\rho}_2(r)$ (Table I and Fig. 2). The moments $\langle r^{-2}\rangle\tilde{\rho}_2$ and $\langle r^{-1}\rangle\tilde{\rho}_2$ are less subject to the influence of parameterization. They are determined to within the same accuracy as Q_{ch} by classical techniques (5–20%).[6] The maximum value ρ_{2max} and a small region near the surface of the nucleus are well-determined from the local characteristics.

The standard relation for measuring Q_{ch} also pertains to analyzing the electron data. We showed, however, that when the same density parameterization is used to analyze p- and e-scattering, the ratio of the quadrupole moments of the mass and charge Q_{mass}/Q_{ch} is much better determined (Table I). When analyzing electron scattering it is natural to give preference to the parameterization variant which leads to a value for Q_{ch} that is in agreement with a value obtained by classical spectrometric techniques. Therefore, concurrent analysis of the p- and e-scattering data and reliance on spectroscopic data in terms of measuring Q_{ch} largely eliminate the ambiguity in the analysis—related to the particular parameterization of the nuclear density—and lead to the determination of both the ratio Q_{mass}/Q_{ch} and the value of Q_{mass}. The nuclear parameters found by this technique for Be^9 and B^{11}, as well as the density parameters for the C^{12} and C^{13} ($Q = 0$) spherical nuclei, are given in Table II.

The proposed technique for investigating the density of nonspherical nuclei may also be used for nuclei with $I \geqslant 1$ provided $Q_{mat}/A\langle r^2\rangle \geqslant 0.03$.[6]

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