Refraction effects in quasielastic heavy-ion processes

V. N. Bragin, F. A. Gareev, S. A. Goncharov, A. S. Dem'yanova,
S. N. Ershov, P. P. Korovin, A. L. Lebedev, and A. A. Ogloblin
I. V. Kurchatov Institute of Atomic Energy, Moscow

(Submitted 21 April 1986)
Pis'ma Zh. Eksp. Teor. Fiz. **43**, No. 11, 504–507 (10 June 1986)

The differential cross sections for the elastic scattering of ^{6}Li by ^{14}C and for the charge-exchange reaction ^{14}C(^{6}Li,^{6}He)^{14}N, accompanied by the excitation of the ground state and the 1^+ (3.95-MeV) excited state, have been measured and analyzed in an effort to determine the role played by refraction of the nuclear medium. The measurements were carried out at angles up to $\theta_{\text{c.m.}} \approx 130°$ at the energy $E_{^6\text{Li}} = 93$ MeV.

A nuclear rainbow[1] effect is observed in the elastic scattering of light nuclei at sufficiently high collision energies ($E/A \gtrsim 15$ MeV/nucleon). The classical deflection function corresponding to rainbow scattering has a negative limiting angle θ_R, which determines the boundary of the classically accessible scattering region. The differential cross section has a diffraction structure at small angles and a monotonic exponential decay in the classically inaccessible region ($\theta > \theta_R$), due to the refractive properties of the nuclear field. An important feature of rainbow scattering is a sensitivity to the component of the cross section due to partial waves with small orbital angular momenta and to the behavior of the interaction at small distances between the colliding nuclei.

It is natural to ask whether similar effects might occur in quasielastic processes

0021-3640/86/110652-04$01.00

when the entrance and exit channels are kinematically close together, and the trajectories of the relative motion of the nuclei involved in the reaction are close to the elastic-scattering trajectories. There is the hope that the experimental observation of effects due to the refractive properties of the nuclear field would make it possible to obtain important information on the particular features of the mechanism for the quasielastic processes and on the spatial localization of the corresponding form factors.

Guided by these considerations, we have carried out a study of the charge-exchange reaction $^{14}C(^{6}Li,^{6}He)^{14}N$ accompanied by the excitation of the ground state and the 1^{+} (3.95-MeV) excited state of the ^{14}N nucleus at an incident ion energy $E = 93$ MeV. The measurements were carried out over a broad angular range (up to $\theta_{c.m.} \cong 130°$) at the isochronous cyclotron of the I. V. Kurchatov Institute of Atomic Energy. This particular reaction was chosen because of its high degree of quasielasticity. Its primary mechanism is[2] a single-step charge exchange. The entrance and exit channels are kinematically close together (the reaction Q values are small in comparison with the collision energy; the masses of the nuclei in the entrance and exit channels are essentially the same; and the charges of these nuclei are only slightly different). We have simultaneously measured the cross section for elastic scattering. Refraction effects in the case of the elastic scattering of ^{6}Li by the neighboring ^{12}C nucleus were studied in Ref. 3 at the same collision energy. For this experiment, some thick, self-supporting films (1.0–1.4 mg/cm^{2}) of the isotope ^{14}C (85% enrichment) were prepared. This measure made it possible to raise the count rate at large angles. The ^{6}Li and ^{6}He nuclei were detected with a telescope of silicon semiconductor detectors $[\Delta E(70 - 100\mu) - E(\sim 3 \text{ mm})]$, connected through a spectrometric system to a computer.

The experimental data on the elastic scattering $^{6}Li + ^{14}C$ were analyzed on the basis of the standard optical model with a Woods-Saxon potential. We found the parameters of the potential which give a satisfactory description of the experimental results over the entire range of measured angles. The data on the charge-exchange reaction were analyzed under the assumption of a single-step excitation mechanism by the distorted-wave method. The formalism for the calculations of the form factors and cross sections is described in detail in Ref. 2. The calculated results are shown in Figs. 1 and 2 in comparison with the experimental data. We also carried out an analysis in the collective vibrational model for the inelastic scattering $^{12}C(^{6}Li,^{6}Li)^{12}C^{*}$ involving the excitation of the 2^{+} (4.44-MeV) and 3^{-} (9.64-MeV) states of the target nucleus.

The experimental data show, and the calculations confirm, that there is a qualitative analogy in the shapes of the angular distributions of the elastic and inelastic scattering and the charge-exchange reaction: a diffraction structure at small angles and a monotonic decay of the cross sections at large angles. For a more detailed study of the quasielastic processes we used, by analogy with elastic scattering,[4] the method of resolving the reaction amplitude into short-range component $[f_{s}(\theta)]$ and long-range component $[f_{l}(\theta)]$ for the inelastic scattering and for the charge exchange. To resolve the short-range and long-range components, we used the exact quantum-mechanical expressions in all cases. The corresponding cross sections are also shown in Figs. 1 and 2. We see that the diffraction structure in the angular distributions results

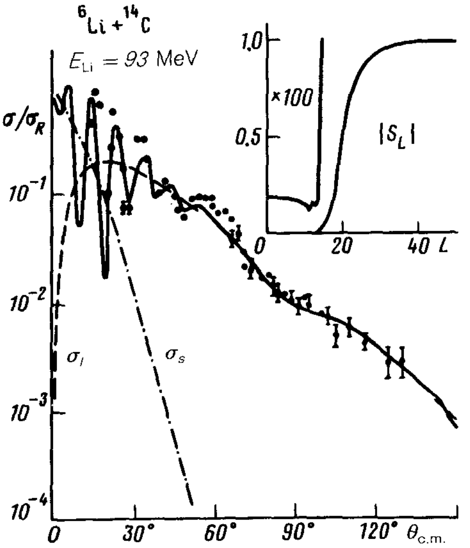

FIG. 1. Differential cross section for elastic scattering, divided by the Rutherford cross section, for $^{6}Li+^{14}C$ at $E = 93$ MeV. Points—experimental values; solid line—theoretical description based on the potential found [$V = -254$ MeV, $r_V = 0.58$ fm, $a_V = 0.787$ fm, $W = -67$ MeV, $r_W = 0.666$ fm, $a_W = 1.043$ fm, where $R_{V,W} = r_{V,W}(A_p^{1/3} + A_T^{1/3})$]; dashed line—calculation corresponding to the long-range component $f_l(\theta)$; dot-dashed line—calculation corresponding to the short-range component $f_s(\theta)$. The inset shows the L dependence of the moduli of the matrix elements.

from an interference of two components at small angles. The oscillation amplitude reaches a maximum near the angle $\bar{\theta}$, which corresponds to the crossing $|f_s(\bar{\theta})| = |f_l(\bar{\theta})|$. In the cases of elastic and inelastic scattering we have $\bar{\theta} > 0°$, because of the role played by the long-range Coulomb interaction. In the case of the charge-exchange reaction, the crossing occurs at a zero angle. At large angles, the cross section is dominated by the long-range component $f_l(\theta)$, which corresponds to scattering through large negative angles—a direct consequence of the refracting properties of the nuclear field.

As our analysis has shown, the region in which the elastic scattering is sensitive to the behavior of the optical potential is the distance interval $r \cong 2.5 - 6.4$ fm. Calculations carried out with a cutoff in terms of the angular momentum revealed that low-index partial waves contribute substantially to the large-angle scattering. Figure 1 illustrates the situation with a plot of the reflection coefficients versus the orbital angular momentum. Corresponding calculations (with a short-range cutoff of the form factors and without a small-l contribution) show that the charge-exchange reaction occurs at longer range than do the elastic scattering and the inelastic scattering accompanied by the excitation of collective levels of the target nucleus.

Let us summarize the results of this study.

1. The cross sections for the elastic scattering $^{6}Li + ^{14}C$ and for the charge exchange $^{14}C(^{6}Li,^{6}He)^{14}N$ have been measured over a broad angular range for the first time.

2. There are qualitative similarities in the behavior of the angular distributions for elastic scattering, inelastic scattering, and the charge exchange: diffraction structure at small angles and a predominance of the long-range component of the amplitude at large angles, indicating an important role of effects resulting from the refractive properties of the nuclear field.

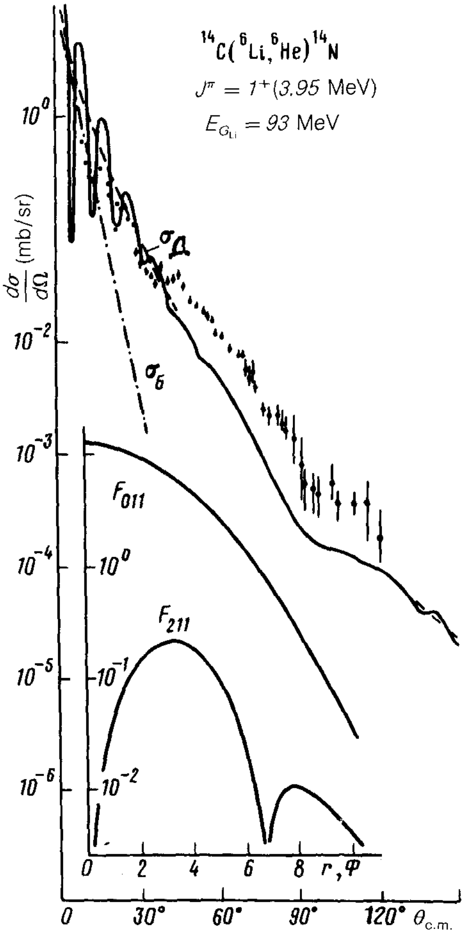

FIG. 2. Differential cross sections for the charge-exchange reaction ^{14}C(^{6}Li,^{6}He)^{14} at $E = 93$ MeV. Points—experimental; solid lines—theoretical, calculated by the distorted-wave method under the assumption of a single-step excitation mechanism with the potential in Fig. 1 in the entrance and exit channels; dashed line—calculation correspond to the long-range component $f_l(\theta)$ and the short-range component $f_s(\theta)$. The inset shows the form factors.

3. The results demonstrate that a study of quasielastic processes involving accelerated ^{6}Li ions over a broad angular range makes it possible to study the behavior of the optical potential and of the form factors for the reactions over distances smaller than the strong-absorption radius ($R_{sa} \cong 6.4$ fm).

[1] D. A. Goldberg, S. M. Smith, and G. F. Burdzik, Phys. Rev. C **10**, 1362 (1974).
[2] D. V. Aleksandrov *et al.*, Nucl. Phys. **A436**, 338 (1985).
[3] Yu. A. Glukhov *et al.*, Yad. Fiz. **34**, 312 (1981) [Sov. J. Nucl. Phys. **34**, 177 (1981)].
[4] R. C. Fuller, Phys. Rev. C **12**, 1561 (1975).

Translated by Dave Parsons