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Observation of a nuclear rainbowlike phenomenon in the (^{3}He,t) charge-exchange reaction

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Using a beam of 72 MeV helions, wide-range angular distributions were recorded for the charge-exchange reaction ^{14}C(^{3}He,t)^{14}N to the ground, analog, and Gamow-Teller states of ^{14}N. At far-side-dominated larger scattering angles, pronounced rainbowlike bumps are observed for the first time in charge-exchange channels, but shifted somewhat forwards compared with the elastic scattering. A distorted-wave Born approximation analysis shows substantial sensitivity to the charge-exchange form factors as well as to the choice of triton versus helion optical potentials.

Rainbowlike phenomena, of refractive origin[1] and hitherto only observed clearly in elastic scattering, are of substantial interest as a possible tool for probing nucleus-nucleus interactions at shorter distances. The analog of this phenomenon has been pointed to[2,3] for direct reactions, for which the motions in the entrance and exit channels are close. In Refs. 4–6 refraction effects caused by the attractive part of the nuclear interaction were studied via population of the 1^+ (3.95 MeV) Gamow-Teller state in ^{14}N in the charge-exchange reaction ^{14}C(^{6}Li,^{6}He)^{14}N at a beam energy of 93 MeV. A substantial absorption in that reaction, however, led to refractive patterns which are more appropriately described as remnants of a rainbowlike phenomenon, or "ghosts."[7] Similar conclusions were derived for the one-nucleon transfer study in ^{12}C+^{13}C.[8]

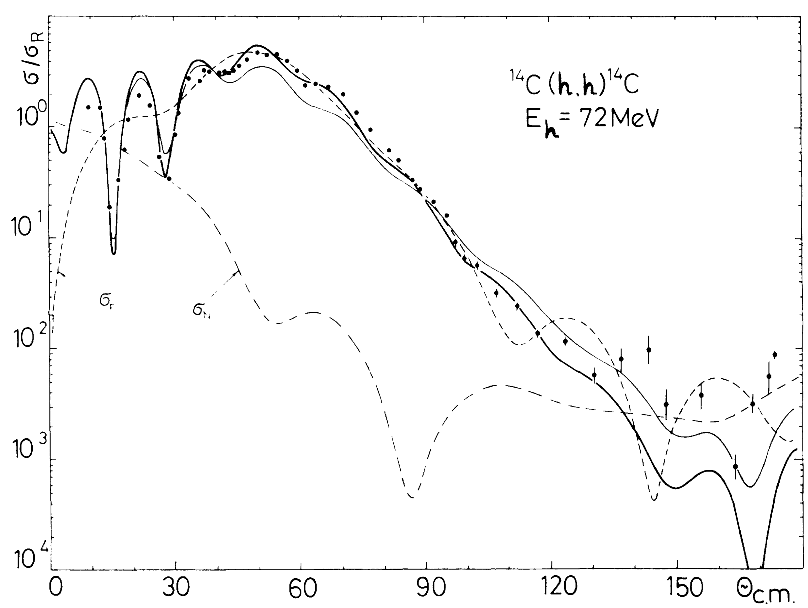

FIG. 1. The elastic scattering data for ^{3}He+^{14}C at $E_{^3\mathrm{He}}$(lab) = 72 MeV in ratio to the Rutherford cross section. The *thick, full curve* gives our best optical model fit, obtained with a folded real potential part. The *thin, full curve* is an angular distribution derived from Woods-Saxon forms for both the real and imaginary potential part, with parameters given in Table I. Partial theoretical cross sections corresponding to a near-side/far-side decomposition of the scattering amplitude are labeled by σ_N and σ_F.

TABLE I. Parameters for Woods-Saxon-type optical potentials used in the analysis, with half-value radii $R_{v,w}(i) = r_{v,w}A_i^{1/3}$ ($i = {}^{14}C, {}^{14}N$).

$-V$ (MeV)	r_v (fm)	a_v (fm)	$-W$ (MeV)	r_w (fm)	a_W (fm)
111.5	1.111	0.828	14.8	1.882	0.637

Elastic scattering data have shown that absorption of mass-3 projectiles is markedly smaller than for mass 6. Hence, the (^{3}He,t) reaction reported on in this Rapid Communication should, *a priori*, have an enhanced probability for probing the interaction more deeply, possibly resulting in more pronounced rainbowlike scattering patterns. The purpose of this paper is to report observations of well-defined rainbowlike bumps in the charge-exchange reaction ^{14}C(^{3}He,t)^{14}N at 72 MeV as well as in the corresponding elastic helion scattering. Furthermore, we will demonstrate that sensitivity to details in the reaction mechanism is enhanced through this scattering phenomenon.

The measurements using a beam of 72 MeV (lab) helions were carried out at the isochronous cyclotron of the Kurchatov Institute of Atomic Energy. Self-supporting targets of the isotope ^{14}C enriched to 85% and of thickness (1.0–1.4 mg/cm^2) were used. Details on the target production are given in Ref. 9. The helions and tritons were detected by means of a telescope of silicon semiconductor counters ($\Delta E - E$), on line with a computer. For the case of the helions ΔE(120–300 μm)$-E$($\sim$3 mm) was used while for the tritons ΔE(400 μm–1.4 mm)$-E$($\sim$3 mm) with silicon filters inserted was used to obtain the necessary full range. An energy resolution not exceeding 700 keV full width at half maximum (FWHM) was obtained.

Figure 1 gives the angular distribution data for the elastic helion scattering measured over an angular range up to 170°. The pattern is typical for light-ion scattering at about 20 MeV per nucleon; a diffractive forward region with oscillations which decrease in amplitude with increasing angle continues into a wide maximum with an exponentially falling tail towards larger angles. As demonstrated in the figure, the elastic scattering is rather well accounted for (except at very backward angles) within a local optical potential model with a real potential part generated by a folding procedure.[10] A description in terms of standard Woods-Saxon potentials is slightly worse, our best fit with such potentials (volume absorption) is also shown in Fig. 1 with potential parameters given in Table I.

Figure 1 also gives separate cross sections corresponding to a near-side/far-side decomposition of the scattering

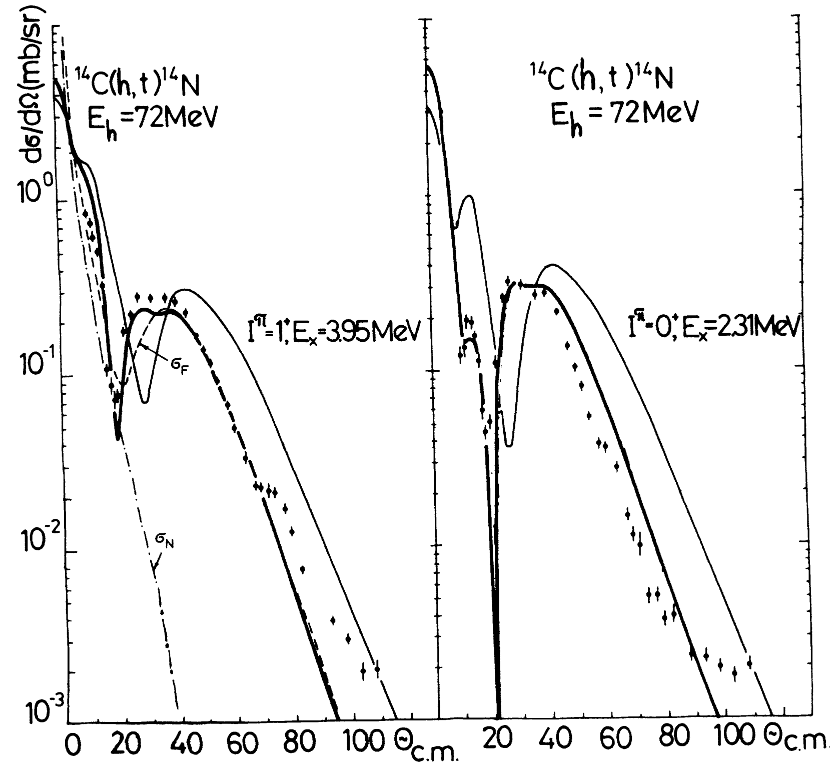

FIG. 2. Experimental and theoretical (DWBA) angular distributions for the charge-exchange population of the 1^+ (3.95 MeV) and 0^+ (2.31 MeV) states in ^{14}N. The *thin, full curves* correspond to using the same Woods-Saxon-type optical potential in both the triton and helion channels, while for the *thick, full curves* the real depth was reduced by about 30% (see main text). The far-side/near-side decomposition is labeled by σ_N and σ_F.

amplitude following Fuller.[11] We interpret the pronounced bump in the far-side (and total) angular distribution at about 60° as a rainbowlike phenomenon. The following observations give partial support for such an interpretation: (i) the appearance of the bump in $\sigma_F(\theta)$; (ii) the height of the bump increases drastically when the absorption is decreased, however, without significant changes in either the peak position or its width; (iii) the classical deflection function has a minimum at large negative angles corresponding to the backside of the observed bump. Still, close analogy with a detailed semiclassical description of the rainbow phenomenon should be taken with some caution (see, for example, Ref. 12 for a discussion), due to the strong wave mechanical effects.

Angular distributions for (^{3}He,t) population of three states in ^{14}N, the 0^+ (2.31 MeV) analog state, the 1^+ (3.95 MeV) Gamow-Teller state, and 1^+ ground state, are shown in Figs. 2 and 3. Data on the Gamow-Teller state were also reported in the previous (^{6}Li,^{6}He) study[6] discussed previously. Population of the 0^+ analog state was in that case forbidden by selection rules, and poor statistics did not allow for detailed conclusions about the weakly populated 1_g^+ ground state. The data in Fig. 2 is an interesting example of a Wigner supermultiplet.[13]

The most outstanding characteristic of the (^{3}He,t) angular distributions for the 0^+ (2.31 MeV) and 1^+ (3.95 MeV) states are the pronounced rainbowlike bumps at larger angles (see Fig. 2) similar to what is observed in the elastic scattering (Fig. 1) but shifted somewhat forwards. The bumps appear in the far-side scattering cross section. At very forward angles we observe a diffraction pattern for all three final states; for the more weakly populated 1^+ ground state, oscillations persist up to about 50° and the rainbowlike bump is less visible. As for the elastic scattering, the very forward diffraction is of Fraunhofer-like type, due to near-side/far-side interference.

The (^{3}He,t) data were analyzed within the distorted-wave Born approximation (DWBA) using form factors for the charge transfer derived from microscopic theory,[14] including central and tensor nucleon-nucleon interactions. Both folding and Woods-Saxon-type optical potentials were tried with rather comparable results. The theory curves in Figs. 2 and 3 correspond to Woods-Saxon-type potentials.

With the same optical potential in the triton and helion channels, the simple volume Woods-Saxon potential of Table I that gave the fit (thin, full curve) to the elastic scattering data in Fig. 1, the gross structures of the charge-exchange data for the analog and Gamow-Teller states were reproduced; and most importantly, the bumps at larger angles. Recall that the observed bumps in the charge transfer are shifted forwards compared with the elastic scattering data. This feature is not reproduced by our theoretical calculations which give bumps in the vicinity of where the rainbowlike bump was observed in the elastic scattering.

One may attempt to reproduce the observed angular distributions by modifying the charge-transfer form factors or the triton exit channel optical potential, which is not experimentally known. The fits (thick, full curves) shown in Fig. 2 were obtained by reducing the depth of

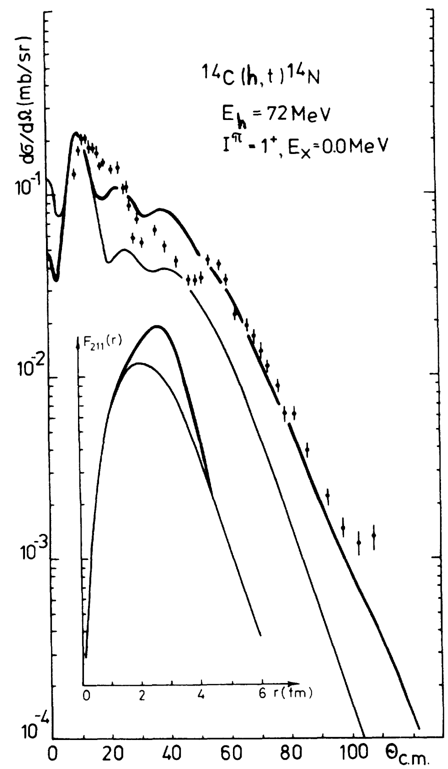

FIG. 3. Data and DWBA theory for charge-exchange population of the 1^+ ground state of ^{14}N. The calculation employs different optical potentials in the helion and triton channels. The thin, full curve corresponds to the microscopically calculated $L=2$ form factor shown in the inset (the weaker $L=0$ is also included), while the thick, solid curve is derived from the *ad hoc* surface modified form factor, also shown in the inset.

the real part of the triton potential from 111.5 to 74.5 MeV. Some reduction is expected from isospin dependence (Lane-type[15] potential $\sim t_3^q T_3^A$), however, it is significantly less than the 30% reduction required to fit the data. Phenomenologically, a reduction of about 15% has previously been employed for comparable cases.[16] A fit of comparable quality could also be obtained with a potential that is the same in both channels. This potential has both volume and surface absorption; a weak but unusually long-ranged volume term and a subsatantial surface term. A more thorough investigation of optical potentials is in progress. The question of the origin of the shift remains somewhat open because sequential processes were not included in our analysis.

We have already pointed out that the 1_g^+ cross section deviates from the other two both in strength, being substantially weaker, and by the enhanced oscillatory structure. These oscillations are not primarily caused by absorption. They also reflect the peaked and surface localized $L=2$ charge-exchange form factor (see inset of Fig. 3) having a width comparable to the wavelength. The *weaker* population of the 1_g^+ state is reproduced in our theoretical calculation and reflects the substantially weaker leading form factor, $L=2$ for this case. The sensitivity to this form factor is demonstrated in Fig. 3 where also the result corresponding to an *ad hoc,* more surface localized, form factor is shown. The agreement with data, in particular for larger angles is significantly improved. Since our knowledge of, and previous possibilities to test this form factor against data have been rather limited, the sensitivity in the present data should encourage further theoretical work. Although the absolute cross section is quite well reproduced, the fit to the 1_g^+ state is less satisfactory than for the more strongly populated states. This could again reflect the presence of sequential transfer processes.

The present collision, as reflected both in the elastic scattering and charge exchange data, probes the nucleus-nucleus interaction at distances way inside the strong absorption radius (~6 fm). We think that reactions producing rainbowlike structures are more than a curiosity, and are in fact, a promising tool for exploring the nucleus-nucleus interaction more deeply.

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