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NUCLEAR-RAINBOW EFFECT BY TRANSFER REACTIONS

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Nuclear-rainbow effects in elastic and inelastic scattering and transfer reactions by the $^3He + ^{12}C$ and $^4He + ^{12}C$ interactions at $E(^3He) = 98$ MeV and $E(^4He) = 90$ MeV respectively are observed analyzing the angular distributions of the $^{2,3}H$, $^{3,4}He$ and ^6Li particles. The data have been analyzed by a near/far-side formalism using Fuller's model. It has been shown that the far-side component plays the main role in all studied processes. The present investigation proposes a method for the optical model parameter choice for entrance and exit channels. We also observe the different characteristics of the rainbow effects and of the shape of the angular distributions for very deep inelastic processes (high excitation energies) and transfer reactions.

1. INTRODUCTION

The rainbow-like phenomenon has been widely observed in elastic and inelastic scattering of light and heavy ions while few results regard the nuclear reactions. The interesting questions are the manifestation and influence of the rainbow in the one- and few-nucleon transfer nuclear reactions. It is to be considered, moreover, that up to now the rainbow in the transfer reactions has been observed only in the reaction with similar entrance and exit channels

In this work we study the rainbow region and the changing of the angular distributions depending on the reaction mechanism for the $^4He + ^{12}C$ and $^3He + ^{12}C$ interactions and we offer a method of optical parameter choice for entrance and exit channels too. A code on the basis of Fuller's formalism [1] has been developed for the calculations.

2. EXPERIMENTAL PROCEDURE AND RESULTS

By using the ^3He and ^4He beams at the isochronous cyclotron of the Institute for Nuclear Research of Kiev, transfer reactions on ^{12}C were measured at $E(^3He) = 98$ MeV and $E(^4He) = 90$ MeV. A self-supporting carbon target was used. The $^{2,3}H$, $^{3,4}He$ particles obtained were detected by means of two telescopes each consisting of 200 μm thick silicon ΔE-detector and

40 mm.thick NaI(Tl)-crystal with the photomultiplier as the E-detector. In the experiment in which ^{6}Li was detected, the telescope consisted of ≈ 30 μm thick silicon ΔE - detector and 1000 μm thick silicon as E - detector. The typical energy spectra of the ^{3}H and ^{6}Li nuclei are shown in figure 1. The results of the measured angular distributions are shown in figures 2 and 3. In these figures one can observe the diffractive structure at the angles below 50° (Fraunhofer diffraction region) and a broad rainbow structure above the rainbow angle. With increasing excitation energy, the size of the oscillations becomes smaller. The angular distributions of the reactions show (see figure 3) a diffractive region at the forward angles - followed by a broad smooth distribution region too - whose size is smaller than in elastic and inelastic cases. Moreover, when the number of transferred nucleons increases, the broad smooth structure in the angular distributions moves - keeping the same slope - towards forward angles as in the elastic and inelastic cases.

The comparison of the elastic scattering angular distribution of ^{4}He ions in the investigated energy range shows that as energy increases the exponential fade-out of the cross sections moves towards forward angles, leading to the decrease of the diffraction region.

3. ANALYSIS AND DISCUSSION

We carried out a quantitative analysis of the few-nucleon transfer reactions obtained by the ^{3}He + ^{12}C and ^{4}He + ^{12}C interactions. The angular distributions for all reactions show two characteristic angular regions:

i) the interval of rudimentary oscillations;

ii) the interval of the exponential drop.

The analysis of the experimental data of the transfer processes was carried out using the distorted wave formalism. The theoretical calculations were performed with the help of the modified version of the DWUCK4RN [2] computer code. The near/far-side amplitude calculations [3] of the reactions were inserted in this code.

The depth of real part is chosen by using the expression [4] $V = nV_0 - \delta$, where V_0 is about 40–45 MeV, n is the nucleon number and δ is the pairing energy. The decomposition of the cross section in far and near components for this reaction shows that the behaviour of the cross section in the region corresponding to nuclear-rainbow is substantially determined by the far-component.

From figures 2 and 3 we see that for higher excited ^{12}C states the second crossing point between the far- and near-component moves to the side of the backward angles. The same effect takes place in reactions with a higher number of transferred nucleons (see figure 3). From the same figures we also observe that the rainbow maxima do not move by passing from the elastic scattering to the transfer reaction. The region of the exponential drop has a different form (the degree of the drop, the range size of the drop) depending on the type of reactions (break - up, pick - up, transfer of one or two nucleons). In the case of the present studied ^{3}He+^{12}C interaction we observe [5]

i) a narrow peak for θ_{rain} , a sharper drop and a decreasing drop region for the break-up ^{12}C(^{3}He , ^{2}H) ^{13}N reaction;

ii) a broadening of the peak in the region of θ_{rain} and a wide drop region for the pick-up ^{12}C(^{3}He , ^{4}He) ^{11}C reaction.

By analysing the experimental data of the ^{12}C(^{3}He , ^{4}He) ^{11}C reaction at E(^{3}He) = 98 MeV we also observe that the exponential drop of the angular distribution is weak and this peculiarity can eventually be related to the second maximum of the rainbow. For the $^{12}C(^{3}He, {}^{2}H)^{13}N$ reaction around the point of overlapping between the ^{3}He and ^{12}C nuclear surface the break-up process of $^{3}He \rightarrow {}^{2}H + {}^{1}H$ is easier. This process takes place in a very narrow part of the diffusional region of the ^{12}C nucleus. This demonstrates the narrow rainbow peak at $\theta_{c.m.}=30°$ and the short drop of the cross section at the angular region $\theta_{c.m.}=40° - 60°$. In this case even Fuller's model does not predict the orbiting or the second rainbow maximum, though the far-component of the reaction amplitude of the break-up reaction well describes the experimental data of the $^{12}C(^{3}He, d)\,^{13}N$ reaction in all the angular range. The same peculiarities in $^{12}C(^{4}He, {}^{3}He)^{13}C$, $^{12}C(^{4}He, {}^{3}H)^{13}N$, $^{12}C(^{4}He, {}^{2}H)^{14}N$, and $^{12}C(^{4}He, {}^{6}Li)^{10}B$ were observed (see figure 3).

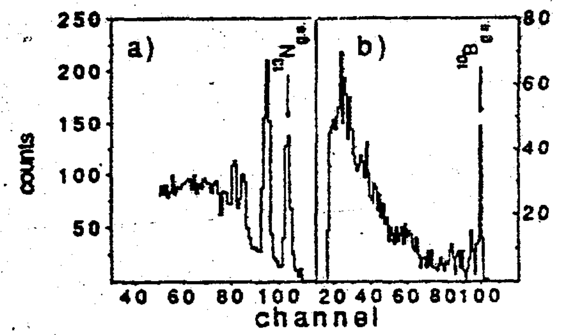

Figure 1. Single-particle energy spectra observed by E-detector at $E(^{4}He)$=90 MeV: a) tritium spectrum by the $(^{4}He, {}^{3}H)$ reaction at θ_{lab} =27.5°; b) lithium-6 by the $(^{4}He, {}^{6}Li)$ reaction at θ_{lab}=10°.

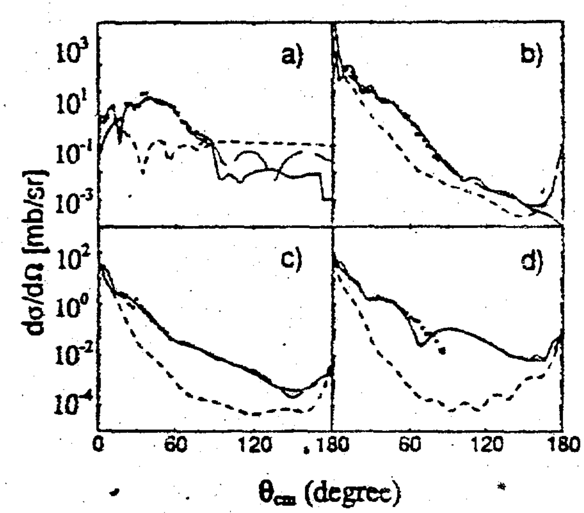

Figure 2. Angular distributions by the $^{3}He + {}^{12}C$ interaction at $E(^{3}He)$=98 MeV. Full points are the experimental data. Dashed line represents the near-component, long dashed line is the far-component. Full line is the total contribution. a) $d\sigma/d\sigma_{Ruth}$ for the $^{3}He + {}^{12}C$ elastic scattering; b) $d\sigma/d\Omega$ (mb/sr) for the $^{12}C(^{3}He, {}^{3}He)\,^{12}C^{*}_{4.44}$ inelastic scattering; c) deuteron angular distributions by the $^{12}C(^{3}He, {}^{2}H)\,^{13}N_{g.s.}$ reaction; d) helium-4 angular distributions by the $^{12}C(^{3}He, {}^{4}He)\,^{11}C_{g.s.}$ reaction.

4. CONCLUSIONS

We can conclude that by investigating the elastic and inelastic scattering and one- and two-nucleon transfer reactions a nuclear rainbow effect occurs. From an analysis on the basis of Fuller's formalism and a method that we propose for the choice of the preliminary optical model parameters, we find that in the investigated angular range the far-side component agrees well with the experimental data at the forward angles where the near-side component is a few orders of magnitude lower too. The obtained experimental data and the analysis of the transfer reaction in the far- and near- component limit the region of the nuclear transfer at a diffusional layer of about 0.6 – 0.7 fm of the nuclear surface. Therefore, it can be believed that the nuclear rainbow effects in the elastic and inelastic scattering and the transfer reactions take place at the orbiting or the complex system formation from the two ^{3}He and ^{12}C nuclei and which has a short lifetime (about $10^{-21} - 10^{-22}$ s).

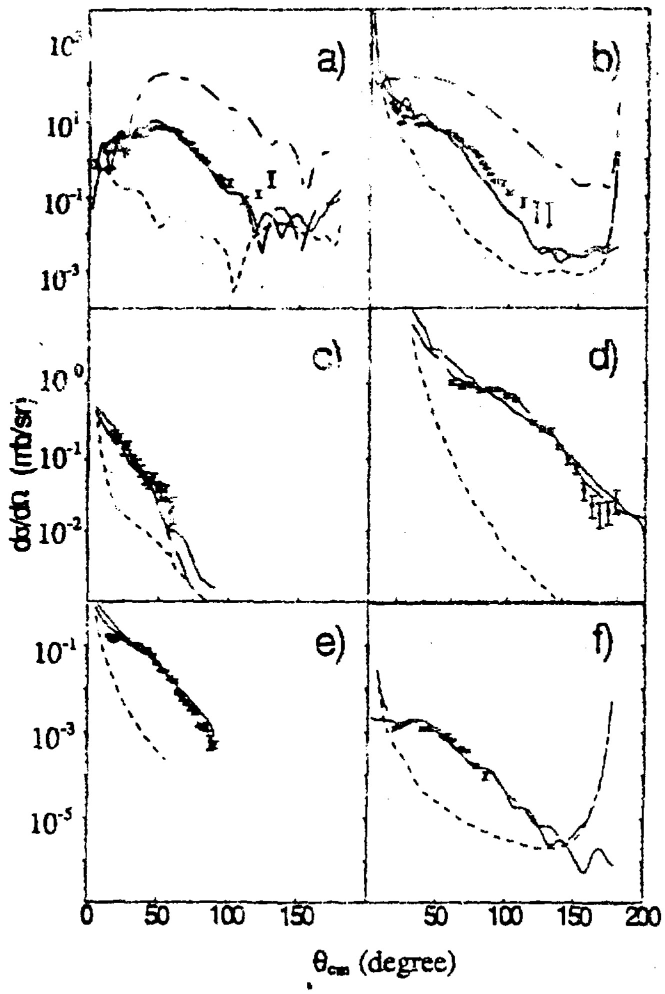

Figure 3. Angular distributions by the ^{4}He + ^{12}C interaction at E(^{4}He)=90 MeV. Full points are the experimental data. Dashed line represents the near component, long-dashed line is the far component. Full line is the total contribution. a) $d\sigma/d\sigma_{Ruth}$ by the ^{4}He + ^{12}C elastic scattering (for comparison the far model calculation is also reported when only a real potential is assumed (dash-dotted line)); b) $d\sigma/d\Omega$ (mb/sr) by the ^{12}C(^{4}He, ^{4}He)^{12}C*$_{4.44}$ inelastic scattering; c) deuteron angular distributions by the ^{12}C(^{4}He, ^{2}H)^{14}N$_{g.s.}$ reaction; d) tritium angular distributions by the ^{12}C(^{4}He, ^{3}H)^{13}N$_{g.s.}$ reaction; e) helium-3 angular distributions by the ^{12}C(^{4}He, ^{3}He)^{13}C$_{g.s.}$ reaction; f) lithium-6 by the ^{12}C(^{4}He, ^{6}Li)^{10}B$_{g.s.}$.

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