EPJ Web of Conferences **66**, 03051 (2014)
DOI: 10.1051/epjconf/20146603051

A study of proton breakup from exotic nuclei through various reaction mechanisms in 40A - 80AMeV energy range

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Abstract. We have studied the single proton breakup from weakly bound exotic nuclei due to several reaction mechanisms separately and their total and the interference effects, in order to clarify quantitatively which mechanism would dominate the measured observables. We have considered: (i) the recoil effect of the core-target Coulomb potential which we distinguish from the direct proton-target Coulomb potential, and (ii) nuclear breakup, which consists of stripping and diffraction. Thus, we have calculated the absolute values of breakup cross sections and parallel momentum distributions (LMD) for ^{8}B and ^{17}F projectiles on a light and a heavy target in a range of intermediate incident energies (40A–80A MeV) for each reaction mechanism. Furthermore the interference among the two Coulomb effects and nuclear diffraction has been studied in detail. The calculation of the direct and recoil Coulomb effects separately and of their interference is the new and most relevant aspect of this work.

1.Introduction

The break up of loosely bound neutron-rich nuclei has been studied extensively and it is fairly well understood [1, 2]. This is not completely true for proton-rich nuclei in which the loosely bound valence protons actively participate in the reaction. Besides the well-known astrophysical implications, proton rich nuclei present a number of unusual features such as two-proton radioactivity and β-delayed proton emission, which make them very appealing to study and to compare with neutron-rich nuclei. An account of the richness of the "physics of the proton-rich side of the nuclear chart" is given in Ref. [3]. Recently, Liang *et al.* [4] stressed the importance of the dynamic polarization effect, which they interpret as a displacement of the valence proton behind the nuclear core and a subsequent shielding from the target. This effect manifests itself as a reduction in the

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breakup probability compared to first-order perturbation theory predictions. It has also been suggested that the inclusion of higher-order corrections is required [5,6]. Hence, in order to extract reliable information, the different reaction mechanisms and their interferences have to be understood in detail. In the present work we have studied the breakup reactions of ^{8}B and ^{17}F on a light and a heavy target in a range of 40*A* MeV to 80*A* MeV incident energies, because this is a typical energy range used in most laboratories worldwide and for which our results should be reliable. Here, we have calculated longitudinal momentum distribution and absolute cross sections due to the nuclear and Coulomb breakup (recoil and direct) separately and then show how much the interference effects modify the simple sum of the cross sections. This is very important in view of spectroscopic studies of proton rich nuclei and consequently in their applications in nuclear astrophysics. Our theoretical formalism is an all order formalism based on the eikonal approximation, details of which are given in ref. [7-9].

2. Results and Discussion

Table 1 contains the absolute values of the cross sections for the one proton breakup from ^{8}B and ^{17}F on ^{12}C and ^{208}Pb at 40*A*, 60*A*, and 80*A* MeV. The cross sections due to the stripping and diffraction mechanisms and the direct and recoil terms of Coulomb breakup are shown separately. We give also the total Coulomb cross sections, which contain the interference effects of direct and recoil terms. Furthermore the total elastic breakup (diffraction plus Coulomb) cross sections are given. They contain all interference effects between the three possible mechanisms (nuclear, direct Coulomb, recoil Coulomb) following which the proton would be measurable in coincidence with the core. In stripping the nucleon is considered absorbed by the target, in the sense of the optical model absorption and its energy degraded such that it would not be detected in coincidence with the core of origin. Such a mechanism cannot interfere with diffraction nor with Coulomb breakup.

Table 1. σ_{bup}(mb) for nuclear and Coulomb mechanisms as indicated for ^{8}B, 1$p_{3/2}$ initial state, and ^{17}F, 1$d_{5/2}$ initial state, on ^{12}C and ^{208}Pb targets at E_{inc} = 40*A*, 60*A*, 80*A* MeV.

Target	**12C**						**208Pb**					
E_{inc}	**40 AMeV**		**60AMeV**		**80AMeV**		**40 AMeV**		**60AMeV**		**80AMeV**	
Projectile	**8B**	**17F**	**8B**	**17F**	**8B**	**17F**	**8B**	**17F**	**8B**	**17F**	**8B**	**17F**
Stripping	**51.6**	**18.1**	**41.2**	**13.5**	**34.8**	**10.9**	**105.94**	**29.97**	**88.59**	**23.09**	**78.16**	**19.29**
Diffraction	**31.7**	**8.19**	**23.2**	**5.4**	**18.9**	**4.2**	**70.42**	**14.08**	**58.84**	**10.99**	**52.39**	**9.36**
Coulomb recoil	**0.10**	**0.01**	**0.1**	**0.01**	**0.03**	**0.002**	**534.2**	**65.98**	**262.2**	**31.74**	**159.1**	**19.14**
Coulomb direct	**2.1**	**0.58**	**1.0**	**0.28**	**0.61**	**0.17**	**4562.7**	**1209.4**	**2578.8**	**624.6**	**1741.**	**394.54**
Total Coulomb	**2.5**	**0.67**	**1.2**	**0.32**	**0.73**	**0.19**	**4129.5**	**1542.4**	**2796.8**	**874.4**	**1925.3**	**611.52**
Coulomb and Diffraction	**60.2**	**22.8**	**39.7**	**13.2**	**30.9**	**9.42**	**4228.6**	**1608.4**	**2740.8**	**956.6**	**1928.0**	**691.09**

Parallel momentum distributions due to the Coulomb recoil and Coulomb direct terms from ^{8}B and ^{17}F and their combined effect including interference are shown in Figs. 1 and 3, respectively, while Figs. 2 and 4 show parallel momentum distributions due to nuclear and Coulomb breakup from the same projectiles and their total effect including interference. Notice that in Fig. 3 some asymmetries appear due to the interference of the direct and recoil Coulomb effects. In the case of the ^{8}B projectile at 40*A* MeV incident energy on the ^{208}Pb target both the cross section values in Table 1 and Fig. 1(c) show that the direct and recoil Coulomb terms interfere destructively and total Coulomb is almost exactly the difference of the two. Increasing the incident energy, the two Coulomb effects show very small interference and the total is very close to the sum of the two in the total cross section (cf Table1)

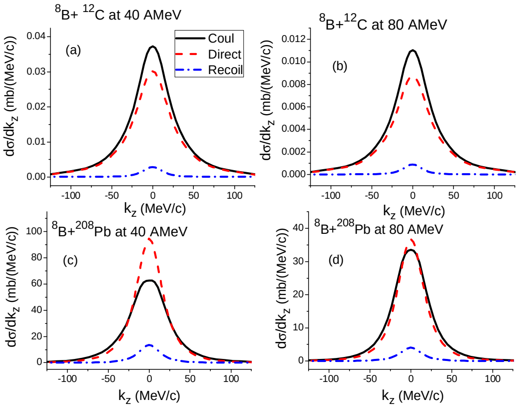

Figure. 1. (Color online) Parallel momentum distributions due to the Coulomb recoil and direct terms from ^{8}B on ^{12}C and ^{208}Pb.

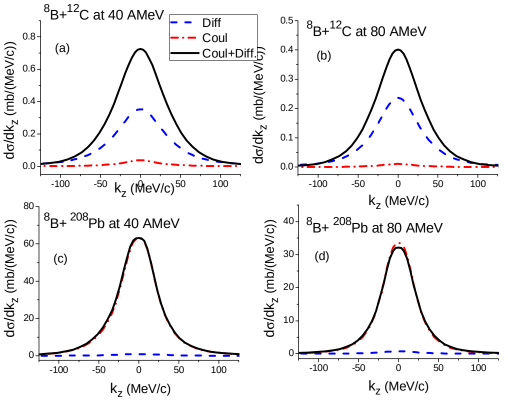

Figure. 2. (Color online) Parallel momentum distributions due to diffraction and Coulomb breakup from ^{8}B on ^{12}C and ^{208}Pb.

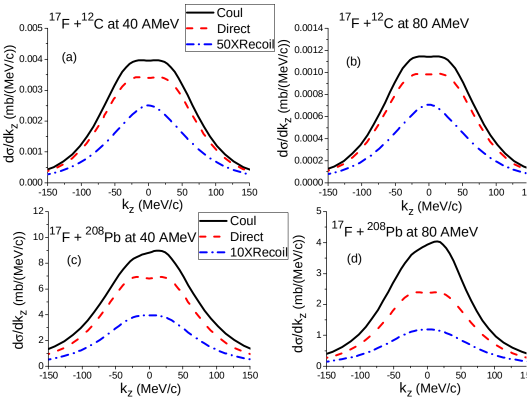

Figure. 3. (Color online) Parallel momentum distributions due to the Coulomb recoil and direct terms from ^{17}F on ^{12}C and ^{208}Pb.

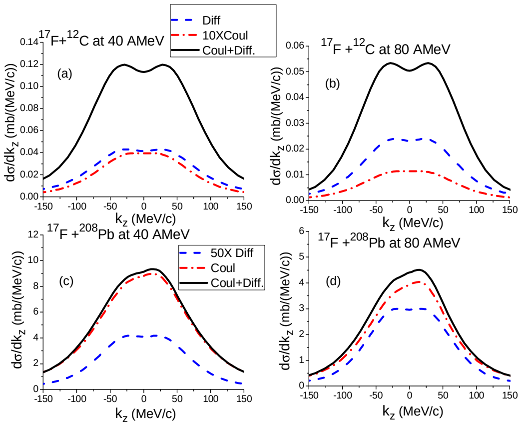

Figure. 4. (Color online) Parallel momentum distributions due to diffraction and Coulomb breakup from ^{17}F on ^{12}C and ^{208}Pb.

while in the momentum distributions shown in Fig. 1(d) at the very small parallel momentum values it is given by the difference of the two with the recoil term just contributing more. The interference between diffraction and Coulomb is also very small and it is destructive or constructive depending on the incident energy on the heavy target, Figs. 2(c) and 2(d). As expected, on the light ^{12}C target the recoil effect is really negligible and the Coulomb breakup is mainly due to the direct term at all incident energies, Figs. 1(a) and 1(b). Thus the interference is small and always constructive. Diffraction cross sections on the other hand have much higher values than Coulomb breakup cross sections for the light target. The interference is so strong at low energy that it almost doubles the simple sum of diffraction and Coulomb breakup, Figs. 2(a) and 2(b). This effect is very interesting and it shows that by including the Coulomb breakup the cross section can increase a lot but not because the Coulomb itself is large, but because of the interference. In the case of the ^{17}F projectile the effects are similar but the interference, in the cases shown here, is always constructive both between direct and recoil Coulomb as well as between Coulomb and diffraction as can been seen from Figs. 3 and 4. On the other hand looking at Table 1 one sees also that for both projectiles the total nuclear breakup cross sections are always of the same order of magnitude than the recoil Coulomb breakup on a heavy target but much smaller than the direct Coulomb and the total Coulomb cross sections. Thus we confirm what has already been suggested by other authors [5,10,11], on why in the past, calculated nuclear breakup of a proton has been found comparable to or even larger than the Coulomb breakup. The misinterpretation was simply due to an underestimate of the direct Coulomb breakup due to both the dipole approximation and its treatment to first order and to the fact that interference effects were overlooked.

3.Conclusion

In this paper, we have studied all mechanisms that can produce breakup of a weakly bound proton in the reactions of ^{8}B and ^{17}F nuclei impinging on a light and a heavy target. The semiclassical method used allows us to treat both the full nuclear and Coulomb interactions to all orders and all multipolarities. On a light target the total nuclear breakup is always larger than the Coulomb breakup. On the other hand although the Coulomb breakup is very small the interference between diffraction and Coulomb is constructive and such that the total becomes quite large. On a heavy target instead the total nuclear breakup is of the same order of magnitude as the Coulomb recoil effect while the direct Coulomb breakup is one order of magnitude larger. Thus this term dominates not only in the total Coulomb breakup but also in the total diffraction plus Coulomb term. The quantitative assessment of the direct Coulomb breakup and of its interference with other mechanisms is very important and given here for the first time in the literature. It is then clear that the breakup mechanism of a proton is much more complicated than that of a neutron and disentangling various effects is of fundamental importance when interpreting experimental data and/or to make predictions in order to plan future experiments.

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