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Flubber experiment: analysing the Coulomb breakup of ^{17}F

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Coulomb breakup has been proposed as an indirect technique to infer radiative-capture cross sections at low energies. To test this idea we have performed the Flubber experiment at the FRIBs facility of the Laboratori Nazionali del Sud (Catania, Italy). In this experiment, we have measured the breakup of ^{17}F on lead at 40*A*MeV. The motivation of this measurement is reported as well as preliminary experimental data.

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1. Introduction

Coulomb breakup is used in various fields of nuclear physics. In this reaction, the projectile dissociates into its more elementary constituents through interaction with the Coulomb-dominated field of a heavy target. It is one of the few techniques that enable the study of the structure of exotic nuclei produced in Radioactive-Ion Beam (RIB) facilities. In particular it provides useful information about halo nuclei [1]. Coulomb breakup has also been proposed to infer the cross section of radiative-capture reactions of astrophysical interest [2, 3]. At stellar energies, the Coulomb barrier between the colliding nuclei is so broad that a direct measurement of radiative capture in the laboratory is nearly impossible. To obtain the cross sections needed in stellar models, one usually extrapolates cross sections measured at higher energies, where laboratory measurements are feasible, down to the energies of interest. However, this requires a reliable reaction model and is not free from biases. In the Coulomb-breakup technique, the radiative-capture cross section is inferred from measurements of the breakup of the nucleus synthesised in the radiative capture. Being Coulomb dominated, the dissociation can be seen as resulting from the exchange of virtual photons between the projectile and the target. Hence, Coulomb breakup can be seen as the time-reversed reaction of radiative capture. Following this line of thought, radiative-capture cross sections can be extracted from Coulomb-breakup ones following a detailed balance [3]. This indirect technique is very appealing since measuring Coulomb breakup is much easier than radiative capture: The former can indeed be performed at high energies, well over the Coulomb barrier. Moreover, the high intensity of current RIBs and the precision of the detector setups enable accurate measurements of Coulomb breakup.

Though appealing, the Coulomb-breakup technique rely on a few assumptions that should not be ignored. First, the breakup should be due to the sole Coulomb interaction, meaning that nuclear interaction between the projectile and the target should be negligible. Second, since the radiative-capture is dominated by E1 transitions in the energy range of interest, the breakup due to higher multipoles should be negligible as well. Third, the detailed balance used to infer radiative-capture cross sections from breakup measurements assumes a one-step transition from the projectile bound state to its continuum [3]. Hence, multi-step processes, such as couplings in the continuum, should also be negligible. To test the validity of these hypotheses, we need to compare directly measured radiative-capture cross sections to cross sections extracted from Coulomb breakup measurements.

2. Coulomb breakup of ^{8}B and ^{17}F

The Coulomb-breakup technique has been applied several times to infer the cross section of the radiative capture $^{7}\mathrm{Be}(\mathrm{p},\gamma)^{8}\mathrm{B}$ [4, 5, 6]. This is one of the reactions that take place in the pp chain [7] and which play a significant role in the study of solar neutrinos. However, these indirect determinations of the radiative-capture cross section systematically underestimate the direct measurements. The Coulomb-breakup technique therefore does not help reducing the uncertainty due to the extrapolation of the direct measurements down to astrophysical energies. Various theoretical analyses indicate that at least two of the aforementioned conditions are not satisfied in the Coulomb breakup of ^{8}B [8, 9, 10, 11], suggesting this to be the cause of the discrepancy between direct and indirect measurements. This is illustrated in Fig. 1, where the breakup cross section of ^{8}B is plot-

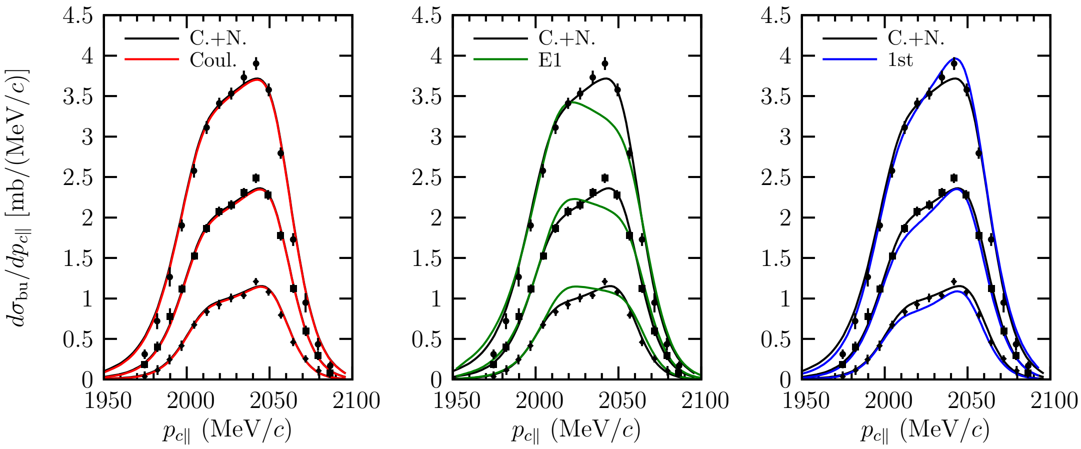

Figure 1: Coulomb-breakup cross section of ^{8}B into ^{7}Be and p on Pb at 44*A*MeV as a function of the ^{7}Be longitudinal momentum. Effect of the nuclear projectile-target interaction (left), of the Coulomb multipoles (centre), and of the higher-orders (right) [9]. Data from Ref. [5].

ted as a function of the parallel-momentum distribution of ^{7}Be after dissociation. The calculations are performed within the Dynamical Eikonal Approximation (DEA) [9]. The data are taken at the angular cuts: $\theta_{^7\rm Be} < 1.5°$ (diamonds), 2.4° (squares), and 3.5° (circles) [5].

The left panel illustrates the negligible influence of the nuclear interaction between the projectile and the target in the reaction process when the data are restricted to forward angles. The calculations performed with a purely Coulomb interaction (red lines) are superimposed on the calculations including both Coulomb and nuclear potentials (black lines). The central panel shows calculations performed with the sole E1 dipole term of the Coulomb interaction (green lines) in comparison with the full calculations (black lines). This shows the significance of the quadrupole and higher-multipoles in this breakup observable, in particular in the asymmetry of the distribution. This confirms the necessity of including at least the E2 term in Coulomb breakup calculations to reproduce experimental data [8, 9]. In the right panel, higher-order effects are evaluated. Fully dynamical calculations (black lines) are compared to results obtained at the first order of the perturbation theory [12] (blue lines), i. e. assuming a single step transition between the initial ^{8}B bound state and the continuum. This result confirms that multi-step processes tend to reduce the asymmetry of the longitudinal-momentum distribution [8, 9]. The significant effects of E2 transitions and higher-order effects may explain the discrepancy between the cross sections for the radiative capture ^{7}Be(p,γ)^{8}B obtained from direct measurements and Coulomb-breakup data [10, 11].

These theoretical analyses of ^{8}B breakup measurements hence suggest that the Coulomb-breakup technique is not as precise as initially thought. However, ^{8}B is not the best test case for this method. First the direct measurements of the radiative-capture cross sections are scattered on a wide range of values. Second, the structure of ^{8}B is poorly described as a proton loosely bound to a spherical and structureless ^{7}Be, which has been used up to now in all reaction models. The internal structure of ^{7}Be may indeed play a role in the reaction process and may be responsible for the aforementioned discrepancy. In this respect, the case of ^{17}F is much better suited for this analysis [3]. First, the direct radiative capture ^{16}O(p,γ)^{17}F has been precisely measured down to low energies [13]. Second, ^{17}F is very-well described as a spherical ^{16}O core in its 0^+ ground state to which a proton is loosely bound [14]. Third, since there is no low-energy states in the continuum of ^{17}F, the radiative capture is not influenced by resonant processes. To complete this analysis of the Coulomb-breakup technique, a measurement of the Coulomb breakup of ^{17}F is needed. This is the aim of the FLUBBER experiment, which stands for “Fluorine breakup”.

The FLUBBER experiment has been performed between May and June 2009 at the Laboratori Nazionali del Sud (LNS, Catania) using the in-Flight Radioactive Ion Beams (FRIBs) facility [15], which provided us with a secondary beam of ^{17}F at about 40*A*MeV. The experimental setup is the same previously used in a study of diproton decay of ^{18}Ne [16] and has been detailed during the previous Bormio Meeting [17]. The data are under analysis. Besides summarising the preliminary theoretical analysis, this contribution aims at presenting preliminary data.

3. Theoretical predictions

In order to prepare the FLUBBER experiment, we have performed a preliminary theoretical analysis within the DEA [18]. This reaction model is based on the eikonal approximation. However it does not include the adiabatic approximation, considered in the usual eikonal model. This enables us to consider Coulomb and nuclear interactions on the same footing [18]. The DEA has been used to successfully describe reactions involving one-nucleon halo nuclei [18, 19]. As mentioned above, it has been used to interpret the ^{8}B breakup measurements of Davids *et al.* [5]. The DEA is thus the ideal tool to analyse the FLUBBER experiment.

In the DEA description of the reaction, we consider a two-body model of the ^{17}F projectile: an ^{16}O core in its 0^+ ground state to which a proton is loosely bound. The interaction between both clusters is simulated by the potential developed in Ref. [14]. This potential reproduces the $5/2^+$ ground state of ^{17}F in the $0d5/2$ orbital and the $1/2^+$ excited bound state in the $1s1/2$ orbital (see the right panel of Fig. 2). The former is bound by 600 keV, while the latter is a mere 100 keV below the one-proton separation threshold. This small binding energy and the absence of centrifugal barrier in the $1/2^+$ excited state, makes it a candidate one-proton halo state. The potential of Ref. [14] also reproduces in the $d3/2$ partial wave the $3/2^+$ resonance located at 4.4 MeV in the continuum. The interaction between the projectile constituents and the lead target are simulated by optical potentials. The ^{16}O-Pb interaction is approximated by the potential developed by Roussel-Chomaz *et al.* [21], which describes the ^{16}O-Pb elastic scattering at 94*A*MeV. We neglect the energy dependence of the potential parameters. The p-Pb potential is chosen as the Koning-Delaroche parametrisation [20]. The numerical inputs are similar to those used in the DEA calculation of ^{8}B breakup [9].

In the left panel of Fig. 2, we display the DEA breakup cross section for ^{17}F impinging on Pb at 40*A*MeV as a function of the relative energy E between the valence proton and the ^{16}O core after dissociation. Contributions of the dominant partial waves (p, d, and f) are displayed as well. To simulate a selection of the events at forward angles, we use an impact-parameter cutoff at $b_{\rm min} = 40$ fm. As illustrated in the left panel of Fig. 1, this enables us to remove most of the effects of the nuclear interaction between the projectile and the target. The solid lines correspond to the DEA calculations. As expected, the dominant contribution comes from p and f waves. These partial waves in the continuum can indeed be directly populated from the initial d bound

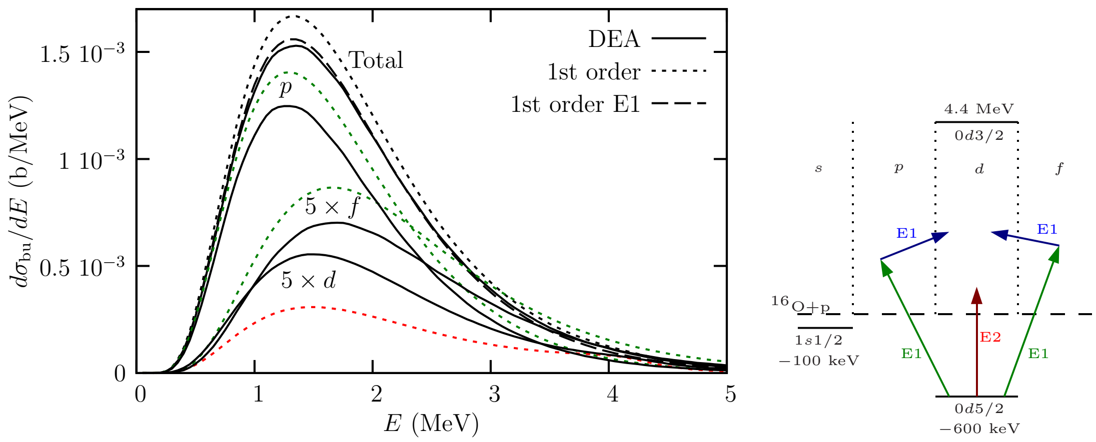

Figure 2: Left: Theoretical prediction of the breakup cross section of ^{17}F on lead at 40*A*MeV limited to forward angles as a function of the relative ^{16}O-p energy after dissociation. Right: Schematic view of the dominant transitions from the initial bound state, and inside the continuum (see text).

state through E1 transitions (green arrows in the right panel of Fig. 2). However, we also observe a significant contribution of the *d* waves, whose population in the continuum cannot be accounted for by a mere E1 transition from the ground state. A simple way to explain the presence of such a *d*-wave contribution is by considering an E2 transition from the ground state (red arrow in the right panel of Fig. 2). This confirms the studies on ^{8}B, which show the significance of higher-order multipolarities illustrated in the central panel of Fig. 1 [5, 9, 10, 11]. To test this simple description of the reaction mechanism, we also perform a calculation at the first-order of the perturbation theory [12] (dotted lines in the left panel of Fig. 2). As already observed in a theoretical analysis of the Coulomb breakup of ^{8}B, this first-order cross section is larger than the DEA one [11]. This indicates a significant effect of higher-orders in the reaction process even though the calculations are restricted to large impact parameters. Interestingly this overestimation of the cross section does not appear in all partial waves: Whereas *p* and *f* contributions are overestimated at the first order of the perturbation theory, the *d* wave is underestimated in this theory. This suggests that the partial waves populated by E1 transitions from the initial bound state are subsequently depopulated towards the *d* waves by E1 couplings in the continuum (blue arrows in the right panel of Fig. 2). This higher-order way to reach the *d* continuum may partially interfere destructively with the direct E2 transition, hence explaining the overestimation of the total breakup cross section at the first order of the perturbation theory. Curiously the total DEA cross section is rather well reproduced by the first-order, purely E1 calculation (dashed line in the left panel of Fig. 2). However, as E2 transitions and higher-order effects are not negligible, the extraction of an E1 strength from breakup data, as proposed in Refs. [2, 3], will lead to an underestimation of the cross section for the radiative-capture at stellar energies [11].

This preliminary theoretical analysis confirms previous calculations performed on ^{8}B [9, 10, 11]. It therefore suggests that the original idea of the Coulomb-breakup technique, i.e. the mere extraction of an E1 strength from breakup data, is subject to caution due to non-negligible effects of E2 transitions and couplings inside the continuum. The idea of the FLUBBER experiment is to

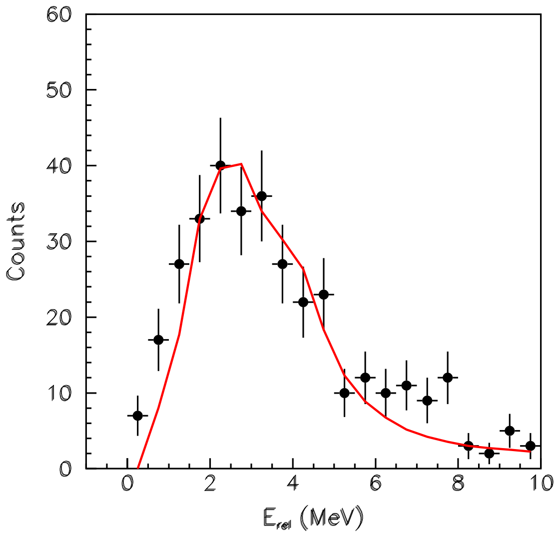

Figure 3: Preliminary experimental energy distribution for the breakup of ^{17}F on lead at 40*A*MeV (arbitrary units). The theoretical DEA prediction folded with the detector resolution is shown as the solid line.

confirm this theoretical interpretation of the reaction mechanism by comparing DEA calculations to accurate experimental Coulomb-breakup data of ^{17}F.

4. Preliminary data

4.1 Energy distribution

The data acquired in 2009 are currently under analysis. However, preliminary data are now available, which provides a first test of the DEA calculations. In Fig. 3, the experimental energy distribution, plotted in arbitrary units, is compared to the theoretical prediction folded with the detector resolution (solid line).

The agreement between theory and experiment is excellent, which confirms the analysis detailed in Sec. 3. However, since E2 transitions and couplings in the continuum affect mostly the magnitude of the energy distribution, definite conclusion about our analysis cannot be drawn before an absolute cross section is extracted from the data.

4.2 Parallel-momentum distribution

To have an idea of the effect of E2 transitions in the breakup process, we follow Davids *et al.* [5], and extract the breakup cross section as a function of the ^{16}O parallel momentum. The resulting parallel-momentum distribution is plotted in arbitrary units in Fig. 4 for three cuts on the ^{17}F scattering angle.

As in Ref. [5], we observe a significant asymmetry in the data. As first suggested by Esbensen and Bertsch [8], this is a signature of E2 transitions (see also central panel of Fig. 1). However, as illustrated in the right panel of Fig. 1, higher orders tend to reduce this asymmetry [8, 9]. A full analysis of the relative contributions of these two effects requires the extraction of absolute cross

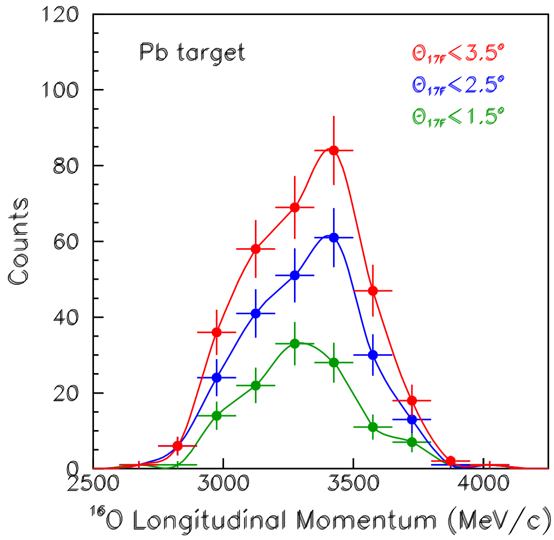

Figure 4: Preliminary experimental breakup cross section as a function of the ^{16}O parallel momentum after the dissociation of ^{17}F on Pb at 40*A*MeV (arbitrary units). Data are obtained for three different cuts on the ^{17}F scattering angle. The lines are only to guide the eye.

sections from these experimental data and their comparison with DEA calculations. Nevertheless, these preliminary data confirm previous analyses of ^{8}B Coulomb breakup that indicate significant E2 transitions in the reaction mechanism.

5. Summary

Coulomb breakup has been proposed as an indirect technique to infer radiative-capture cross sections at stellar energies [2, 3]. Analyses of ^{8}B Coulomb-breakup measurements suggest that two of the assumptions of this indirect technique are not satisfied. First, E2 transitions do not seem to be fully negligible, and second, higher-order effects also seem significant. However, ^{8}B is not the ideal test case for the Coulomb-breakup technique as its complex structure may influence the reaction dynamics. On the other hand, ^{17}F is much better suited for such a test: the direct radiative capture $^{16}\mathrm{O}(\mathrm{p},\gamma)^{17}\mathrm{F}$ has been precisely measured down to low energies [13], and ^{17}F is very well described as a spherical ^{16}O core in its 0^{+} ground state to which a proton is loosely bound [14]. The only missing piece for such an analysis is ^{17}F Coulomb-breakup data.

At the LNS, we have performed the FLUBBER experiment to measure the Coulomb breakup of ^{17}F. We hope to better understand the reaction mechanism and clarify the roles played by E2 transitions and higher-order effects in breakup observables. Preliminary data are in excellent agreement with theoretical predictions, indicating the presence of significant E2 transitions and couplings in the continuum in the reaction process. Analysis of various breakup observables are planned to confirm the reaction mechanism.

In a near future, we plan to compare the radiative-capture cross section extracted from our Coulomb-breakup data in the original idea of Ref. [2] and the values measured directly to evaluate the accuracy of this indirect technique.

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