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Flubber experiment: measuring ^{17}F Coulomb breakup

P. CAPEL[*]
National Superconducting Cyclotron Laboratory
Michigan State University
East Lansing, MI 48824, USA
E-mail: `capel@nscl.msu.edu`

C. SFIENTI, G. CARDELLA, M. DE NAPOLI, F. GIACOPPO, G. RACITI, E. RAPISARDA
Università di Catania and INFN - Sez. Catania
64, Via S. Sofia
I-95123 Catania, Italy

C. MAZZOCCHI
Università degli Studi di Milano and INFN - Sez. Milano
via Celoria 16
I-20133 Milano, Italy

D. BAYE, P. DESCOUVEMONT, J.-M. SPARENBERG
Physique Quantique et Nucléaire (CP 229)
Université Libre de Bruxelles
B-1050 Brussels, Belgium

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, the breakup of ^{17}F has been measured on lead and carbon targets at 40 MeV/nucleon. We plan to evaluate the accuracy of the indirect technique by comparing the radiative-capture cross section inferred from the Coulomb-breakup data to accurate direct measurements. The motivation of this measurement is reported as well as the experimental setup and a preliminary theoretical study.

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[*]Speaker.

1. Introduction

Dissociation of the atomic nucleus using energetic beams is nowadays an essential tool in several domains of nuclear physics. It is one of the few methods used to study the structure of nuclei far from stability, like halo nuclei [1]. It has also been proposed as an indirect technique to measure radiative-capture cross sections at stellar energies [2, 3], e.g., $^7\mathrm{Be}(\mathrm{p},\gamma)^8\mathrm{B}$. At these energies, the Coulomb barrier between the interacting nuclei hinders the capture, leading to so tiny cross sections that they cannot be measured in laboratories. Usually low-energy measurements are extrapolated down to the energy of the Gamow peak through reaction models. Unfortunately, this method is not free from biases. This has lead to the search for indirect techniques like the Coulomb breakup. In that technique, the final nucleus synthesized in the radiative capture (^{8}B in the aforementioned example) is broken up into the initial nuclei (^{7}Be and p in the example) by interaction with a heavy target. This reaction, being Coulomb dominated, may be seen as due to the exchange of virtual photons between the projectile and the target, and hence as the time-reversed reaction of the radiative capture. The basic idea of the Coulomb-breakup technique is thus to extract the radiative-capture cross section from the Coulomb breakup one via a detailed balance [3]. However, this can only be done under a few assumptions. First, the reaction must be purely Coulomb, i.e. the nuclear interaction between the projectile and the target must be negligible. Second, the radiative capture being dominated by E1 transitions at stellar energies, the influence of higher multipoles of the Coulomb interaction in the breakup process must be negligible. Finally, the direct link between the Coulomb-breakup cross section and the radiative capture one can only be made at the first order of the perturbation theory [4]. The dissociation must thus occur in one step from the bound state to the continuum, i.e. higher-order effects like couplings inside the continuum must be negligible.

Several Coulomb-breakup experiments of ^{8}B have been performed to extract the cross section of the reaction $^7\mathrm{Be}(\mathrm{p},\gamma)^8\mathrm{B}$, which is a significant input for the study of solar-neutrino oscillations [5, 6]. Unfortunately, theoretical analyses suggest that E2 transitions [7, 8] and higher-order effects [7, 8, 9, 10] are not negligible. To assess the accuracy of the Coulomb technique, it is necessary to compare the cross section measured directly with the prediction obtained from a Coulomb-breakup measurement. Though extensively studied [5, 6, 7, 8], ^{8}B is not the best test case for this comparison. The direct measurements, being scattered over a wide range of values, are too discrepant for such a comparison. Moreover, the structure of ^{8}B is rather complicated and not well described as a proton loosely-bound to a structureless ^{7}Be, as assumed in most of the reaction models. On the contrary, the ^{17}F case is well suited for such a study [3]: The direct radiative capture $^{16}\mathrm{O}(\mathrm{p},\gamma)^{17}\mathrm{F}$ has been precisely measured down to 200 keV [11]. The nucleus ^{17}F, being just one proton away from the doubly magic ^{16}O, is well described as an ^{16}O core to which a proton is loosely bound [12]. Moreover, there is no resonance in the low-energy spectrum of ^{17}F that could influence the radiative-capture process at stellar energies. The only missing ingredient for this analysis is the Coulomb-breakup cross section, which is the aim of the Flubber experiment.

The Flubber experiment has been proposed—and accepted—at the Laboratori Nazionali del Sud (LNS, Catania). It took place at the end of May 2009, and the data are currently under analysis. In this contribution, we present the experimental setup used for this measurement and a preliminary theoretical analysis of the reaction.

2. Experimental setup

The ^{17}F beam required for the experiment has been produced at the in-Flight Radioactive Ion Beams (FRIBs) facility of the LNS [13]. This secondary beam is obtained by fragmentation on a 500 μm thick ^{9}Be primary target of a primary beam of ^{20}Ne delivered at 45 MeV/nucleon by the K800 Superconductor Cyclotron of the LNS. This produces a mixture of radioactive isotopes at an energy of about 40 MeV/nucleon, among which one finds ^{17}F. This radioactive cocktail passes in a fragment separator, that makes a first selection among the nuclei synthetised according to their magnetic rigidity. The data have been collected on an event by event basis, and the final selection of ^{17}F is done off-line by means of the energy loss and the time-of-flight of the isotopes measured in a 300 μm thick Double-Sided Silicon Strip Detector (DSSSD) placed ahead of the secondary target. The rate for ^{17}F at the secondary target is about 3 10^3 pps.

We use two different secondary targets: a lead one and a carbon one in order to study both Coulomb- and nuclear-induced reactions. The detection setup, placed at about 80 cm from the interaction target, consists of two Si-CsI hodoscopes, that cover the angular range between $\theta_{\rm Lab} = 0^\circ$ and 21.5° with high granularity and excellent isotopic resolution. The first is composed by 81 two-fold telescopes (300 μm Si detector 1×1 cm^2 of active area followed by a 10 cm long CsI(Tl)) covering the forward angular range $\theta_{\rm Lab} < 5^\circ$. The second consists of 89 three-fold telescopes ($50 + 300$ μm Si detectors 3×3 cm^2 active area followed by a 6 cm long CsI(Tl)) covering the angular range between $\theta_{\rm Lab} = 5^\circ$ and 21.5°. This experimental setup has already been used in the study of diproton decay of ^{18}Ne [14]. It allows the measurement, event-by-event, of the transverse coordinates of the interaction point on the target as well as of the momenta and angles of all outgoing decay particles in a solid angle of 0.34 sr around the beam direction with a geometrical efficiency of 72%. This set-up is thus well optimized for the measurement of the ^{17}F excitation energy as well as the individual and relative momenta, energies and angles of the two detected fragments (^{16}O and proton), with a resolution of approximately 300 keV.

3. Theoretical predictions

In parallel to the measurements, we have performed a preliminary theoretical analysis of this reaction. The model considered is the Dynamical Eikonal Approximation (DEA) [15]. It corresponds to the eikonal approximation without the adiabatic approximation, which is usually subsequently made. The DEA therefore takes full account of the internal dynamics of the projectile, which enables us to describe both nuclear- and Coulomb-dominated reactions within one model. It has successfully described various reactions involving loosely-bound nuclei [15, 8]. In particular the DEA could explain most of the features of the observables measured in Coulomb-breakup experiments of ^{8}B at intermediate energies [8]. This makes thus the DEA the ideal theoretical model to analyse the Flubber experiment.

We describe ^{17}F as a proton loosely bound to an ^{16}O core, assumed to be in its 0^+ ground state. The interaction between these two clusters is described by a Woods-Saxon potential fitted to reproduce the energy and quantum numbers of the two bound states of ^{17}F [12]. The $5/2^+$ ground state at 600 keV below the one-proton separation threshold is modelled as a $0d5/2$ state, while the $1/2^+$ excited bound state bound by a mere 100 keV is described as a $1s1/2$ state. The potential

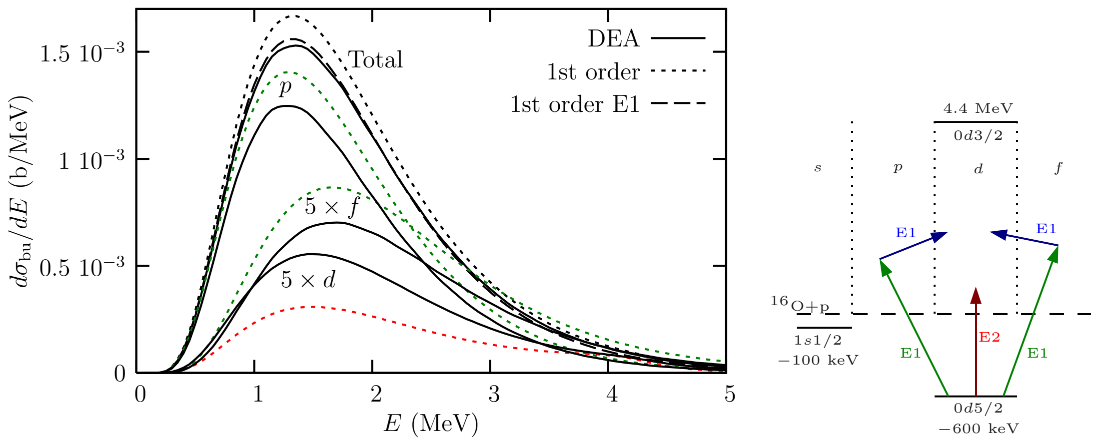

Figure 1: Left: Theoretical prediction of the breakup cross section of ^{17}F on lead at 40 MeV/nucleon limited to forward angles as a function of the relative ^{16}O-p energy after dissociation. Right: Schematic view of the dominant transitions from the initial bound state, and inside the continuum (see text).

also reproduces the $3/2^+$ resonance at 4.4 MeV above the one-proton separation threshold in the $d3/2$ partial wave. The interaction between the two components of the projectile with the target are simulated by optical potentials chosen in the literature. For the p-target potential, we consider the global parametrisation of Koning and Delaroche [16]. For the ^{16}O-target interaction, we adopt the optical potentials developed by Roussel-Chomaz *et al.* [17] to describe the elastic scattering of ^{16}O on various targets at 94 MeV/nucleon. We neglect the energy dependence in the latter case.

The left-hand side of Fig. 1 displays the theoretical prediction for the breakup cross section of ^{17}F on lead at 40 MeV/nucleon as a function of the relative energy E between ^{16}O and the proton after dissociation. A forward-angle selection is simulated by an impact parameter cutoff at $b_{\rm min} = 40$ fm. The contribution of the major partial waves are shown as well. The full lines correspond to the DEA calculation, while the dotted lines are the results obtained at the first-order of the perturbation theory [4]. As can be seen, the reaction is dominated by E1 transitions from the d ground state to the p and f continua. However, we note a non-negligible d contribution that can be explained at the first-order only by E2 transitions. We also observe that the first-order calculation differs from the dynamical one: The former indeed overestimates the latter. However, this overestimation is not observed in all partial waves. Indeed, while both the p and f contributions are overestimated at the first-order (green lines), the d wave (red line) is underestimated. In agreement with a previous study [10], we interpret this as a signature of higher-order effects sketched in the right-hand side of Fig. 1. In these higher-order effects, the p and f continua, directly populated from the ground state by E1 transitions (green arrows), are depopulated towards the d partial waves through E1 couplings inside the continuum (blue arrows). These higher-order effects increase the population of the d waves in the continuum already fed by direct E2 transitions from the bound state (red arrow). Curiously the dynamical calculation is rather well simulated by a first-order calculation including only E1 transitions (dashed line in the left-hand side of Fig. 1), as already noted in an analysis of ^{8}B breakup [10].

This preliminary study suggests that all the conditions for the original Coulomb-breakup technique to be valid are not fulfilled. Indeed, both E2 transitions, and higher-order effects cannot be neglected. It remains to confirm these effects by comparing the experimental data to these theoretical predictions. As suggested in previous analyses of ^{8}B breakup, they may explain the systematic discrepancy between direct and indirect measurements of the cross section of the radiative capture $^{7}\mathrm{Be}(\mathrm{p},\gamma)^{8}\mathrm{B}$ [9, 10].

4. Conclusion

The Flubber experiment has been performed with the aim of testing the accuracy of the Coulomb-breakup indirect technique used to infer radiative-capture cross sections at low energies. This technique has been used in the $^{7}\mathrm{Be}(\mathrm{p},\gamma)^{8}\mathrm{B}$ case [5, 6], but has never been tested. By measuring the breakup of ^{17}F into ^{16}O+p, and comparing the inferred cross section for $^{16}\mathrm{O}(\mathrm{p},\gamma)^{17}\mathrm{F}$ to direct precise measurements [11], we hope to evaluate the influence of E2 transitions and higher-order effects, that are theoretically predicted to be significant in Coulomb-breakup reactions [9, 10]. The measurements, performed in 2009, are currently under analysis.

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