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Breakup of proton-rich nuclei ^{24}Si, ^{23}Al, ^{22}Mg, ^{21}Na at intermediate energies for reaction rates in explosive H-burning in novae

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We discuss the use of one proton-removal reactions of loosely bound nuclei at intermediate energies as an indirect method in nuclear astrophysics, with particular reference to the results of a GANIL experiment with a cocktail beam around ^{23}Al at 50 MeV/nucleon. Momentum distributions of the core fragments, inclusive and in coincidence with gamma rays detected with EXOGAM, were measured. From them we determine mixing ratios in the structure of the ground states of the projectile nuclei and the asymptotic normalization of their wave functions. The method has the advantage that can be used for beams of low quality, such as cocktail beams, and intensities as low as a few pps. The proton breakup reactions provide information to determine astrophysical (p,γ) reaction rates that are outside the reach of other direct or indirect methods, or complementary information to the use of transfer reactions (the ANC method) which require radioactive beams of much better purity and intensity. Preliminary results on proton breakup of ^{24}Si, ^{23}Al, ^{22}Mg and ^{21}Na will be presented.

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[1] Speaker

1. Introduction

An important challenge of direct nuclear astrophysics measurements at low energies stems from the very low cross sections when reactions between charged particles are involved, due to Coulomb repulsion. This is, for example, the case with radioactive proton capture (p,γ) reactions occurring in H-burning. Another challenge in the direct study of stellar reactions in general is that in most cases the targets involved are unstable nuclei. These two reasons combined lead to the use of indirect methods.

A number of indirect methods have been proposed and used for nuclear astrophysics, with some of them adopted from general nuclear physics studies and some tailored specifically for this purpose. The list, however, is not very long: Coulomb dissociation [1,2], transfer reactions (the ANC method) [3], breakup at intermediate energies [4,5], the Trojan horse method [6], and other spectroscopic methods, in particular the location and study of resonances.

We will discuss in the following the breakup method with its characteristics and advantages for radioactive ion beams, emphasizing a recent breakup experiment that we carried out at GANIL in France.

2. Breakup reactions = Spectroscopic tool

Work done in the last decade in several laboratories has demonstrated that one-nucleon removal reactions (or breakup reactions) can be a good and reliable spectroscopic tool. In a typical experiment, a loosely bound projectile impinges on a target and loses one nucleon. The momentum distributions (parallel/or transversal) of the measured remaining core give information about the momentum distribution of the removed nucleon in the wave function of the ground state of the projectile. The shape of the momentum distributions allow to determine the quantum numbers *nlj* of the single particle (s.p.) wave function. This type of measurements was made mostly for neutron-rich nuclei related to the problem of halo nuclei, and results are summarized in a quite a few publications of which we mention Refs. [7, 8]. Figure 1 of Ref. [8] is a good illustrative example showing a number of parallel momentum distributions measured for $^{14-18}$C isotopes at energies around 50 MeV/nucleon. A “normal” momentum distribution in ^{14}C, a very narrow one in ^{15}C, pointing to a large spatial extension (halo nucleus), an $s_{1/2}$ neutron state, and one distribution reflecting configuration mixing in ^{17}C, are all seen in neighboring isotopes. Far fewer cases of proton-rich nuclei were studied so far, primarily because the Coulomb barrier prevents extended proton halos. Our GANIL E491 experiment was dedicated to the study of nuclei close to the proton dripline.

It was shown in Ref. [4] that breakup reactions are very peripheral and was demonstrated that the integrated breakup cross sections can be used to extract the asymptotic normalization coefficients (ANCs) of the s. p. wave function (in this context, peripheral means that in the wave function of the projectile, the large distances between the proton and the core give the major contribution). For this to be correct, we need careful reaction model calculations. They need to reproduce all available data from such measurements if they are to be trusted. We have investigated this aspect in detail in Ref. [5]. The definition of the ANC is presented in Ref. [3].

It was shown earlier [9, 10] that the s. p. quantum numbers and the above mentioned ANCs are sufficient to determine the astrophysical *S* factors for radiative proton capture reactions, due to the peripheral character of these captures.

3. Breakup reactions in nuclear astrophysics

3.1 Breakup of ^{8}B: an independent determination of $S_{17}(0)$

It was shown in Refs. [4, 5] that using all available ^{8}B one-proton removal data existent at that time in the literature one can determine the ANC of its ground state wave function. The data were obtained in different laboratories, with various methods and setups, on targets ranging from light (^{9}Be) to heavy (^{208}Pb) and at energies between 28 and 1000 MeV/nucleon. They were analyzed using Glauber model type calculations, in a potential approach and in the optical limit, with various effective nucleon-nucleon (NN) interactions appropriate for the energies of each case, but with no new parameters. The authors have also verified that all measured momentum distributions are reproduced by the calculations before using them to extract absolute values for the ANC of ^{8}B g.s.

The following two conclusions were drawn: (1) a consistent ANC value was extracted from all experiments, and (2) there was a certain dependence on the effective interactions used which sets a limit of about 10% on the accuracy of the ANC values we can obtained with this method. The average ANC value obtained was used to determine the astrophysical *S* factor for the ^{7}Be(p,γ)^{8}B reaction, the crucial reaction for the production of solar neutrinos. The value found $S_{17}(0) = 18.7 \pm 1.9$ eVb, is slightly lower than other measurements made by direct and indirect methods, but consistent (within the error bars) with their average. As possible systematic errors are totally different here, this independent determination has its importance.

3.2 Breakup of ^{9}C: a case where breakup has no competition

Relatively scarce (and not very precise) data exist on the breakup of ^{9}C. From them we have determined the ANC of the last proton in ^{9}C and evaluated the $S_{18}(0)$ astrophysical factor for the ^{8}B(p,γ)^{9}C reaction [11]. The reaction is important in the hot pp chains. The method used is the one sketched above, except that here no momentum distributions were available to check the calculations and the experimental errors are larger than the differences found between the calculations made with several effective NN interactions. Rather, the remarkable fact here is that virtually no other types of measurements were possible to date and probably even in future. The data competing here are from nuclear [11] and Coulomb breakup [12].

3.3 Breakup of ^{23}Al: to determine ANCs and configuration mixing

Space-based gamma-ray telescopes have had for some time the ability to detect gamma rays of cosmic origin, proving that nucleosynthesis is an ongoing process in our own Galaxy. Gamma rays following the β-decay of long-lived ^{26}Al, ^{44}Ti, ^{56}Ni, etc., have been detected. It was also predicted that ^{22}Na ($T_{1/2}$ = 2.6 y) is produced in enough amounts in the thermonuclear runaway of the so-called ONe (Oxygen-Neon) novae [13] so that its decay gamma-ray line $E\gamma$= 1275 keV to be observed at the sensitivity level of current satellite based telescopes. However, this is not the case. The arising question is why? Maybe nuclear reaction rates are not precise enough! Two reactions were proposed as mechanisms for the depletion of ^{22}Na or its precursor ^{22}Mg: ^{22}Na(p,γ)^{23}Mg and ^{22}Mg(p,γ)^{23}Al.

The ground state spin and parity of ^{23}Al was uncertain before our experiments. It was important for both nuclear structure and nuclear astrophysics to determine unambiguously the spin and parity of the ground state of ^{23}Al. We proposed to do it in two ways. One way was by measuring the core momentum distribution from ^{23}Al breakup at intermediate energies. The other way was to use β-decay measurements [14].

Here we present only preliminary results of the ^{23}Al breakup experiment, which was proposed at GANIL that could determine the spin and parity, the ANC and the configuration mixing in the ground state of ^{23}Al from measurement of the momentum distribution of the ^{22}Mg core after the proton breakup on a light target. The experiment was carried out using a special setup: eight Ge clover detectors of EXOGAM were arranged in a new configuration at the target position of the magnetic spectrograph SPEG. Also 12 NaI detectors were included in the system. The primary beam 95 MeV/nucleon ^{32}S was delivered on a 450 mg/cm^2 carbon target in SISSI. The beam analyser following SISSI was tuned for ^{23}Al secondary beam at a magnetic rigidity Bρ = 1.95 Tm which gave about 15 kHz of secondary beams on the SPEG target (C at 185 mg/cm^2), a cocktail made mostly of ^{24}Si, ^{23}Al, ^{22}Mg and ^{21}Na, with ^{23}Al at 50 MeV/nucleon being about 1.7% of the total. With SPEG tuned at 1.75 Tm, we measured the momentum distributions (inclusive and in coincidence with gamma rays) for the cores of the beam nuclei after the removal of one proton. We show here in Figure 1 (left-hand side) preliminary results for the inclusive momentum distributions (in the center-of-mass) for the core fragments: ^{23}Al, ^{22}Mg, ^{21}Na, ^{20}Ne.

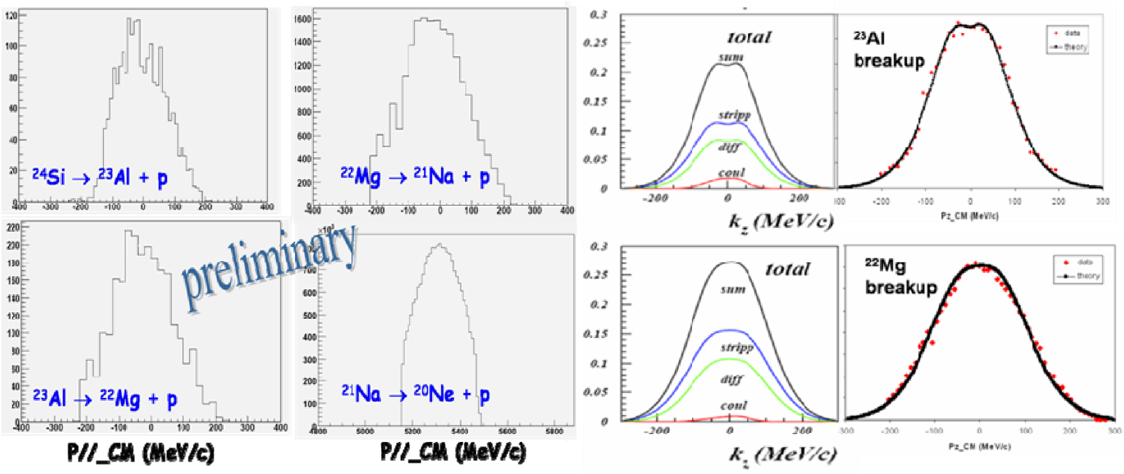

Figure 1: (left-hand side) Inclusive momentum distributions (center-of-mass reference) for core breakup fragments of ^{24}Si, ^{23}Al, ^{22}Mg, ^{21}Na. (right-hand side) Comparison between theory (extended Gluaber model [15]) and data for the case of ^{23}Al breakup for which the proton ground state configuration is dominated by a $1d_{5/2}$ state, and for the case of ^{22}Mg breakup which ground state configuration is a mixing between $1d_{5/2}$ and $2s_{1/2}$ orbitals. The theory is reproduced very well the shape of the experimental inclusive core fragment momentum distributions.

In Figure 1 (right-hand side) we compare momentum distributions calculated within the formalism of an extended Glauber breakup model [15] with experimental inclusive momentum distributions for the ^{22}Mg and ^{21}Na (as an example) core fragments resulted from the breakup of

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^{23}Al and ^{22}Mg, respectively. Data analysis is at a preliminary stage, however the first results are promising enabling us to conclude that the method works and we will be able to extract ANCs for a number of other nuclei present in the beam cocktail (14 species in total). Those ANCs will be used to determine direct capture astrophysical *S* factors and rates relevant for reactions in H-burning, all impossible to determine from any other measurements. This is the main advantage of breakup reactions at intermediate energies: it can be used for cocktail beams of low quality. Some of them, like ^{24}Si and ^{23}Al, cannot be easily studied with other methods; for others cases, valuable complementary information will be obtained.

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