The structure of ^{23}Al and ^{24}Si nuclei from proton breakup at intermediate energies

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This report is a follow-up of Ref. [1] in which we described the use of one proton-removal reactions of loosely bound nuclei at intermediate energies as an indirect method in nuclear astrophysics. We presented the E491 experiment carried out at GANIL that investigated reactions produced by a cocktail beam around ^{23}Al at 50 MeV/nucleon. Here we emphasize the results of the study of ^{23}Al and ^{24}Si nuclei from proton breakup in that experiment. These breakup reactions provide information on H-burning reaction rates for ^{22}Mg(p,γ)^{23}Al and ^{23}Al(p,γ)^{24}Si, important in novae and X-ray bursts, respectively [1]. To obtain those reaction rates from the data, we applied the ANC method [2, 3].

In the experiment E491 at GANIL, a primary ^{32}S beam at 95 MeV/u impinged on a C target and SISSI was used to separate 14 secondary beams at 1.95 Tm rigidity. They impinged on another C target at the entrance of the spectrometer SPEG that was tuned to measure the momentum of the cores after one-proton removal. EXOGAM detectors were positioned around the target. All these are illustrated in Fig. 1.

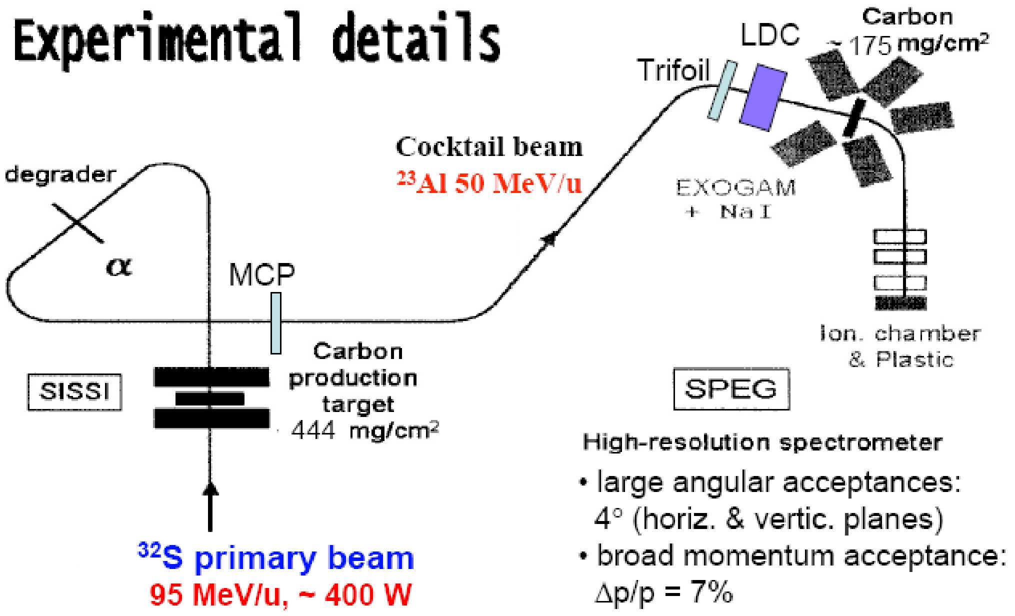

FIG. 1. Experimental setup for the E491 run at GANIL. See text for details.

Momentum distributions of the core breakup fragments, inclusive and in coincidence with gamma-rays, were measured. From them, we have determined configuration mixing in the structure of the ground states of the projectile nuclei.

In the following, we present results for the structure of ^{24}Si and ^{23}Al nuclei. Fig. 2 shows the gamma lines detected by EXOGAM in coincidence with the fragments resulting from the breakup of ^{23}Al. An add-back procedure was implemented and used here to increase the gamma-ray detection efficiency, and the spectrum is corrected for Doppler shift. The lines observed correspond to transitions in ^{22}Mg implying that the ^{22}Mg breakup core is left in various excited states after the removal of the least bound proton. That provides us with information about the configuration mixing that characterizes the ground state of ^{23}Al. We observe clearly three gamma lines: 1247.0 keV ($2_1^+ \rightarrow 0_{gs}^+$), 2061.1 keV ($4_1^+ \rightarrow 2_1^+$), and 1984.8 keV ($(3^+,4^+,5^+) \rightarrow 4_1^+$), attesting for a large and complex configuration mixing.

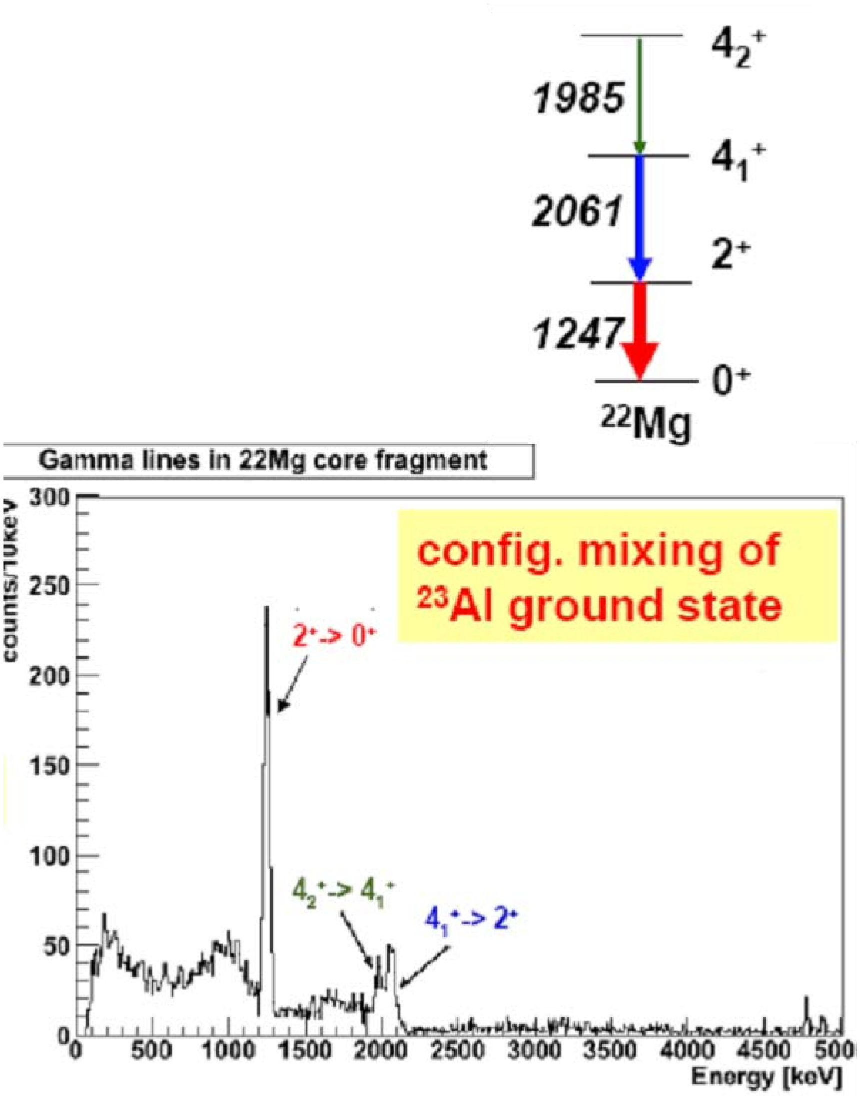

FIG. 2. Measured gamma lines (Doppler corrected) de-populating excited states in ^{22}Mg breakup fragments: 1246.98 keV, 1984.8 keV, and 2061.09 keV giving us information about the configuration mixing characterizing the ground state of ^{23}Al.

We did not observe gamma rays de-populating excited states from ^{23}Al as breakup core of ^{24}Si projectile implying that the ground state of ^{24}Si is built upon a configuration in which ^{23}Al core is left in its ground state after the one-proton removal process. Also, ^{23}Al has no bound excited states.

In Fig. 3 we present inclusive center-of-mass differential cross-sections for ^{23}Al and ^{24}Si proton breakup reaction as measured in this experiment, and compare them with theoretical calculations carried out with an extended version of the Glauber model [4].

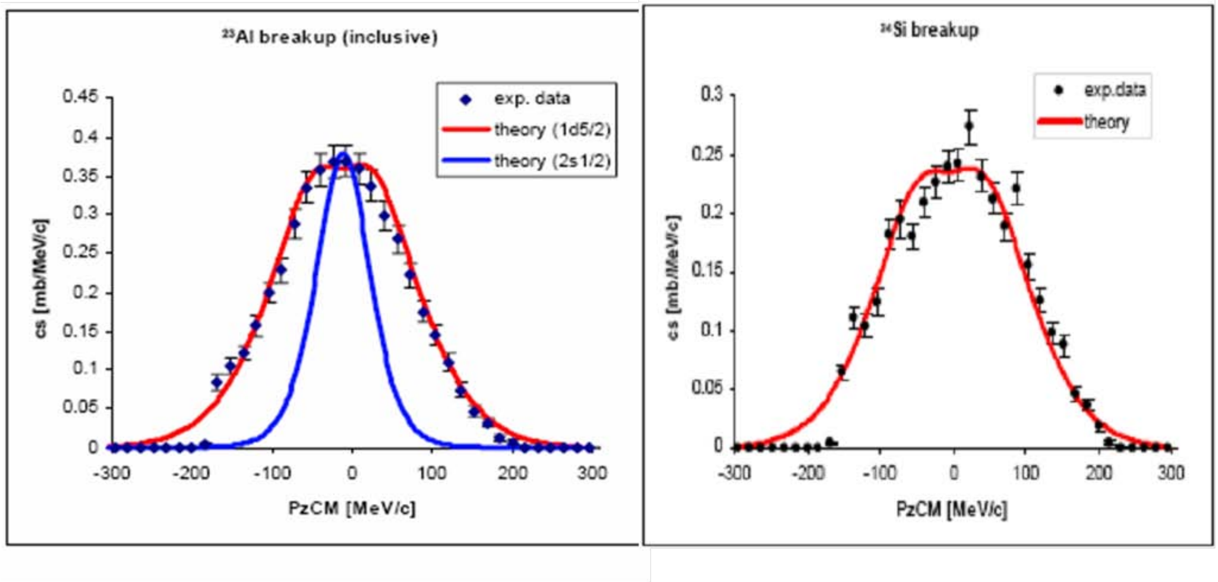

FIG. 3. Experimental inclusive differential cross-sections obtained for ^{23}Al (left) and ^{24}Si (right) one-proton breakup compared with theoretical calculations of Glauber-type model involving JLM effecting nucleon-nucleon interactions. See text for details.

In the case of ^{23}Al proton breakup, the measured momentum distributions for the ^{22}Mg core fragment agree in shape with the calculations that assume a $1d_{5/2}$ orbital (red line in Fig. 3) and do not agree with the calculations assume a $2s_{1/2}$ orbital (blue line in Figure 3). This confirms the ground state spin and parity for ^{23}Al to be $J^{\pi} = 5/2^{+}$, not $1/2^{+}$, a distinction very important for the rate of the astrophysical reaction ^{22}Mg(p,γ)^{23}Al, implying that direct proton capture on the ^{22}Mg in the ground state of ^{23}Al can not support the depletion of ^{22}Na in novae environments [5]. This was the original motivation of the experiment. Based on the mixing found in our measurement we can determine the ^{23}Al ground state wave function with the following configuration:

$$\left|{}^{23}Al(5/2^{+})\right\rangle_{gs} = A_1\Big\|core(0^{+}_{gs})\Big\rangle\otimes\Big|p(1d_{5/2})\Big\rangle\Big\rfloor_{5/2^{+}} + A_2\Big\|core(2^{+}_{1})\Big\rangle\otimes\Big|p(1d_{5/2})\Big\rangle\Big\rfloor_{5/2^{+}} + A_3\Big\|core(4^{+}_{1})\Big\rangle\otimes\Big|p(1d_{5/2})\Big\rangle\Big\rfloor_{5/2^{+}} + A_4\Big\|core(4^{+}_{2})\Big\rangle\otimes\Big|p(1d_{5/2})\Big\rangle\Big\rfloor_{5/2^{+}}$$

Here *core* refers to ^{22}Mg and *p* rfers to the removed proton, the two-body system that can characterize the ground state of the loosely bound ^{23}Al nucleus in the breakup process. The A_i (i=1-4) coefficients squared have the physics interpretation of spectroscopic factors that determine the orbital configuration mixing in ^{23}Al ground state wave function. It is this expression of the ^{23}Al ground state wave function that translates into the breakdown of the inclusive differential cross-section into four components of exclusive differential cross-sections.

The component of differential cross-section for ^{23}Al breakup of astrophysical interest can be determined by subtracting the three exclusive experimental differential cross-sections (each obtained in coincidence with the corresponding γ-ray line of the three γ-ray lines detected) from the inclusive experimental differential cross-section.

By comparison between experimental differential breakup cross-sections and the corresponding theoretical calculations, we extract the squared asymptotic normalization coefficients for the two-body systems – core plus valence proton – under investigation here.

Hence, in the case of ^{23}Al one-proton removal, we obtained a squared ANC with a value of $C^2(1d_{5/2})=4.4*10^3$ fm^{-1}. The corresponding spectroscopic factor was determined to be 0.5 for the configuration with ^{22}Mg core in ground state and the valence proton occupying the $1d_{5/2}$ orbital (and assuming a proton binding potential with r_0 = 1.20 fm and a = 0.65fm). The value obtained in this experiment for the ANC is in excellent agreement with the value of $(4.63 \pm 0.77)*10^3$ fm^{-1} extracted from neutron transfer on the mirror nucleus ^{23}Ne [6]. In the of ^{24}Si one-proton removal, we obtained a squared ANC with a value of $C^2(1d_{5/2})=62.4 \pm 7.1$ fm^{-1} for a similar proton binding potential, and a corresponding spectroscopic factor of 2.7.

Based on the values of ANCs extracted from our data of ^{24}Si and ^{23}Al proton breakup reactions, we determine the astrophysical S-factors and from there calculate the reaction rates for direct radiative captures ^{22}Mg(p,γ)^{23}Al and ^{23}Al(p,γ)^{24}Si in the stellar temperature and density environments such as novae and X-ray burst. Details about these evaluations can be found soon here [7].

[1] A. Banu *et al.*, *Progress in Research*, Cyclotron Institute, Texas A&M University (2008-2009), p. I-13

[2] L. Trache *et al.*, Phys. Rev. Lett. **87**, 271102 (2001); L. Trache, F. Carstoiu, C.A. Gagliardi, R.E. Tribble, Phys. Rev. C **69**, 032802(R) (2004).

[3] H.M. Xu, C.A. Gagliardi, R.E. Tribble, A.M. Mukhamedzhanov, and N.K. Timofeyuk, Phys. Rev. Lett. **73**, 2027 (1994); A.M. Mukhamedzhanov *et al.*, Phys. Rev. C **56**, 1302 (1997); C.A. Gagliardi *et al.*, Phys. Rev. C **59**, 1149 (1999).

[4] F. Carstoiu, E. Sauvan, N.A. Orr, and A. Bonaccorso, Phys. Rev. C **70**, 054602 (2004).

[5] L. Trache *et al.*, Eur. Phys. J. A **27**, 237 (2006); V.E. Iacob *et al.*, Phys. Rev. C **74**, 045810 (2006).

[6] T. Al-Abdullah *et al.*, Phys. Rev. C **81**, 035802 (2010).

[7] A. Banu *et al.*, to be published.