LIfetime meaSurement with AGATA for AstrophysiCs - ^{21}Na (ISAAC-21)

AGATA

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Abstract

To assess the Universe chemical evolution a crucial ingredient is the cross section of nuclear reactions taking place in stars. Given its low value, pico- to femto-barn, at astrophysical energies, that prevents direct measurements and we still have to rely on extrapolation. The contribution of narrow or of large sub-threshold resonances, which may dominate the reaction rate, cannot be, however, accounted for by the extrapolation. In this scenario, accessing to low energy and sub-threshold resonance lifetime is of paramount importance to constrain the extrapolation and parameterize their contribution to the cross section at the energies of interest. The proposed measurement aims to measure the lifetime of a subthreshold resonance, at $E_{\rm r} = -6.7$ keV, of the ^{20}Ne(p,γ)^{21}Na reaction, which has a key role in AGB star nucleosynthesis of isotopes up to A = 40. The corresponding excited level in ^{21}Na, $E_{\rm x} = 2424$ keV (J^{π} = 1/2^{+}), will be populate via the ^{21}Ne(p,n)^{21}Na channel in inverse kinematic. The 40 nm thick H implanted target will be irradiated by ^{21}Ne beam, with $E_{\rm b} = 8$ AMeV and $I_{\rm b} = 2$ pnA. Two substrates will be used for the implanted target: Si and Au, allowing, together with AGATA detection system, to exploit DSAM technique with high sensitivity and independent from simulations. For the present measurement the required beamtime is 6 days.

I. SCIENTIFIC MOTIVATION

Thermonuclear reactions shape the life and death of stars and they synthesize the chemical elements in the Universe. The key ingredient to improve our knowledge on stellar and Universe chemical evolution is the cross section, particularly at the energy at which the reactions take place, the so called Gamow peak. The extremely low value of the cross section at the stellar energies, ranging from pico to femto-barn and even below, has always prevented their measurement. In recent years underground facilities, pioneered by LUNA collaboration [1], as well as new indirect methods have improved our cross section knowledge at low energies, however we still need to rely on extrapolation, leading to substantial uncertainties. In particular, the reaction mechanism might change, or there might be the contribution of narrow or of large sub-threshold resonances which cannot be accounted for by the extrapolation, but which could completely dominate the reaction rate at the stellar energies. In this scenario, accessing to low energy and sub-threshold resonance lifetime is of paramount importance to constrain the extrapolation and parameterize their contribution to the cross section at energies of interest.

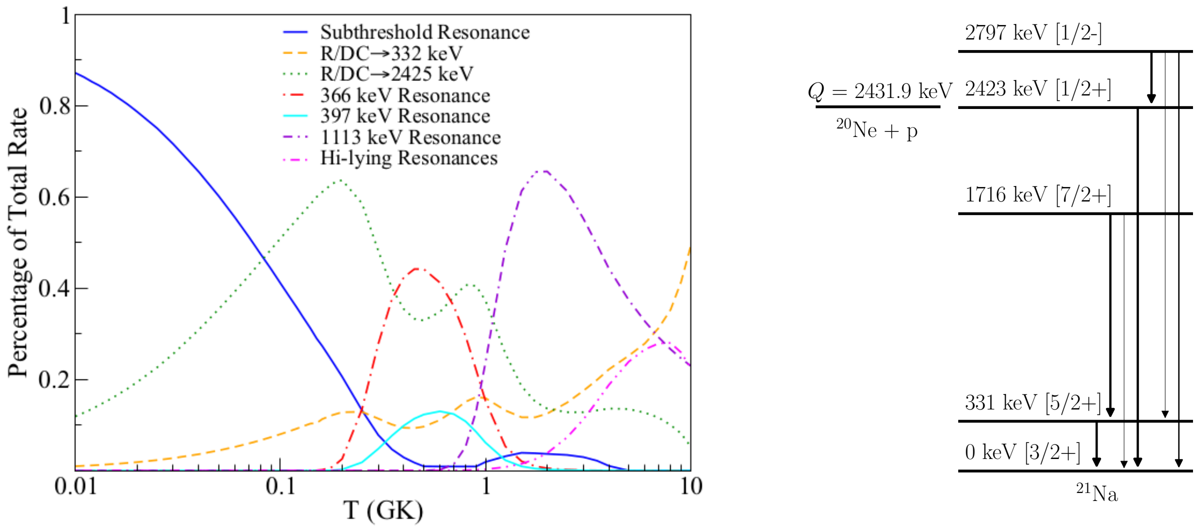

FIG. 1: (Left) Ratio of the various contributes to the ^{20}Ne(p,γ)^{21}Na total rate as a function of the temperature in GK. (Right) The ^{21}Na level scheme and Q-value for the ^{20}Ne(p,γ)^{21}Na reaction.

Among the many reactions of interest we selected a case which is suitable for lifetime measurement via Doppler Shift Attenuation Method (DSAM), exploiting the AGATA array. The NeNa cycle taking place during Hot Bottom Burning (HBB) of Asymptotic Giant Branch (AGB) stars and explosive hydrogen burning in novae, affects the nucleosynthesis of isotopes up to A$\leq$40 [2]. The NeNa cycle rate is ruled by the slowest reaction: the ^{20}Ne(p,γ)^{21}Na which, together with the ^{23}Na(p,α)^{20}Ne, carries the most of the uncertainty. The former was recently measured by LUNA collaboration down to E_p = 260 keV [3] while the latter is ongoing at LUNA. At temperatures T$\leq$0.1 GK, relevant to the HBB (corresponding to $E_{\mathrm{c.m.}}$=65-155 keV, the ^{20}Ne(p,γ)^{21}Na reaction

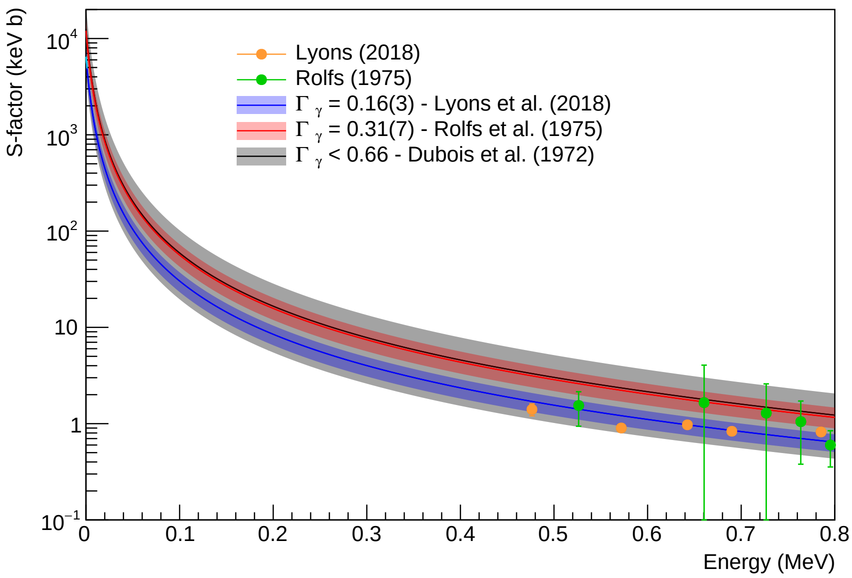

FIG. 2: Comparison between R-Matrix fits of literature data (green and orange point) for the ^{20}Ne(p,γ)^{21}Na reaction, transition to ground state only, performed assuming for the E_r = - 6.7 keV sub-threshold resonance the most recent radiation width [8] (blue line), the value obtained by [5] (red line) and the lower limit from [4] (black line).

rate (Q-value = 2431.9 keV) is dominated by the high energy tail of a sub-threshold resonance at E_r = - 6.7 keV, corresponding to the E_x = 2424 keV ($J^\pi = 1/2^+$) excited level in ^{21}Na, see Fig. 1 and Fig. **??**. Few literature data are available for the sub-threshold resonance, in [4] the 2424 keV excited state was populated via the ^{20}Ne(p,γ)^{21}Na reaction and from the observed Doppler Shift Attenuation (DSA) factor a lower limit was derived for the resonance radiative width Γ_γ of 0.66 eV, corresponding to an upper limit on lifetime of 1 fs. Following studies based either on direct data extrapolation [5] or on DSA measurement [6] reported results of Γ_γ = 0.31(7) and 0.17(5) eV, respectively, which are in tensions among each other and with previous evaluation by [4]. A more recent re-analysis of experimental data in [5] found a Γ_γ = 0.16(4) eV [7], which is partially confirmed by the R-matrix fit results reported in [8], performed on the most recent experimental data to date. Both latter works, however, call for new high sensitivity lifetime measurement for the 2424 keV excited state, given the impact on present extrapolations due to the tension between reported Γ_γ results, as shown in Fig. 2. The reported lifetime for 2424 keV [4–6] cannot be excluded for extrapolation given the high uncertainty affecting the few cross section data available, at present solely down to $E_\mathrm{c.m.} \sim 400$ keV, thus far from astrophysical energies ($E_\mathrm{c.m.} \leq 0.2$ MeV), see Fig. 2.

II. PROPOSED EXPERIMENT

The proposed experiment will employ the ^{21}Ne(p,n)^{21}Na reaction in inverse kinematics to produce the ^{21}Na in the 2424 keV excited state. The ^{21}Ne beam, at beam energy of 8 AMeV, is currently not available at the PIAVE-ALPI, however neon gas enriched in ^{21}Ne can be easily purchased and the expected current is 2 pnA as tabulated for ^{20,22}Ne beams. For the target, a 40 nm thick hydrogen layer inside both Au and Si backings will be used. Using two different target substrates, Si with A = 28 and Au with A = 197, will allow to apply the DSAM technique with high sensitivity. The ^{21}Na will emit the γ-ray of interest with two different energy distributions due to two different stopping powers inside each medium. Thus, by correcting the γ-ray for the Doppler effect, the shift in the corrected γ-peaks can be used to calculate the half-life of the decaying nuclei.

The observed γ-ray will be corrected for the Doppler effect by using a mean estimate of ^{21}Na energy. The β of the recoil nucleus is mildly affected by the direction of emission of the neutron because, when the 2424-keV state is populated, the neutron emitted has a kinetic energy of less than 1 MeV. As a consequence, as demonstrated with the simulations reported in figure **??**, the Doppler correction has high precision even if the neutron is not detected.

Finally, since no cross section data are available for this reaction, TALYS code was used[9]. The expected cross section for the exclusive population of the 2424-keV state is 12 mb. This is also supported by the experimental results for the ^{17}O(p,n)^{17}F reaction case [10]. With the cross sections estimated, considering a target thickness of 1 mg/cm^2 of Au with 10^{17} atom/cm^2 proton implanted, we expect to obtain a yield of 15 Hz for the decay of the 2424 keV level. With a 3% efficiency of AGATA we expect to obtain 4×10^4 counts per day.

The measurement will consist in 4 days of measurement alternating Au and Si proton implanted targets. Additional 2 days will be dedicated to measure the beam induced background mainly due to fusion evaporation in the Au and Si. For this measurement similar targets without proton implanted will be used.

Alternative reactions are being evaluated. For example, using a ^{24}Mg beam instead of ^{20}Ne would populate the resonance via the ^{24}Mg(p,α)^{21}Na reaction. The cross section estimated by TALYS for this reaction is slightly lower for the 2424-keV state, around 3 mb at a beam energy of 13 MeV/A. However, it offers the advantage of detecting the α particle to identify the reaction using a silicon detector such as SAURON or TRACE.

Another possibility currently under evaluation is to perform the experiment for the ^{24}Mg(p,α)^{21}Na reaction in direct kinematics using a proton beam with an energy of 13 MeV. The main limitation in this case would be the low velocity of the ^{21}Na ion, $\beta \sim 0.005$. Nevertheless, this drawback might be compensated by the strong reduction in fusion-evaporation background that is expected in the inverse kinematic reaction.

Moreover, in this scenario, the experiment could be performed during the TANDEM-only campaign scheduled for this year, further reducing the fusion-evaporation background expected in the inverse kinematic reaction. These possibilities are currently under evaluation and will be discussed during the presentation.

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