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## Astrophysical( $\alpha, \gamma$ ) reaction in inverse kinematics; Electron screening effect in the beta-decay

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**Abstract.** The abundance calculations of the p-nuclei produced in explosive stellar sites rely on the Hauser-Feshbach (HF) theory with the alpha-particle optical model potential ( $\alpha$ -OMP) one of its major ingredients. To date, most of the ( $\alpha, \gamma$ ) cross sections measured show that HF calculations can be wrong by a factor of ten or more especially when phenomenological  $\alpha$ -OMP are employed. To investigate the relevant uncertainties entering the HF calculations and furthermore develop global microscopic  $\alpha$ -OMPs, systematic ( $\alpha, \gamma$ ) cross-section measurements are necessary. This led us to perform a feasibility study of ( $\alpha, \gamma$ ) measurements in inverse kinematics that will allow us to employ also radioactive beams in the future. Hence, the  ${}^4\text{He}({}^{78}\text{Kr}, \gamma){}^{82}\text{Sr}$  reaction was studied using the LISE3 spectrometer to separate the  ${}^{82}\text{Sr}$  recoils from the primary  ${}^{78}\text{Kr}$  beam. Although an excellent rejection factor  $> 10^{10}$  was achieved, the position of the ions of interest was unexpectedly masked by a secondary beam of high intensity. Given these, new setup improvements are proposed to remove the pollutant ions.

Recently, many experiments were conducted in order to study the influence of the environment (especially in a metallic material) on the decay probability of radioactive nuclei. Additionally, hydrogen-like fusion reactions were performed indicating a change in the cross-section due to the influence of the Coulomb field screening induced by quasi-free electrons in metals. This was explained by the Debye screening model which treats metallic electrons within Maxwell-Boltzmann statistics. We measured the decay rate of  ${}^{19}\text{O}$  in metallic, insulating and superconducting environments whereas the electrons in the superconductors should obey the Bose-Einstein statistics. The decay rate measurement was supported by a branching ratios measurement. We found that the effect on the decay rate, if any, is less than the 0.1%, far below the theoretical predictions.

## 1. Introduction

Abundance calculations of p nuclei make an use of the nuclear statistical model for the calculation of the reaction rates needed for the solution of an extended reaction network involving over than 20000 nuclear reactions on  $\approx 2000$  nuclei [1]. The majority of calculations have to rely on cross-section predicted by the Hauser-Feshbach (HF) theory. Some of the very few  $(\alpha, \gamma)$  data show that the reaction rates calculated using phenomenological alpha-particle optical potentials can be wrong by a factor of ten or more. These uncertainties might be reduced by systematic cross-section measurements of  $\alpha$ -particle capture reactions at relevant energies, mainly in the  $A=80-140$  and  $A=170-200$  region [2]. The  $(\alpha, \gamma)$  measurements at sub-Coulomb energies in inverse kinematics using state-of-the-art detectors combined with velocity filters could be the best solution. In the present work we report on the  $^{78}\text{Kr}(\alpha, \gamma)^{82}\text{Sr}$  reaction, the first feasibility study of an  $\alpha$ -particle capture reaction in inverse kinematics at energies relevant to the p process, performed on the Wien Filter (WF) of the LISE3 spectrometer at GANIL.

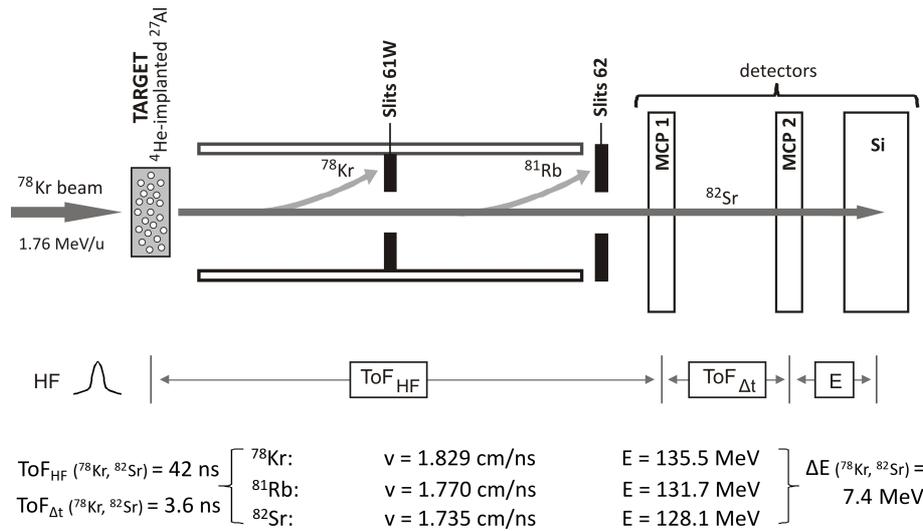
In the second part of this article we will describe the electron screening effect in the beta-decay. It is possible to calculate the influence of the screening effect (SE) on the beta decay rate by considering Fermi golden rule. Many light elements fusion experiments were conducted where metals were used as a host for hydrogen, deuterium or helium and it was noticed in many of these experiments that the SE is larger than the maximal theoretical limit. These findings have been confirmed by different groups [3, 4, 5] and also for some beta decaying nuclei (e.g. [6]). It was found that the high SE occurs in general in metals. The electrons in metals obeys the Pauli principle of exclusions and thus obey the Fermi distribution. However, bosons obey the Bose-Einstein distribution and as the electrons in superconductors (SC) are organized as pairs called "Cooper pairs" which are bosons, it was decided to examine the SE in superconductors. Actually, Stoppini [7] predicted that the Cooper pairs could induce high SE.

## 2. Experimental setup of the $^{78}\text{Kr}(\alpha, \gamma)^{82}\text{Sr}$ reaction in inverse kinematics

The  $^{78}\text{Kr}(\alpha, \gamma)^{82}\text{Sr}$  reaction was investigated at an energy of 1.76 MeV/u using the LISE3 spectrometer installed at GANIL. The target used at GANIL consisted of  $\approx 1.3 \times 10^{17}$  atoms/cm<sup>2</sup> of Helium implanted into a 50  $\mu\text{g}/\text{cm}^2$  Al foil. The expected cross-section for the reaction was ( $\approx 100 \mu\text{b}$ ) and the difference between the velocity of the  $^{78}\text{Kr}$  beam and the compound nucleus  $^{82}\text{Sr}$  is  $\sim 5\%$  only. Such a small velocity difference is a real challenge for the separation of the recoiling nuclei and the beam. The 12 meters long block of Wien Filter of the LISE spectrometer was used for the separation of the  $^{82}\text{Sr}$  nuclei from the primary stable beam  $^{78}\text{Kr}^{+8}$ . The advantage of this device is the fact that the selection of the nuclei of interest is based on the velocity and not on the charge state of the ions. The intensity of the primary beam was  $7.8 \times 10^9$  pps. The main part of the primary beam was stopped on the "61W" slits located in the center of the WF and the rest was stopped on the "62" slits located at the end of the spectrometer, as shown in Figure 1. In this setup with closed slits the velocity acceptance was 0.55 %. Extensive ion optics simulations were necessary, where it was necessary to have a fine tuning of the quadrupoles as well. For these purposes, the ZGOUBI code version 5.1.0. was used.

## 3. Results and conclusions of the $^{78}\text{Kr}(\alpha, \gamma)^{82}\text{Sr}$ reaction in inverse kinematics

The analysis of the data has shown that the measured rejection factor of the primary beam is very good, i.e. higher than  $10^{10}$ . However, we have observed particles at  $\sim 84$  MeV which cannot be explained by energy loss and scattering in the target, neither by the scattering elsewhere in the separator. The SRIM simulation has shown that the energy and the counting rate of the locus at 84 MeV cannot be explained by the straggling in the target. Since the target is very thin, the most probable reason for this energy discrepancy is microscopic dust deposited on the target. The dust particles of diameter from 10  $\mu\text{m}$  down to 1  $\mu\text{m}$  are present in the atmosphere



**Figure 1.** Experimental setup employed  $^{78}\text{Kr}(\alpha, \gamma)$  reaction in inverse kinematics

with density of  $1 \text{ cm}^{-3}$ . We used simplified model of a spherical PVC dust particle of  $2.5 \mu\text{m}$  in diameter deposited on the surface of the target. If such particle is placed at the beam spot on the target, it can produce the energy seen at the locus 84 MeV and regarding its effective surface, it explains the measured count rate of the locus 84 MeV.

We didn't succeed to separate any events attributed to the  $^{82}\text{Sr}$ , mainly due to the high presence of the background at our zone of interest coming from the locus 84 MeV. However, we can conclude that the obtained rejection factor was quite good - higher than  $10^{10}$ . Regarding the high risk of the scattering on the dust deposited on the solid target, the use of the gas windowless target is indispensable. Considering the achieved rejection factor of the primary beam and the possible use of the windowless gas target, this type of experiment is promising.

#### 4. Experimental setup of the half-life measurement in superconductive environment

As a host superconductor we used a niobium as it has convenient critical temperature of  $\approx 9.2 \text{ K}$ , which allows us to use simple cooling system based on liquid helium. Additionally, the niobium can support high irradiation by heavy ions and still retain the superconductive attributes [8]. We measured the half-lives of  $^{19}\text{O}$  and  $^{19}\text{Ne}$ , and the branching ratio of  $^{19}\text{O}$ , since each branch has its own Q value and the same screening energy will have different influence on different branches. It was intended to measure the decay curve repeating the implantation-measurement cycles until we achieve enough statistics to obtain the precision of the measurement of 0.1%. The implantation period was chosen to last for approximately two duration of two half-lives of  $^{19}\text{O}$  ( $^{19}\text{Ne}$ ), while the measurement time was about 20 half-lives of given nucleus. In order to lower down the possible systematic influences on the measurement it was decided to measure in one by one hour cycles. Namely, we measured several implantation-measure cycles during one hour in a superconducting (SC) phase of the Nb, then we would change the temperature and measure several implantation-measure cycles during one hour in a metallic phase of Nb.

#### 5. Results and conclusions of the half-life measurement in superconductive environment

The obtained results are shown on the table 1. Although, all measured half-lives and branching ratios are practically within the one sigma error bars, we can notice certain systematic behavior.

**Table 1.** The measured change of the half-life and branching ratio of  $^{19}\text{O}$  in different environments and temperatures [9]. The uncertainty of the estimated half-lives shows the statistical uncertainty and the uncertainty due to the correction on the  $^{19}\text{Ne}$  contamination.

Material and phase	Temp. [K]	BR of 197/1554	BR of 197/4377	Half-life $^{19}\text{O}$ [s]	Half-life $^{19}\text{Ne}$ [s]
Nb SC	4	$3.611 \pm 0.015$	$3000 \pm 200$	$26.454 \pm 0.015 \pm 0.007$	$17.231 \pm 0.007$
Nb metal	16	$3.607 \pm 0.015$	$2700 \pm 170$	$26.427 \pm 0.016 \pm 0.007$	$17.236 \pm 0.006$
Nb SC	4	$3.595 \pm 0.017$	$3100 \pm 200$	$26.472 \pm 0.015 \pm 0.007$	$17.231 \pm 0.008$
Nb metal	90	$3.582 \pm 0.017$	$2800 \pm 200$	$26.461 \pm 0.016 \pm 0.007$	$17.237 \pm 0.009$
Teflon	300	$3.606 \pm 0.038$	$4300 \pm 800$	$26.502 \pm 0.085 \pm 0.008$	N/A

If we compare each measurement of  $^{19}\text{O}$  at superconducting phase and its corresponding measurement in metallic phase we can see that the branching ratio and the half-life is always higher in the superconducting environment. We have the same situation for the  $^{19}\text{Ne}$  with opposite change between superconducting and metallic phase since  $^{19}\text{Ne}$  decays by  $\beta^+$  and  $^{19}\text{O}$  decays by  $\beta^-$ . This behavior is exactly what should be expected if the screening effect on the decay probability would exist. Thus, we decided to combine all these measurement – the branching ratio and half-life of oxygen and the half-life of neon and to estimate the average effect. The average screening effect in superconducting phase in comparison to metallic phase was  $1.1\% \pm 0.9\%$  of the effect predicted by the screening model in superconductors. These changes would correspond to the screening energy of 880 eV for the oxygen and 360 eV for the neon. However, we also realized that method used in previous publications, to calculate a screening energy cannot be true, since both parent and daughter nucleus are subjected to the screening and this has to be included in the estimation of the Q-value:

$$Q_{scr} = \left[ M(A, Z)c^2 - U_{scr}(Z) \right] - \left[ M_{-1}(A, Z \pm 1)c^2 - U_{scr}(Z \pm 1) \right] - m_e c^2 = Q_\beta - U_{scr}(Z = 1),$$

where  $U_{scr} = \frac{1}{4\pi\epsilon_0} \frac{Z_e Z e^2}{R_{scr}}$ , where  $Z_e = 1$  is the charge of electron 1 and  $Z$  is the atomic number of the considered nucleus. This equation means that the screening potential is independent on the atomic number of the considered nucleus and it is always equal to the screening potential on the hydrogen nuclei for the given screening radius. This cast strong doubts about the efficiency of the screening effect on the change of the probability of the beta-decay.

## 6. Acknowledgements

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