Decay of $^{48-50}$Ar isotopes

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Abstract: Information on β-decay properties of neutron-rich $^{48-50}$Ar was obtained at the ISOLDE mass-separator facility at CERN using isobaric selectivity. This was achieved by a combination of a plasma-ion source with a cooled transfer line and subsequent mass-separation. Normally, argon beams cannot be mass-separated from intense multi-charged symmetric fission krypton and xenon. Several techniques were used successfully in order to overcome this problem. Implication of the obtained information for a better understanding of the origin of the ^{48}Ca/^{46}Ca isotopic anomaly discovered in inclusions from the Allende meteorite is discussed.

1. Introduction

Knowledge of the nuclear properties from the Z~20 and N≤28 mass region of the nuclear chart is important for understanding one of long persisting astrophysical problems, the Ca/Ti/Cr isotopic anomalies observed in some meteoritic inclusions [1,2]. The decay properties of neutron-rich argon isotopes are the least known compared to other nuclei relevant for clarification of the ^{48}Ca/^{46}Ca meteorite anomaly. As the ^{48}Ar nucleus is, most likely, the main progenitor of the ^{48}Ca isotope the lack of information on its decay properties limits considerably the predictive power of the astrophysical network calculations [3]. These nuclei are also of great interest of nuclear structure physics due to unexpected observation of collectivity and N=28 shell erosion in that region [4]. Therefore any new experimental information on neutron-rich argon isotopes is highly desirable.

Sufficient yields of the neutron-rich argon nuclei can be obtained at ISOL facilities as ISOLDE (CERN). However ,an experimental problem significantly hinders such measurements. The radioactive argon isotopes extracted and mass-separated from a FEBIAD plasma ion sources with cooled transfer line [5] could not be mass-separated from multiply charged krypton and xenon symmetric fission noble gas products that have the same A/q ratio. This results in an overwhelming doubly-charged krypton and triply-charged xenon backgrounds for the singly-charged argon beams [6]. In the case of ^{48}Ar isotope, which is of main importance, the signal-to-noise ratio is especially unfavorable.

In several short experiments performed during 2002-2004 years we have tested several techniques in order to overcome this problem and study decay of neutron-rich argons:

1. Separating doubly-charged argon beams rather than single-charge ones significantly reduced multicharged krypton and xenon background. However, the overwhelming singly charged neon background presents the problem for the case of even argon isotopes like ^{48}Ar [6]. In the latter case use of a detector setup with a beta telescope allows one to clean greatly the signal from neon decay.

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2. Comparison of the γ-spectra collected from the direct proton bombardment of an actinide target to those arising from the use of the neutron converter [7] results in an unambiguous identification of the γ-rays originating from decay of the argon isotopes [8].

3. Finally, a mixture of mass-separated radioactive noble gases was injected into a PHOENIX type Electron Cyclotron Resonance Ion Source (ECRIS) that has been installed in recent years at an ISOLDE beam line for testing of charge-breeding techniques. Modification of the charge-state distributions of the different elements with consequent mass-separation allows for a significant improvement in the quality of the argon signal [9] .

In this paper we briefly describe the experiment and summarize results of decay spectroscopy studies of neutron-rich ^{48,49,50}Ar isotopes obtained by the techniques listed above. The results confirm the picture where the ^{48}Ar is the main progenitor of ^{48}Ca.

2. Experimental Results

Format limitations of this contribution do not allow for detailed description of the experimental setup, experimental procedure and the results. The experimental details as target or neutron converter irradiation conditions, setting of the ion source and the mass-separator, the detector setups and the calibration procedures can be found in [Wei04, Fri06]. Very briefly: the ions were extracted by a 60 kV voltage, mass-separated and implanted into an aluminized tape, which allowed to remove the long-lived daughter activity away from the detector setup.

The implantation point was placed close to Kapton windows, and was surrounded by thin plastic beta detectors. Two Ge detectors of 75 % and 65 % relative efficiency were placed next to the implantation point for detection of γ-radiation. The time and energy signals were collected by a VME-based data acquisition system. Typical time cycle included opening the mass-separator gate for some period after a proton pulse and its closure till the next pulse for study of decay curves. The time cycle was optimized for each particular case.

2.1 ^{50}Ar

The most neutron-rich ^{50}Ar isotope, presented the easiest case as it did not suffer from multicharged background. Two β-gated γ-spectra were collected for the mass-separator A/q value of 50 (singly charged ^{50}Ar beam) for direct proton bombardment of the uranium target and for bombardment of the neutron converter. A number of unknown γ-transitions, 93, 128, 172, 770, 3425 and 3596 keV, were observed in the "direct bombardment" spectrum. In addition the 3084 keV transition from ^{49}Ca decay was also observed. These transitions were not seen in the "neutron converter" spectrum indicating that the transitions of interest belong to the decay of ^{50}Ar nucleus and its daughters. Application of gates on the strongest γ-transitions indicated coincidences between 3425 and 128, 172 keV lines. A correlation was also established between 93 and a weak, 770 keV transition (both transitions belongs to the ^{49}Ar decay (see below)). The transitions of interest exhibited the similar half-lives within the experimental uncertainties, ensuring the assumption that they belong to the same ^{50} Ar decay. The averaging of the half-lives obtained from gating a trigger spectrum by six the γ-transitions yielded 106(6) ms. The implantation rate of ^{50}Ar was estimated from intensities of these transitions as 11 atoms per μC of protons on the target. The neutron emission probability in the ^{50}Ar decay was estimated to be 37(7) %.

2.2 ^{49}Ar

Two β-gated γ-spectra collected for the mass-separator A/q value of 49 (singly charged ^{49}Ar beam) for direct proton bombardment of the uranium target and for bombardment of the neutron converter. Number of transitions, 93, 278, 450, 770, 1240 and 1300 keV, are observed in the direct bombardment spectrum and are not seen in the background spectra. Moreover the 143 keV transitions in the direct bombardment spectrum are stronger than corresponding transitions in the neutron converter spectrum (144 keV from ^{98}Rb). The 780, 3084, 3832 keV transitions from the decay of A=49 and A=48 descendant nuclei are also seen in the direct bombardment spectrum. Application of gates on the strongest γ-transitions indicated the coincidences between the 93 keV line and 770, 1240, 1300 keV lines, as well as the coincidence between the 278 keV and 450 keV lines. No coincidences were established with the 143 keV transition. The decay half-lives were obtained by fitting the trigger time spectra gated by the γ-transitions of interest. The averaged half-live obtained with six transitions is 236(8) ms. The neutron emission probability in the ^{49}Ar decay was estimated to be 29(6) %. The implantation rate of ^{49}Ar was estimated from intensities of these transitions as 80 atoms per μC of protons on the target.

2.3 ^{48}Ar

2.3.1 Measurement with the β-γ detector setup

A few short measurements were made at A/q=48 settings of the mass-separator (singly-charged ^{48}Ar beam). Numerous transitions from A=96 and A=144 chains resulted to overwhelming background and high dead time. A weak the 3832 keV transition from ^{48}K decay is the only indication of the presence of the ^{48}Ar isotope in the beam. In addition only the unknown 3196 keV transition, which did not appear in the neutron-converter spectrum, can be singled out as the one belonging to the ^{48}Ar decay. The half-life obtained by gating the trigger signal by the transition is 381(35) ms, which is not consistent with any decays of M=96 and M=144 chains. Applying a coincidence gate on the 3196 keV transition yielded correlation to the 143 keV γ-line.

2.3.2 Measurement with the β-telescope setup

Another measurement at A/q=24 separator settings (doubly-charged ^{48}Ar) was performed with a detector setup utilizing an implantation tape, a *β*-telescope and two Ge detectors. The detailed description of that set-up will be given in [10]. The beam was dominated by very intense singly-charged ^{24}Ne ($T_{1/2}$=3.38 min), however, the large difference in the ^{24}Ne and ^{48}Ar decay Q-values was utilized for improvement of the signal-to-noise ratio. Applying of the high-energy gate ($E_{\_\beta}$>2.5 MeV) on the time stamp signal resulted in the significantly different decay curve comparing to the ungated time spectrum. Fitting of the decay curve yielded ^{48}Ar half-life of 412(19) ms. This value is consistent with the result recently reported by the GANIL group, 475(40) ms [11]. The fitting range was insensitive to the contribution from the decay of the longer-lived ^{47,48}K daughters. Thus it was not possible to determine from the measurement the neutron emission probability. Only the 143 keV γ-ray was observed after gating the Ge detector spectrum by the high-energy betas.

2.3.3 Measurement with the secondary ECR ion source.

A short separate measurement was performed using the secondary ECR Ion source (ECRIS) source. This ion source was installed at an ISOLDE beam line to study possibility of charge-breeding of the radioactive beams [12]. The ISOLDE beam at the mass-separator setting of A/q=48 beam was injected into the ECRIS. The separator beam gate was open for 1 second after each proton pulse. The ions were ejected from the ECRIS after 80 ms charge-breeding time. The highly charge ions were ejected from the source, mass-separated by the secondary 102 degree mass separator and implanted into aluminized tape surrounded by a β-γ detector setup. The main experimental problems were associated with X-rays from the ECR source and the background from the radioactive neutral atoms diffused into the source, and stable beams of closed magnetic rigidity [9]. The mass-separated $^{48}Ar^{9+}$ beam charge state corresponded to the best signal-to-noise ratio. The background taken at the same separator and proton cycle conditions but with closed beam gated (X-rays from the ECRIS and breeding of radioactive neutral) was subtracted from the spectrum. During implantation the tape was moved only once in every 3 minutes. One can observe from the spectrum both 143 and 3196 keV γ-transitions, along with 2013.5 and 3832 keV transitions from the decay of the longer-lived ^{47}K and ^{48}K daughter products. A relatively weak signal from A=96 chain is seen, while no activity originating from the A=144 chain was observed at all. The averaging of the half-lives obtained by gating the trigger spectrum by 143 and 3196 keV γ-transitions yields 430(70) ms, which is in agreement with the previous results. The neutron emission probability in the ^{48}Ar decay was estimated from the intensities of the 2013.5 and 3832 keV transitions and was found to be to be 38(6) %.

3. Discussion

The frame of this proceeding does not allow one neither detailed presentation of the experimental results, nor extended comparison with the results of the QRPA and large-scale shell model calculations. This will be done in the upcoming publication [10]. Here we discuss only integration of the obtained the gross-decay properties of the $^{47-50}$Ar isotopes into the astrophysical picture which attempts to explain the high ^{48}Ca/^{46}Ca anomaly in the EK-1-4-1 inclusions of the Allende meteorite.

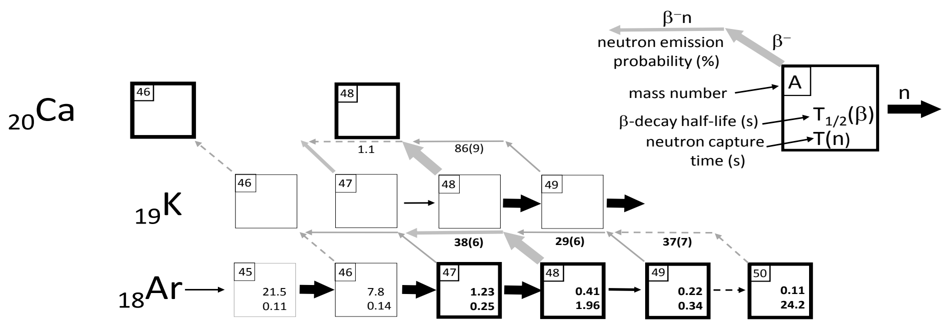

Figure. 1 Population of the ^{48,46}Ca isotopes as result of a weak r-process**.**

A weak r-process is an astrophysical scenario which could explain the overproduction of ^{48}Ca [3]. The process takes place at the moderate neutron densities and temperature. The competition between neutron capture and beta-decay determines the weak r-process path. The weak process path calculated for neutron density of $4\bullet10^{19}$ n/cm^3 and temperature of 0.8T_9 [3] is presented in Fig. 1. At these conditions the calcium isotopes are mostly produced by beta-decay of their argon progenitors. The argon chain is populated via the ^{45}Cl waiting point, which decay half-life was found to be much shorter than expected due to erosion of the N=28 gap for S and Cl isotopes [13]. The ^{46}Ar half-life is much longer than the neutron capture probability (Fig. 1). Therefore this isotope and, hence ^{46}Ca, will be weakly populated as result of the process. For the ^{48}Ar isotope the decay half-life becomes significantly shorter than the neutron capture time ensure the waiting point character and its strong population. About two thirds of the produced ^{48}Ar population becomes ^{48}Ca. The rest ends up as ^{47}Ti after beta-delayed neutron emission in the ^{48}Ar decay. Any population of ^{49}Ar isotope eventually ends up as ^{48}Ca due to relatively high P_n-value of the ^{49}Ar decay and very high P_n-value of the ^{49}K decay.

In conclusion, we have performed a study of beta-decay of neutron-rich isotopes. Several experimental techniques were used in order to overcome the experimental problems associated with the ISOL method. The results favor the assumption that the origin of the ^{48}Ca/^{46}Ca anomaly is due to the weak r-process. The obtained information on the decay of the argon isotopes together with the recent measurements of the neutron capture rates on ^{44,46}Ar [14] can be implemented now in the new generation of astrophysical network calculations in order to narrow down the astrophysical conditions at which overproduction of ^{48}Ca takes place.

4. References

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