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Investigation of astrophysically relevant neutron-rich argon nuclei.

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Abstract

We propose to measure beta-decay properties especially the half-lives and P_n-values of the neutron-rich $^{47,48,49}Ar$ nuclei. The acquired information will be important for a better understanding of the origin of the $^{48}Ca/^{46}Ca$ isotopic "FUN" anomalies discovered in several refractory inclusions (in particular EK-1-4-1) of the Allende meteorite.

Introduction.

The isotopic homogeneity of the Solar System formed from a "well-mixed primordial nebula of chemically and isotopically uniform composition" [Sue65] was regarded in the 1960s and early 1970 as "one of the few assumptions that can be considered well-justified and firmly established"[Sue65]. However, the discovery of highly unusual isotopic compositions in meteorite grains, attributed to fractionation (F) and unknown (U) nuclear (N) effects and therefore designated "FUN" anomalies, considerably complicated that rather simplified assumption [Ott93]. Especially striking isotopic anomalies were discovered in the refractory inclusion of the Allende meteorite [Lee78,Nie80] where the abundance ratio of the $^{48}Ca/^{46}Ca$ isotopes was found to be 5 times higher than the Solar System value. The meteorite inclusions are formed at the earliest stage of the solar nebula evolution. These inclusions, formed from not completely mixed matter, provide information on some of several nucleosynthesis mechanisms that took place during stellar evolution. Therefore, to understand these highly unusual isotopic abundances, one has to look for suitable nucleosynthesis scenarios. Among the various processes studied a quasi-statistical equilibrium and r-process-like scenario seem to be the most promising ones. Although a lot of progress has been achieved in astrophysical network calculations since the discovery of the Allende meteorite anomalies, the "Allende puzzle" is still far from being consistently solved [Kra01]. The situation could be improved considerably by obtaining a better knowledge of the relevant nuclear physics data around double-magic ^{48}Ca, continuing the earlier work at GANIL and ISOLDE. Several studies of neutron-rich $^{48-51}K$ [Car82,Zie85], ^{43}P, $^{42-45}S$, $^{44-46}Cl$, ^{47}Ar [Sor93,Sor91,Boh96] nuclei were performed to measure half-lives and P_n values of these nuclei "south" of ^{48}Ca. These experiments demonstrated that the information on nuclear-structure properties is helpful for the understanding of the unusual abundance ratio.

At present the properties of neutron-rich Ar isotopes are the poorest known compared to other relevant nuclei in the region around ^{48}Ca . The lack of information about these nuclei still limits considerably the predictive power of the present astrophysical network calculations. In this context, the properties of the ^{48}Ar nucleus (half-life, P_n-value) are of special importance, since in r-process-like scenarios ^{48}Ca is mainly generated by its progenitor ^{48}Ar [Kra01]. At the same time, it is very interesting to perform decay spectroscopy of these isotopes in order to obtain experimental data on single-particle states in the daughter nuclei. Such information will allow to improve the quality of shell-model calculations which are, for example, important for calculating the neutron capture cross-section on a microscopic basis.

To improve our understanding of the astrophysical process that caused the "Allende puzzle" we propose to perform a dedicated experiment to measure properties of the neutron-rich $^{47,48,49}Ar$ nuclei. For all three isotopes we would like to determine their half-lives and P_n values. For the case of the ^{47}Ar, which has a high production yield at ISOLDE, we would like to perform also more detailed beta-delayed gamma spectroscopy. One should note that, in addition to the astrophysical motivation given above, the study of the level structure of the neutron-magic daughter nucleus ^{47}K (Z=19,N=28) is of great interest for nuclear physics, since in these data one can probe pure proton hole states around the magic ^{48}Ca core. This study will be complimentary to another ISOLDE proposal [INTC] devoted to investigation of the excited states in neutron-rich Ca isotopes.

The target tests at ISOLDE (2000).

A number of target tests that were performed during the year 2000. Some of these tests used standard ISOLDE UC targets and a cold-plasma ion source. Only single and higher charged noble gas reaction products are extracted from the ion source. Although most of the yield measurements were done for neutron-rich Kr and Xe fission products, a measurement for the neutron-rich ^{47}Ar fragmentation product has also been performed. The result of the measurement indicates a relatively high production yield of $2\ 10^5$ of ^{47}Ar per μC for 1GeV proton beam. No systematic measurements of the neutron-rich Ar release curve from the target were done so far, therefore the yield estimate is rather approximate and lies on the conservative side. This high yield allowed a rough measurement of the half-life and an upper limit for the P_n-value of ^{47}Ar (Fig 1). These data were collected for only 19 proton pulses on the target. The preliminary values from this measurement are consistent with the results of two GANIL runs [Boh96,Sor91] and an earlier ISOLDE measurement [Bau89].

The major difficulty in measuring the neutron-rich Ar isotopes is the background from doubly and triply charged Kr and Xe fission products that have much higher production yields than products from fragmentation reactions. There are several possibilities to enhance fragmentation products with respect to the fission fragments or to **differentiate** between them:

1. One can take advantage of the fact that the corresponding doubly charge Kr isotopes have considerably shorter half-life, allowing to optimize the beam time cycle (Fig. 1).

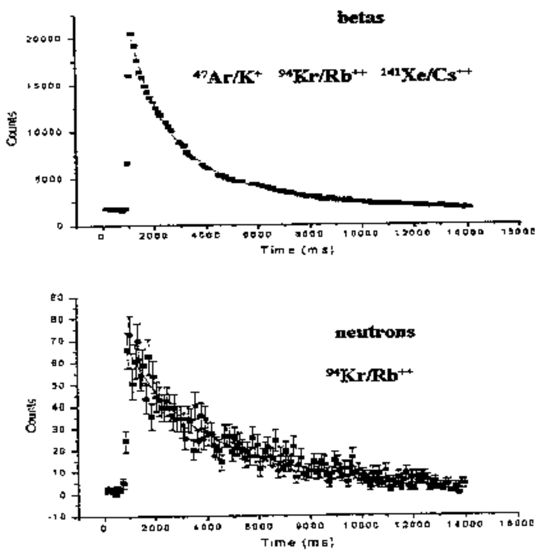

Fig1. Time spectra measured with beta and neutron detectors. Time zero corresponds to proton pulse

2. The yield of fragmentation products in this region can be increased by a factor 2.5-3 compared to fission yields if a higher proton energy is used (1.4 GeV). This fact is confirmed by both experimental results of ISOLDE target tests [Geo00] as well as by computer calculations [Cug97,Jun98].
3. The m/q difference between $^{x}Ar^{+}$, $^{2x}Kr^{++}$ and $^{3x}Xe^{+++}$ nuclei corresponds to a M/ΔM value of ~1000-2000. In this respect the use of the HRS will significantly reduce the fission product contamination.
4. The cold-plasma ion source can be optimized for single charged Ar^{+} production by varying the support gas pressure and other source parameters.
5. During the ISOLDE target tests a new technique has been developed and investigated [ISO01]. Data obtained by direct proton bombardment of the UC target and proton bombardment of a Ta neutron converter placed close to the target are compared. In the latter case the target is irradiated by neutrons from the converter having the fission as the only possible reaction channel. The difference between two spectra shown in Fig. 2 is only due to the products from the fragmentation reactions.

Proposed experiment.

The experience accumulated during the recent ISOLDE target tests gives confidence that in a dedicated experiment, performed under optimized conditions (1.4 GeV proton energy, with a better experimental setup, and the use of the HRS), the properties of neutron-rich Ar isotopes can be measured successfully. One has to stress that although at the present stage the neutron converter is not optimized to the highest yield of the fission products no any special target development is required for the proposal. On the contrary the existing target/converter configuration is optimized for production of the fragmentation products and the neutron converter serves only for production the reference spectra. It is also important to point out that the switch to the direct target bombardment demands only a change of beam deflector voltage and does not consume any time and efforts.

Detection station.

During the target tests a rather simple experimental setup has been used. The beam was implanted into a flange with a Kapton window. It was not possible to remove the longer-lived daughter activity. The implantation point was surrounded by a long neutron detector from Gothenburg University (19% neutron detection efficiency) and a thick beta-detector was placed in contact with the Kapton window (18% beta- detection efficiency).

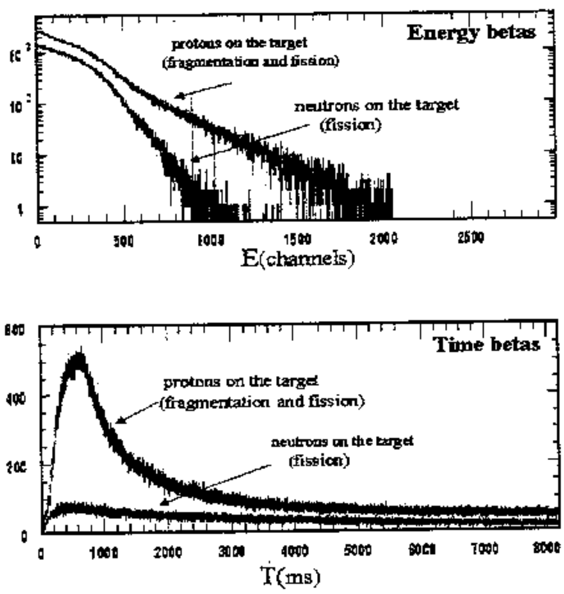

Fig2. The comparison of M=47 beta-energy and beta-time spectra for direct proton bombardment of the target and use of the neutron converter

For the proposed experiment we will use a new spectroscopy station with a possibility of swift removal of long-lived activity by a tape transport system. The design of the spectroscopy station is practically finished and it is planned to be manufactured early in 2001. The tape drive for the new station has already been produced by Mainz University and was extensively tested. The implantation point in the new station will be surrounded by 5 Kapton windows that will allow to place segmented thin plastic beta-detectors at large solid angle with a beta-detection efficiency of about 50% [Wei99]. The small thickness of the plastic detectors is needed to minimize their response to neutrons and gamma-rays. For delayed-neutron detection the Mainz 4π long counter will be used. The counter consists of 64 ^{3}He proportional counters in three concentric rings with a total efficiency of about 45 %.

The same tape station with the beta-detectors will be used for the decay spectroscopy experiment. In this case two big Ge-detectors will be placed in a close geometry with respect to the implantation point to ensure the high efficiency for beta-gamma coincidences.

Experiment logistics and beam request.

Prior to the actual experiment we would need to perform an additional target test with the purpose of optimization of the ion source parameters in order to enhance the single charged ions production and obtaining more accurate information on the ^{47}Ar release curve. After that we could optimize the beam cycle and detection cycle for ^{47}Ar and perform an accurate measurement of the half-life and P_n-value. We estimate that **two shifts** will be enough for these measurements. The next stage of the experiment will be devoted to the ^{48}Ar measurement. Knowing the release curve for ^{47}Ar we could extrapolate it for ^{48}Ar and optimize the beam cycle. The only way to prove that the observed activity belongs to ^{48}Ar is to compare the spectra obtained from direct target bombardment with that from the neutron converter spectra. During the target tests we had a short run for mass 48 (two measurements of 10 proton pulses). Apart from the overall counting rate, we have not seen any difference in the slope of the two types of measurement. We are confident, however, that under better experimental conditions (1.4 GeV proton energy, HRS, optimized beam cycle and better experimental setup) we will obtain a much better signal-to-noise ratio and will have a good chance to perform the measurement within **five shifts.** One shift out of these five is intended for beam tuning and the setup calibration. The other four will be divided equally between the measurements with the direct target bombardment and the neutron converter. At the next stage we will perform the beta-decay spectroscopy experiment of ^{47}Ar and collect beta-gated gamma spectra for both the direct target bombardment and the neutron converter. We again ask for **five shifts** for this part of the experiment. The beam time will be divided the same way as in case of the ^{48}Ar measurements.

In the case of a successful ^{48}Ar measurement we will report on those results and submit an addendum for an additional beam time dedicated to the ^{49}Ar experiment.

In summary we ask for **12 shifts** of beam time to measure the half-lives and P_n values, and to perform decay-spectroscopy of the ^{47,48}Ar nuclei. The 1.4 GeV proton-beam energy and the use of the HRS is highly desirable. We would need 4-6 equidistant proton pulses. We request furthermore to have at least a short break between the experiment with the neutron detector and the gamma-spectroscopy setup.

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