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Measurement of β-Delayed Neutron Resonances from $^{47-50}Ar$ and ^{50}K Decays and their Translation into Cross Sections for the Inverse Process of $^{46-49}K$ and ^{49}Ca Neutron Capture: The Correlated Ca and Ti Isotopic Anomalies and the Astrophysical nβ-Process

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The discovery of anomalies in isotopic abundances in nature and in meteorites has initiated a wide range of investigations in experimental and theoretical nuclear astrophysics. For example, it is still unknown how the neutron rich Ca and Ti isotopes observed in nature were synthesized. In particular, all astrophysical models using the standard Hauser-Feshbach formalism for average continuum neutron-capture cross sections predict the isotope abundance ratio $^{46}Ca/^{48}Ca > 1$, whereas the observed ratio is only about 0.02.

Recently, Sandler et al. [1] have suggested that neutron rich Ca and Ti isotopes are not produced via neutron-capture in the Ca and Ti chains, but rather through a neutron-capture/β-decay (nβ) process in the K and Ca chains, respectively. However, even in this scenario simultaneous agreement with all observed isotopic abundances could only be obtained when straightforward increasing the (n,γ) cross sections for ^{46}K and ^{49}Ca by a factor of ten above the statistical model continuum values. The authors argue, that from simple shell model considerations there are, indeed, reasons to question the validity of a statistical theory of nuclear reactions for the situation of $^{46}K(n,\gamma)$ and $^{49}Ca(n,\gamma)$. Both nuclei are near closed shells (N = 28 and Z = 20) and therefore have relatively small level densities at low excitation energies [2]. Individual levels, however, have correspondingly larger neutron capture widths.

Since ^{46}K and ^{49}Ca are radioactive, their capture cross sections cannot be measured directly. Simple estimates of radiative capture contributions do not give sufficient enhancements in the (n,γ) cross sections. On the other hand, the necessary enhancement can be provided by s-wave resonances near the Maxwell-Boltzmann distribution maximum for the temperature at which the $n\beta$-process occurs. These resonances must have electric-dipole radiation widths to the low-lying states of ^{47}K and ^{50}Ca, respectively, which are substantial fractions (~ 0.1) of a Weisskopf unit.

Shell model considerations suggest that low-energy resonances of sufficient strength to produce enhanced (n,γ) rates may exist. In the case of $^{46}K(n,\gamma)$, the ^{47}K neutron separation energy is 8.35 MeV, so that for <300 keV neutrons a resonance is required at an excitation energy of 8.4 to 8.7 MeV. States formed in $^{48}Ca(d,{}^{3}He)^{47}K$ with $\Delta l = 2$ for the stripped proton have been tabulated for ^{47}K at 8.02 and 8.53 MeV by Lederer et al. [2]. Since the ^{46}K ground state is $J^{\pi} = 2^{-}$, the resonance must either be $3/2^{-}$ or $5/2^{-}$ (near-thermal s-wave neutrons are $1/2^{+}$). But as the ^{47}K ground state is $J^{\pi} = 1/2^{+}$ $(\pi s_{1/2}^{-1}, \nu f_{7/2}^{8})$, E1 transitions to the ground state can only arise from a $3/2^{-}$ resonance. One simple E1 excitation from the ground state of ^{47}K is the proton configuration $\pi s_{1/2}^{-1}\, d_{3/2}^{-1}\, p_{3/2}$, whose excitation energy can be estimated to be about 8.9 MeV, close to the required range.

In the case of $^{49}Ca(n,\gamma)^{50}Ca$, the neutron separation energy is 6.36 MeV. Since the ^{49}Ca ground state is $3/2^{-}$ and the ^{50}Ca ground state is 0^{+} $(\nu p_{3/2}^{2})$, we require a 1^{-}

state in ^{50}Ca at an excitation energy of 6.4 to 6.7 MeV. One possible candidate is the $\nu d_{3/2}^{-1}\, p_{3/2}^{3}$ configuration, estimated to lie at about 7.4 MeV, slightly higher than the required energy.

From these estimates, Sandler et al. [1] conclude that there may be significant E1 strength for both $^{46}K(n,\gamma)$ and $^{49}Ca(n,\gamma)$ just above the respective neutron separation energies. For an experimental verification of states in the appropriate energy ranges, the authors suggest to study reactions like $^{48}Ca(d,^{3}He)$, (t,α) and (t,p).

However, these reactions, besides probably having only very small cross sections for the hypothesized structures, are not the only way of producing $3/2^-$ and 1^- states above S_n in ^{47}K and ^{50}Ca, respectively. Due to decay energetics [3] and the spins and parities of the levels involved [2], such states can also be populated via the inverse reaction to neutron-capture, i.e. β-delayed neutron emission from ^{47}Ar and ^{50}K, respectively. And, indeed, for the latter case, the low-energy part of the neutron spectrum measured some time ago at ISOLDE [4] shows a single strong resonance at 155 keV which corresponds to a level in ^{50}Ca at 6.52 MeV, in good agreement with the estimate of Sandler et al. [1].

It therefore seems feasible to measure high-resolution β-delayed neutron spectra of $^{47(-50)}Ar$ and ^{50}K in order to obtain the necessary parameters for the neutron-capture cross sections of the respective K and Ca isotopes responsible for the Ca-Ti isotopic anomalies.

We suggest to first measure the singles neutron and nγ-coincidence spectra of $^{47-50}Ar$ by applying ^{3}He ionization chambers and TOF-systems using NE 213 liquid scintillators. The corresponding data on neutron-rich K isotopes exist already [4,5]. For the measurements of Ar delayed neutrons we would need a total of about 15 shifts.

For ^{50}K and those cases of Ar precursors where neutron peaks below about 300 keV are observed, in a second experiment we intend to measure the low-energy parts of the neutron spectra with an energy resolution of <1 keV by utilizing TOF-systems with ^{6}Li-glass and ^{3}He-scintillation detectors. The anticipated energy resolution should be adequate to obtain neutron widths Γ_n by shape analysis. With the measured Γ_n, the neutron wave types and level densities, the cross sections for the inverse process of capture of low-energy neutrons by the short-lived K and Ca isotopes can be derived. For this experiment we would require about 4 shifts for each isotope, ^{47}Ar and ^{50}K certainly having the highest priority.

Our experiments require very low neutron and γ-ray background conditions. We therefore propose to carry out the measurements at the shielded position UR 9. For part of the proposed experiments we would furthermore like to use the existing small tape system.

Concerning the neutron-rich Ar isotopes, we are aware of the fact that the Ar beams contain considerable contaminations of Kr^{2+}. We believe, however, that that these problems could be overcome, e.g. by discharge of Kr^{2+} in a slightly reduced vacuum. Furthermore, we are aware of a letter of intent on β-decay of ^{47}Ar, submitted by the French spectroscopy group in Jan. 1980. It is a matter of course to coordinate our plans and collaborate with the Strasbourg group on this subject.

References

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