

Letter of Intent

**Determination of $^{44}\text{Ar}(n,\gamma)^{45}\text{Ar}$, and $^{46}\text{Ar}(n,\gamma)^{47}\text{Ar}$ reaction rates
by (d,p) transfer reactions**

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Abstract:

The aim of the present experiment is to determine the $^{44}\text{Ar}(n,\gamma)^{45}\text{Ar}_{27}$ and $^{46}\text{Ar}(n,\gamma)^{47}\text{Ar}_{29}$ reaction rates by measuring the $^{44}\text{Ar}(d,p)^{45}\text{Ar}$ and $^{46}\text{Ar}(d,p)^{47}\text{Ar}$ transfer reactions. We shall evaluate the role of the N=28 closed shell on the neutron-capture rates and determine the size of the N=28 gap. The motivation of this experiment is therefore twofold. One is of astrophysical interest, the other of nuclear physics interest. In astrophysics, this experiment will help to understand the larger than solar $^{48}\text{Ca}/^{46}\text{Ca}$ abundance ratio in certain inclusions of meteorites. The ^{46}Ar is thought to be the main progenitor of ^{46}Ca and the determination of its neutron capture cross section provides a constraint for astrophysicists on the neutron densities which should be present in explosive stellar environments to account for this large Ca isotopic ratio. In nuclear physics, neither the size of the N=28 shell gap (between $f_{7/2}$ and $p_{3/2}$), nor the occupation of these orbitals have been determined in any of these nuclei so far. The study of ^{44}Ar and ^{46}Ar transfer reactions will determine the size of the N=28 gap as well as the occupation probabilities of the two neutron orbitals $f_{7/2}$ and $p_{3/2}$. These results will firmly establish an erosion or persistence of the N=28 closed-shell below ^{48}Ca . The measurements should be performed at the REX-ISOLDE beamline.

General Motivations:

The evolution of nucleosynthesis in explosive stellar environments is closely linked to the existence and strength of shell-closures far from stability. In particular, the rapid neutron-capture process (r-process), which is thought to occur during explosions of supernovae, develops within some hundreds of ms from the valley of stability to very neutron-rich nuclei until a shell closure is present. Beyond this limit, the neutron separation energy suddenly drops down by some MeV. Consequently, neutron captures are hindered, due to the strong photodisintegration probability which destroys the nuclei as soon as they are formed at temperatures of about 5×10^8 K. The process may be stalled in an (n, γ) - (γ, n) equilibrium until beta-decay or neutron capture occurs. As a result, an accumulation of nuclei is formed at these waiting points which contain the main progenitors of isobaric stable nuclei. The study of shell closures and their evolution at large neutron excess is of basic importance to understand the development of the r-process (time elapsed, sensitivity to neutron density, amount of nuclei accumulated) and the abundance of the elements in the Universe.

Recent observations of old, ultra-metal-poor stars in the galactic halo indicate a robust primary “main” r-process component, that seems to synthesize the heavy r-elements beyond $A=130$, while the under-solar abundances below $A=130$ suggest the existence of another component of secondary origin at a later stage of chemical evolution. (K.-L. Kratz 2000 <http://fr.arXiv.org/abs/astro-ph/0012217>, J. W. Truran et al. NPA 688(2001)330c). This “weak” r-process, which takes place at lower neutron density, could also produce the neutron-rich stable nuclei in the Ca-...-Ni region and account for the isotopic anomalies found in extra-solar inclusions of meteorites. In such a case of weaker neutron densities, the (n, γ) - (γ, n) equilibrium is probably not reached, and neutron-captures far from stability are required.

Present studies of the r-process have been focused on beta-decay studies and determinations of masses. Experimental studies have not yet been started to determine the neutron capture cross sections (and hereafter the neutron capture times) for unstable nuclei involved in the r-process. The direct determination of these reaction rates for short-lived radioactive species is technically impossible. An alternative way consists of using the transfer reaction (d,p) to determine the (n, γ) reaction in the region of energy where the direct neutron capture occurs in exploding stars. The neutron capture cross sections for key nuclei in the r-process are hitherto calculated mainly using the Hauser Feschbach (HF) formalism. This formalism assumes that a compound nucleus (CN) is created. However, reactions where a neutron is directly captured into bound states (DC) dominate the neutron capture for nuclei with low level density in the vicinity of the neutron separation energy S_n . This is especially the case for light mass nuclei, for isotopes close to magic neutron numbers and for nuclei far from β -stability with low S_n values. Therefore, both CN and DC contributions are very important. Experimental work on stable nucleus ^{48}Ca at $N=28$ closed-shell has been achieved both using the (d,p) and the direct (n, γ) reaction. From these studies, it has been shown that 95% of the neutron-capture cross section is of DC origin (E. Kraussmann et al. PRC 53 (96)469). This process mainly occurs through

E1-transitions from an incident s-wave neutron since the centrifugal barrier in the entrance channel strongly suppresses the transition at higher orbital momentum. Hence, the determination of the DC part is very sensitive to the location of the p-states below the neutron emission threshold and to their spectroscopic factors (Fig.1 left). A similar study has been achieved in the case of the $^{36}\text{S}(n, \gamma)$ reaction where 80-100% of the cross section is due to DC components (H. Oberhummer et al. (Proc ENAM95, p. 649)).

The aim of the intended experiment is to determine the $^{44}\text{Ar}(n, \gamma)^{45}\text{Ar}_{27}$ and $^{46}\text{Ar}(n, \gamma)^{47}\text{Ar}_{29}$ reaction rates by measuring the $^{44}\text{Ar}(d,p)^{45}\text{Ar}$ and $^{46}\text{Ar}(d,p)^{47}\text{Ar}$ transfer reactions. The case of the neutron-rich ^{46}Ar should be very similar to that of ^{48}Ca since they have almost the same S_n and lie at the neutron closed shell $N=28$ (Fig. 1 right). From these experiments, we shall evaluate the role of the $N=28$ closed shell on the neutron-capture rates. In the following, both the astrophysical motivation as well as the nuclear physics interest in this experiment will be examined.

The $^{48}\text{Ca}/^{46}\text{Ca}$ anomaly:

Concerning the astrophysical point of view, the large correlated overabundances of ^{48}Ca , ^{50}Ti , ^{54}Cr , ^{58}Ti , ^{64}Ni with respect to ‘normal’ solar matter found in certain CaAl-rich inclusions of meteorites remain a mystery. In particular, the $^{48}\text{Ca} / ^{46}\text{Ca}$ abundance ratio observed in the EK-1-4-1 inclusion of the Allende meteorite is five times larger than the solar system value. Such inclusions are thought to preserve the direct fingerprint of a given stellar event during the millenia that have expired since their formation. Hence, a process that favours the production of ^{48}Ca with respect to that of ^{46}Ca needs to be identified. A “weak” r-process scenario could be a solution, since the main progenitors of ^{48}Ca and ^{46}Ca lie at or close to the $N=28$ shell closure at lower Z . These nuclei, e.g. ^{46}Cl and ^{48}Ar (cf. Fig. 2) would be produced by successive neutron-captures from stable nuclei. The location of the branching points in each isotopic chain depends on the competition between neutron capture and beta-decay times (Fig. 2) at a given stellar neutron-density. Hence, main progenitors of ^{46}Ca and ^{48}Ca should be found at masses $A=46$ and $A=48$, respectively. Although the beta-decay half-lives of the neutron-rich isotopes in this mass region have extensively been studied at GANIL (O. Sorlin et al. PRC 47 (1993) 2941, NPA 583 (1995) 763), the neutron capture cross sections have only been predicted to date (K.-L. Kratz et al., Mem Soc. Astron. It. 72 (2001) 2). Hence, the experimental determination of the neutron capture cross section is of key importance in order to constraint the neutron density of stellar environment that is needed to reproduce the observed $^{48}\text{Ca} / ^{46}\text{Ca}$ meteoritic abundance ratio mentioned above. In addition, the neutron capture cross section will provide an indication as to whether the matter flow in the Ar-chain terminates already at $A=46$ or continues up to $A=48$.

The $N=28$ shell closure:

Addressing the nuclear physics point, the erosion of the $N=28$ closed shell has been demonstrated by our work on beta-decays properties of ^{43}P , ^{44}S and ^{45}Cl . Their experimental half-lives could only be explained assuming an onset of quadrupole deformation south to ^{48}Ca , which was neither predicted nor accepted at that time by the nuclear-structure community. However, this idea was soon confirmed by both theory and Coulomb excitation experiments (H. Scheit et al, PRL 77 (1996) 3967). Neither the size of the $N=28$ shell gap (between $f_{7/2}$ and $p_{3/2}$) nor the occupation of these orbitals have yet been determined. Our spherical calculations using QRPA are in agreement with the full shell model calculations of F. Nowacki (private comm.). Both yield a gap of 3.7 MeV in ^{46}Ar , which is slightly smaller than that in ^{48}Ca (4.3MeV). This does

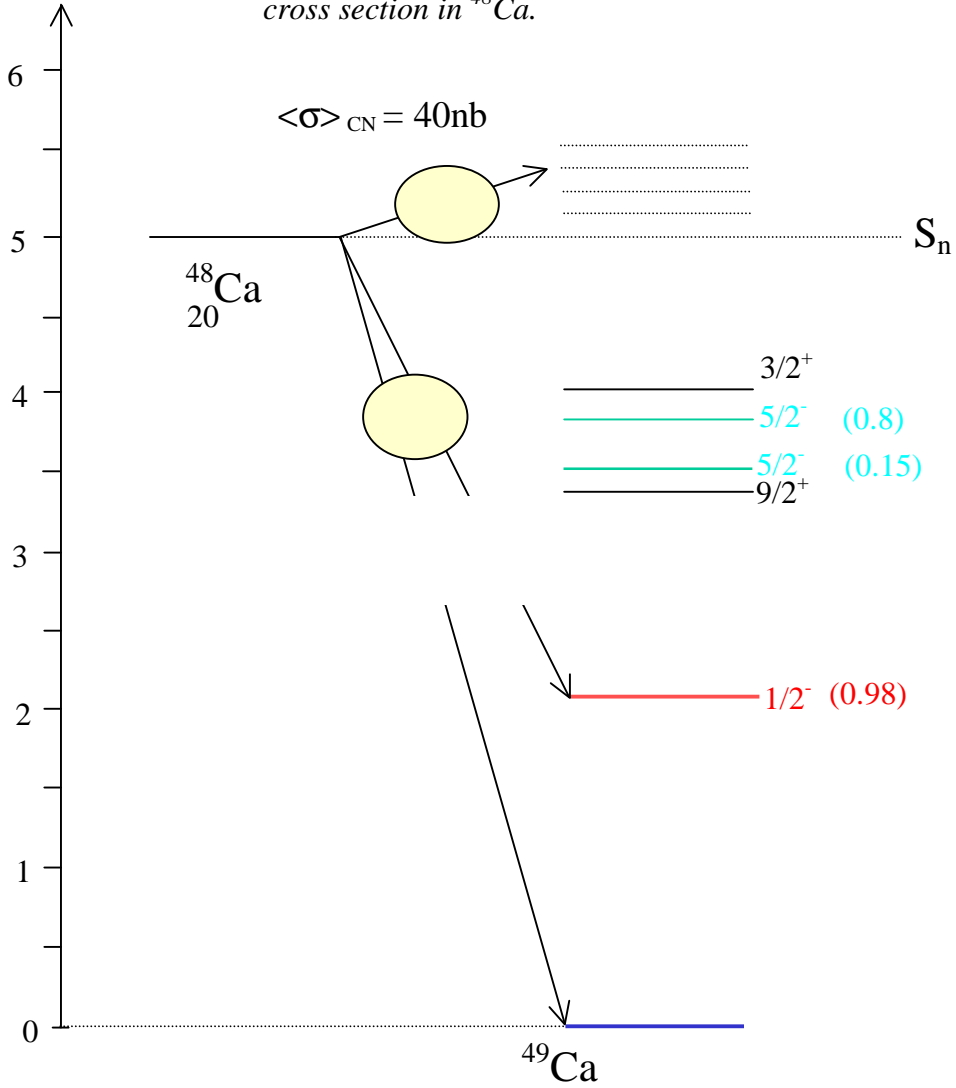
not correspond to a strong erosion of N=28. However, QRPA calculations based on a deformed potential suggest a decrease of the N=28 gap of the order of 1MeV. Hence, the study of ^{44}Ar and ^{46}Ar transfer reactions will determine the size of the N=28 gap and the occupation probabilities of the $f_{7/2}$ and $p_{3/2}$ orbitals, thus testing the erosion or persistence of the N=28 shell gap below ^{48}Ca .

Experimental procedure:

Expected secondary beam rates of ^{44}Ar and ^{46}Ar at REX-ISOLDE are 10^6 and 3×10^4 pps, respectively. An energy of 3.1 A.MeV will become available, if the energy upgrade will take place that has been proposed to this INTC by the REX-ISOLDE collaboration (Spokesperson: O. Kester, Contactperson: T. Sieber). Transfer reactions are induced on thick $(\text{CD}_2)_n$ -target. The protons are detected by the 164 modules of a CD detector located at backward angles. The residual projectile is detected in an annular detector located downstream. When the transfer occurs to unbound states, the emerging nuclei will be unchanged, whereas formation of bound states will yield fragments that possess a mass of A+1. Both reactions are of interest for the purpose of this experiment. A Monte Carlo simulation of the whole experiment has been done, inspired by the case of the $^{48}\text{Ca}(d,p)^{49}\text{Ca}$ reaction done by R. Abegg et al. (NPA 303 (1978) 121) with a deuteron beam of 6 A.MeV. Since the ^{47}Ar nucleus is an isotone of ^{49}Ca , their level schemes may not be very different. It is, however, expected that the level scheme of ^{47}Ar would contain more core-breaking admixtures. The simulation has been done with a total number of 10^{10} nuclei (which corresponds to about 4 days of beam-time for ^{46}Ar), assuming that mainly three levels are populated. These are according to the shell model calculations of F. Nowacki: the $p_{3/2}$ g.s., the $p_{1/2}$ state at 1.3 MeV, and a $f_{5/2}$ state at 2.7 MeV (Fig. 1). In addition, DWBA calculations have been performed using the optical potential of R. Abegg et al. For the three levels considered here, we have taken the calculated spectroscopic factors of 0.64, 0.82 and 0.2 respectively. The results of these calculations suggest that one can distinguish between $l=1$ and $l=3$ states from the cross-section patterns as a function of the proton angle.

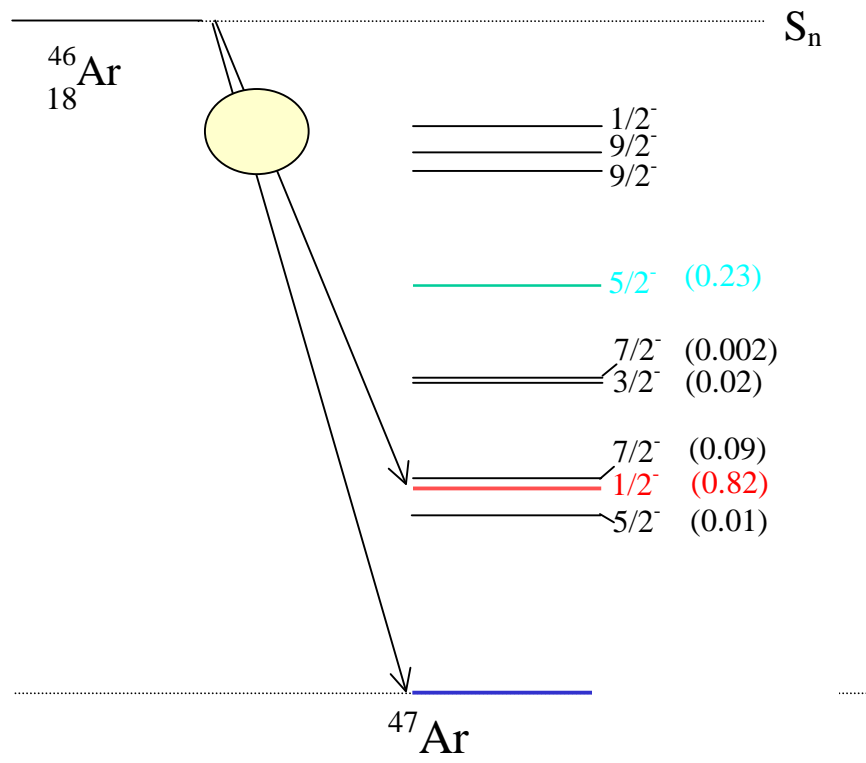
Fig. 1: Illustration of the neutron captures in ^{48}Ca (left) and ^{46}Ar (right). Spectroscopic factors are written in parenthesis for the levels. They have been measured in the case of ^{48}Ca and calculated for ^{46}Ar . The Direct Capture component represents 95% of the cross section in ^{48}Ca .

E^* [MeV]



E. Krausmann et al. PRC 53 (1996) 469.
R. Abegg et al. NPA 303 (1978) 121.

↻ 95% of the cross section is DC



Calculations Shell Model
F. Nowacki

↻ Similar behaviour expected in ^{46}Ar

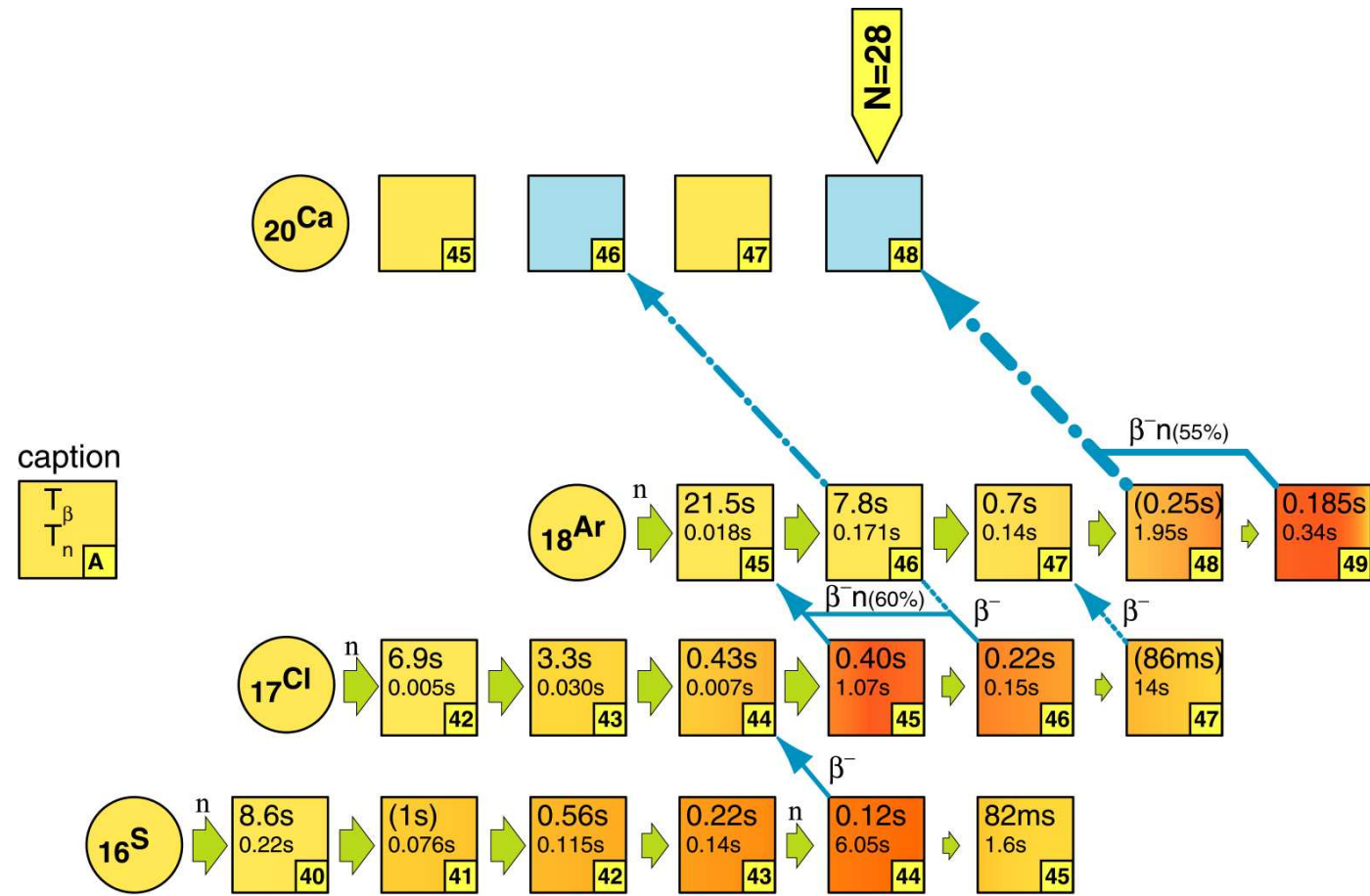


Fig. 2 : Illustration of the neutron-capture beta-decay path south to ^{48}Ca for neutron densities and temperatures of $4 \cdot 10^{19} \text{ cm}^{-3}$ and $8 \cdot 10^8 \text{ K}$ respectively. The nuclei ^{44}S , ^{45}Cl , ^{48}Ar are the most important branching point. Calculated neutron capture times are indicated on the second line in the squares and the measured β -decay times on the first line.

