Interpretation of the Solar $^{48}Ca/^{46}Ca$ Abundance Ratio and the Correlated Ca-Ti Isotopic Anomalies in the EK-1-4-1 Inclusion of the Allende Meteorite

W. Ziegert, M. Wiescher, and K.-L. Kratz
Institut für Kernchemie, Universität Mainz, D-6500 Mainz, Germany

P. Möller and J. Krumlinde
Department of Mathematical Physics, Lund University, S-22100 Lund, Sweden

and

F.-K. Thielemann and W. Hillebrandt
Max-Planck-Institut für Physik und Astrophysik, Institut für Astrophysik, D-8046 Garching, Germany
(Received 17 June 1985)

β-delayed neutron-emission probabilities of neutron-rich S to K isotopes are calculated with nuclear-structure effects taken into account. These results strongly affect predictions made in high–neutron-density astrophysical scenarios for isotopic abundances of several elements. In particular, it is demonstrated that the solar abundance ratio $^{48}Ca/^{46}Ca$ as well as the correlated Ca and Ti isotopic anomalies can be explained by the same nucleosynthesis process.

PACS numbers: 97.10.Cv, 23.40.Hc, 95.30.Cq, 98.80.Ft

Progress in nuclear *astrophysics* is intimately related to continued experimental and theoretical efforts in *nuclear physics.* For example, astrophysical models encountered severe difficulties when they tried to reproduce the solar $^{46,48}Ca$ abundances[1] or the correlated Ca and Ti isotopic anomalies observed in inclusions of the Allende meteorite,[2,3] which may be due to the poor knowledge of the relevant nuclear-physics data for neutron-rich isotopes around ^{48}Ca. Therefore, we have investigated the influence of nuclear-structure properties of short-lived S to K nuclides on the production of their Ca and Ti β-decay daughters in astrophysical neutron-capture processes.

While the lighter Ca isotopes up to ^{44}Ca are produced in explosive O and Si burning[4,5] with possible s-process contributions,[6] the rare heavy isotopes $^{46,48}Ca$ are probably the result of a different, independent nucleosynthesis process. The products of this process may then later be mixed into presolar material to form the observed solar abundances, or, if remaining unmixed, may show up as primordial meteoritic inclusions with the original isotopic abundance composition which may be different from the solar one.

Various attempts have been made to identify the exotic origin of the heavy Ca and Ti isotopes. Sandler, Koonin, and Fowler[7] (SKF) suggested that these isotopes could have been produced in a high–neutron-density environment of 10^{-7} mol/cm^3 with a neutron exposure time of 10^3 s, in which both neutron captures and β decays are effective ($n\beta$ process). Assuming the initial abundances to be solar and applying statistical Hauser-Feshbach (HF) neutron-capture cross sections,[8] SKF have calculated a $^{48}Ca/^{46}Ca$ abundance ratio of 21.5, which is only a factor of 2.6 smaller than the observed solar value of 56.[1] However, the predicted isotopic anomalies for ^{46}Ca and ^{49}Ti were too large compared to those in the EK-1-4-1 inclusion of the Allende meteorite.[2,3] In order to reduce the abundances of these two isotopes, SKF proposed a low-lying s-wave resonance in $^{46}K(n,\gamma)$ and $^{49}Ca(n,\gamma)$, respectively. These resonances would enhance the global HF rates by a factor of 10; and with this, the depletion of the above progenitors of ^{46}Ca and ^{49}Ti would be increased considerably.

In the case of $^{49}Ca(n,\gamma)$, indeed, such a low-lying s-wave neutron-capture resonance was observed experimentally in the "inverse reaction" to neutron absorption, i.e., β-delayed neutron emission (abbreviated by βn_d in the following) of 740-ms ^{50}K.[9] However, subsequent measurements of the partial decay widths of this state of $\Gamma_n = 5.4$ keV and $\Gamma_\gamma \leq 30$ eV have put constraints on the Breit-Wigner–resonance neutron-capture rate. It will be smaller than the HF rate for stellar temperatures of $T \leq 7.5\times10^8$ K, but may be enhanced by up to a factor of 4 over the average continuum cross section for $T \geq 1.2\times10^9$ K. Nevertheless, this is not sufficient to support the explanation of the meteoritic ^{49}Ti abundance suggested by SKF.[7]

Recently Käppeler *et al.*[10] have used their experimental neutron-capture cross sections for estimating the steady-state abundance ratio of ^{48}Ca to ^{46}Ca in a high–neutron-density ($n_n \gtrsim 10^{12}$ cm^{-3}) environment but could not reproduce the solar-system value. In a different approach Hartmann *et al.*[11] have calculated the nuclear abundances of matter that, in the deep interior of a supernova, has gone through a phase of nuclear statistical equilibrium and is ejected with a rather large neutron excess. They were able to fit the solar-system $^{48}Ca/^{46}Ca$ ratio but the ^{48}Ca and ^{50}Ti isotopic anomalies of the EK-1-4-1 inclusion were not well reproduced. Moreover, since in their model ^{48}Ca is a primary nucleus, strong restrictions on the amount of such matter ejected in a typical supernova event had to be imposed in order to avoid huge overproduction.

Motivated by those difficulties and by the unexpectedly high βn_d-emission probability of $P_n = 86\%$ for ^{49}K,[12] we have investigated possible implications of this decay mode on the Ca and Ti isotopic abundances. The idea behind this attempt is the following: If we assume the nucleosynthesis path around $A=48$ to lie in the K chain with considerable production of ^{49}K, βn_d emission from this precursor will predominantly form ^{48}Ca, whereas ^{49}Ti will only be populated weakly through direct β decay of ^{49}K. This would enhance the ^{48}Ca abundance and reduce the abundance of ^{49}Ti. Similarly, the low ^{46}Ca abundance could be due to βn_d emission of its $A=46$ progenitors.

In the $A=48$ mass region, experimental P_n values exist so far only for K precursors.[12] The strong variation of the βn_d branching ratios (e.g., ^{48}K, 1.1%; ^{49}K, 86%) is well understood as being due to the specific nuclear structure of the respective Ca emitters.[12,13] Since the commonly used statistical gross theory[14] fails badly to reproduce these P_n values (e.g., ^{48}K, 0.17%; ^{49}K, 8.9%), we have used the random-phase approximation (RPA) shell model of Krumlinde and Möllen[15] to derive theoretical βn_d branching ratios for neutron-rich S to Ca precursors from the respective Gamow-Teller strength functions. Since these calculations were quite successful in reproducing the known potassium P_n values (e.g., ^{48}K, 0.65%; ^{49}K, 95%), we believe that the predicted variations in the P_n values of neighboring S to Ar precursors are reliable too. As examples, in Fig. 1 the shell-model strength functions for $^{44-46}$S and $^{47-49}$Ar are shown; and a comparison of the RPA with the gross-theory P_n values is included in order to illustrate the influence of the particle-hole structure on the βn_d decay of these precursors. In both models, Q_β and B_n values were taken from Wapstra and Audi[16] and von Groote *et al.*[17]

The network calculations of SKF[7] did not include βn_d emission; but the $n\beta$-process path lies rather close to the line of β stability, so that in this model βn_d branching will not cause substantial changes in the residual isotopic abundances. At higher neutron densities, however, the nucleosynthesis path will be shifted far off β stability, where the decay mode of βn_d emission plays a significant role in altering the decay back to the stability line after freeze out. Such an astrophysical scenario may be explosive He burning (n process),[18,19] which may be associated with a supernova shock front in the He-burning shell of a massive presupernova star. With neutron densities of 10^{-5}–10^{-3} mol/cm^3 at short time scales of <1 s, fast neutron capture will shift the process path to isotopes with β decay half-lives of $\leqslant 1$ s.

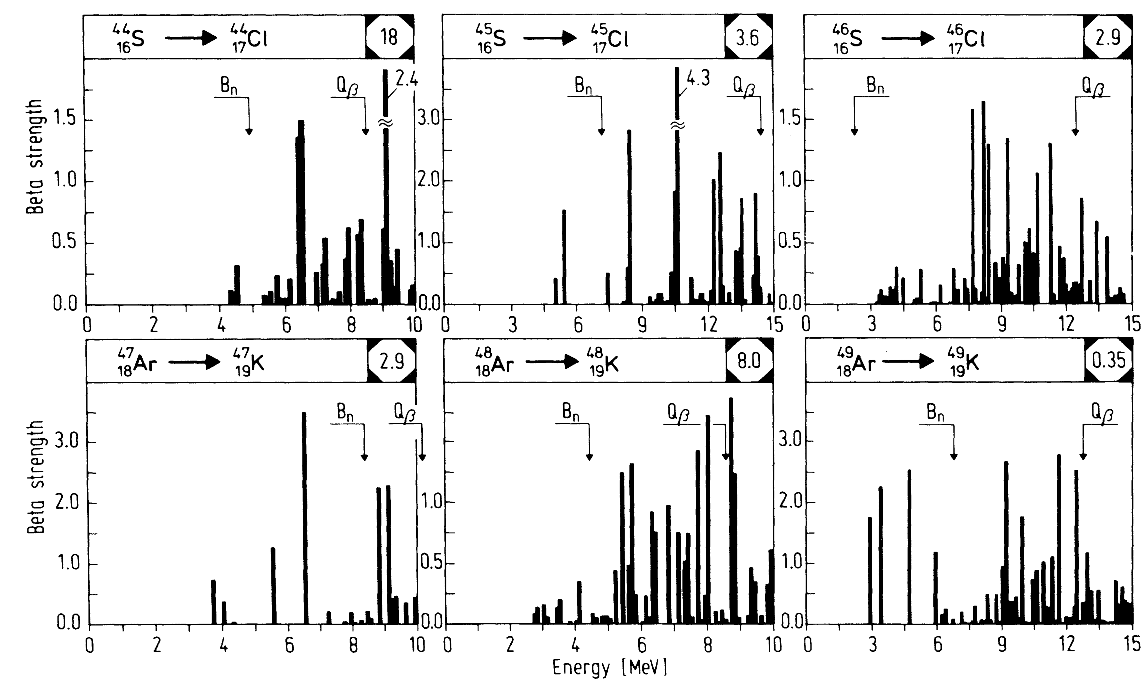

FIG. 1. Gamow-Teller strength functions of $^{44-46}$S and $^{47-49}$Ar, calculated with the RPA shell model of Ref. 15. Q_β and B_n values were taken from Refs. 16 and 17. In order to illustrate the influence of nuclear structure on βn_d decay, in the upper right corner of each figure the P_n ratio [RPA/(gross theory)] is given.

Starting from solar abundances, we have calculated the buildup to isotopic abundance distributions of short-lived S to Ti nuclei as a function of neutron exposure by using HF rates calculated with the code SMOKER (see Mathews *et al.*[20] where the validity of the HF model is also discussed) and the simplification of treating subsequent neutron capture for each element separately, without considering competing β-decay and (γ,n) reactions. Although from the mathematical point of view the solutions of this simplified reaction network depend mainly on the neutron exposure, they are only meaningful if neutron exposure times are ≤ 1 s and temperatures are $< 10^9$ K. The validity of our results is therefore restricted to astrophysical conditions where both requirements are fulfilled, and again explosive He burning may serve as a typical example. From the calculated abundance distributions (see, e.g., Fig. 2) at freeze out, additionally corrected for estimated effects from β decay of the shortest-lived members of each Z chain during neutron exposure, the decay back to the stability line was determined with βn_d branchings taken into account.

With the large odd-even effects in the initial element abundances and with the different buildup times for the $A=46$ and the $A=48$ isotopes in each Z chain according to their distance from β stability, there should be specific astrophysical conditions under which ^{46}Ca will be formed with low abundance and ^{48}Ca with high abundance. One may, for example, imagine a situation where the maximum of the abundance distribution of an even-Z element (with large initial abundance) has just passed $A=46$, whereas the $Z-2$ abundance distribution has not yet reached $A=46$. Then, a relatively low ^{46}Ca abundance would result. Such a situation seems to exist for neutron exposures of about $(3-5)\times 10^{-15}$ mol cm^{-3} s, for which ^{48}Ca will be formed mainly by $^{48}\mathrm{Ar}(\beta^-)\,^{48}\mathrm{K}(\beta^-)\,^{48}\mathrm{Ca}$ and by $^{49}\mathrm{Ar}(\beta^-)\,^{49}\mathrm{K}(\beta^- n)\,^{48}\mathrm{Ca}$. Just at the above neutron exposures, where the overall production of ^{48}Ca progenitors is largely enhanced, the formation of the ^{46}Ca progenitors, ^{46,47}Cl and ^{46,47}Ar, shows a minimum. For these conditions, the final abundance ratio ^{48}Ca/^{46}Ca is calculated to be in the range 40 to 66, which is in excellent agreement with the observed solar abundance ratio.[1]

In order to derive meteoritic Ca and Ti abundances, the resulting n-process abundances at different neutron exposures were mixed into solar material, as done by SKF.[7] From these abundances, isotopic anomalies, as defined in Refs. 2 and 3, were derived. Figure 3 compares the results from our approach with those from the $n\beta$ process[7] and with the observed Ca and Ti anomalies in the EK-1-4-1 inclusion of the Allende meteorite.[2,3] At a neutron exposure of about 7×10^{-5} mol cm^{-3} s, the best overall agreement for the isotopic anomalies is obtained, including the two "problem nuclei" of the $n\beta$ process, ^{46}Ca and ^{49}Ti. With particular regard to the latter two nuclides, βn_d emission from the progenitors ^{46,47}Cl and ^{49,50}K, respectively, seems to be the reason for the low isotopic abundances of ^{46}Ca and ^{49}Ti in the EK-1-4-1 inclusion. It is also interesting to note that for the same neutron exposure we obtain $[^{48}\mathrm{Ca}]/[^{50}\mathrm{Ti}]=3.56$ (where brackets denote abundances relative to their solar-system values) in

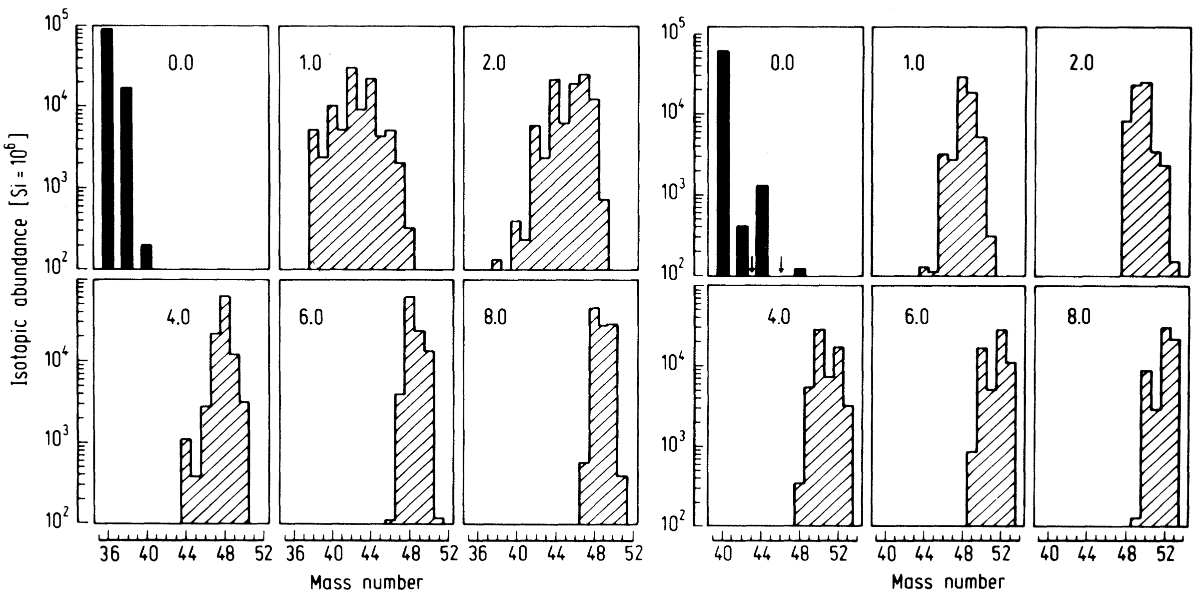

FIG. 2. Abundance distributions of (left) $_{18}$Ar and (right) $_{20}$Ca isotopes as a function of neutron exposure in units of 10^{-5} mol cm^{-3} s. The initial abundances (neutron exposure $=0.0$) are the solar ones (Ref. 1).

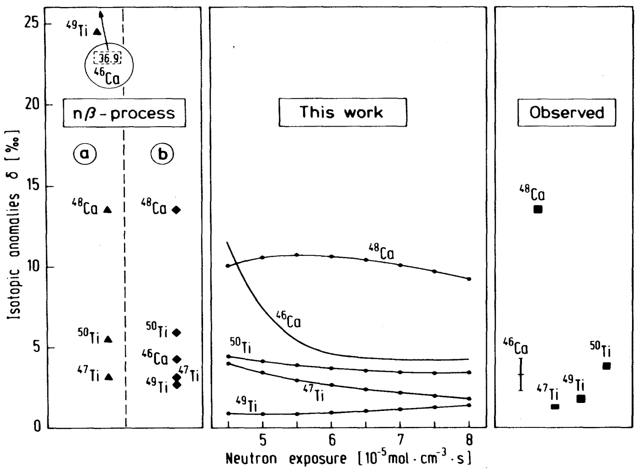

FIG. 3. Comparison of the correlated Ca and Ti isotopic anomalies predicted by the $n\beta$ process (Ref. 7) [(a) with HF rates for all nuclei, and (b) with cross sections increased by a factor 10 for ^{46}K(n,γ) and ^{49}Ca(n,γ)] with our calculations and with the anomalies observed in the EK-1-4-1 inclusion of the Allende meteorite (Refs. 2 and 3).

perfect agreement with the observed ratio of 3.6 ± 0.2 in EK-1-4-1.[3]

Since the astrophysical conditions described here are similar to those that can tranform a solar-system seed composition of heavy elements into an *r*-process abundance distribution,[18,19] the question arises whether the production of ^{48}Ca will be accompanied by intolerably large overabundances of *r* nuclei. In order to answer this question we have solved an *r*-process network including elements from Fe to Ru and found no severe overproductions, mainly because the neutron exposure was still not sufficient to transform all iron-group elements into *r* nuclei.

To summarize, we have demonstrated that with only slightly different neutron exposures the *same* nucleosynthesis process may yield both the solar ^{48}Ca/^{46}Ca abundance ratio and the meteoritic Ca and Ti isotopic anomalies of the EK-1-4-1 inclusion. The consideration of nuclear-structure effects in β-decay properties of neutron-rich S to K isotopes in high-density neutron-capture models seems to be the nuclear-physics clue to the solution of these astrophysical problems. A more quantitative confirmation of our ideas by complete network calculations, including an extension toward isotopic anomalies in neighboring elements (e.g., S and Cr), is in progress.

This work comprises part of the doctoral dissertation of one of us (W.Z.) to be submitted to Johannes Gutenberg-Universität Mainz. We would like to thank A. G. W. Gameron, W. A. Fowler, and J. G. Wasserburg for stimulating discussions, and the Deutsche Forschungsgemeinschaft for financial support.

[1]A. G. W. Cameron, in *Essays in Nuclear Astrophysics*, edited by C. A. Barnes *et al.* (Cambridge Univ. Press, Cambridge, England, 1982), p. 23.

[2]T. Lee *et al.*, Astrophys. J. **220**, L21 (1978), and **228**, L93 (1979).

[3]F. R. Niederer *et al.*, Geochim. Cosmochim. Acta **45**, 1017 (1981).

[4]D. Bodansky *et al.*, Astrophys. J. Suppl. Ser. **148**, 16 (1968).

[5]S. E. Woosley and T. A. Weaver, in Ref. 1, p. 337.

[6]F. Käppeler *et al.*, Astophys. J. **257**, 821 (1982).

[7]D. G. Sandler *et al.*, Astrophys. J. **259**, 908 (1982).

[8]S. E. Woosley *et al.*, At. Data Nucl. Data Tables **22**, 371 (1978).

[9]K.-L. Kratz *et al.*, Astron. Astrophys. **125**, 381 (1983).

[10]F. Käppeler *et al.*, Astrophys. J. **291**, 319 (1985).

[11]D. Hartmann *et al.*, Astrophys. J. (to be published).

[12]L. C. Carraz *et al.*, Phys. Lett. **109B**, 419 (1982).

[13]A. Dobado and A. Poves, in Proceedings of the Summer School on Heavy-Ion Collisions, La Rábida, Spain, 1982 (unpublished).

[14]K. Takahashi, Prog. Theor. Phys. **47**, 1500 (1972).

[15]J. Krumlinde and P. Möller, Nucl. Phys. **A417**, 419 (1984).

[16]A. H. Wapstra and G. Audi, Nucl. Phys. **A432**, 55 (1985).

[17]H. von Groote *et al.*, At. Data Nucl. Data Tables **17**, 471 (1976).

[18]J. W. Truran *et al.*, Astrophys. J. **222**, L63 (1978).

[19]F.-K. Thielemann *et al.*, Astron. Astrophys. **74**, 175 (1979).

[20]G. J. Mathews *et al.*, Astrophys. J. **270**, 740 (1983).