Reaction Rates for ^{146}Sm Production in Supernovae

Thomas Rauscher

Institut für Kernchemie, Universität Mainz, Fritz-Strassmann-Weg 2, D-55099 Mainz, Germany

and

Institut für theoretische Physik, Universität Basel, Klingelbergstr. 82, CH-4056 Basel, Switzerland[*]

e-mail: rauscher@vkcmzd.chemie.uni-mainz.de

Friedrich-Karl Thielemann

Institut für theoretische Physik, Universität Basel, Klingelbergstr. 82, CH-4056 Basel, Switzerland

e-mail: fkt@quasar.physik.unibas.ch

Heinz Oberhummer

Institut für Kernphysik, Technische Universität Wien, Wiedner Hauptstr. 8–10, A-1040 Vienna, Austria

e-mail: hoberhum@ecxph.tuwien.ac.at

Abstract

Correlations of the ^{142}Nd/^{144}Nd ratio with the Sm/Nd ratio in some meteorites have been previously explained by the α-decay of long-lived ^{146}Sm. In order to account for these observations, a necessary production ratio for ^{146}Sm/^{144}Sm in the γ-process of 0.1–0.7 was deduced. The ratio (^{148}Gd(γ,n)^{147}Gd)/(^{148}Gd(γ,α)^{144}Sm), which plays the dominant role in the production of ^{146}Sm/^{144}Sm, has been re-determined in the present paper by improved statistical model calculations. Utilization of folding potentials for

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[*]current address

the α-channel reduce the (γ,α) rate by a factor of 3, which would enhance the production ratios, previously predicted at the lower limit of the allowed range 0.1–0.7. However, additional improvements in the treatment of nuclear level densities also reduce the (γ,n) rate by a factor of 0.4. Thus, in total the new cross section calculations result, at best, only in a modestly enhanced production ratio of ^{146}Sm/^{144}Sm.

Subject headings: nuclear reactions, nucleosynthesis, abundances — supernovae: general

I. INTRODUCTION

Prinzhofer, Papanastassiou, & Wasserburg (1989) showed that the ratio of ^{142}Nd/^{144}Nd is correlated with the Sm/Nd ratio in some meteorites. The nucleus ^{142}Nd is produced by α-decay of ^{146}Sm ($\tau_{1/2} = 1.03 \times 10^8$ yr) and therefore an abundance ratio of ^{146}Sm/^{144}Sm can be deduced. This ratio was inferred to be approximately 0.015 at the time the solar system formed and thus the production ratio should be higher if one allows for decay.

Woosley & Howard (1978) published a detailed study of nucleosynthesis in type II supernovae. In that paper they proposed the existence of the so-called γ-process which was confirmed in later reexaminations (Rayet, Prantzos, & Arnould 1990). However, they also stated that the isotopic ratio of ^{146}Sm/^{144}Sm coming from the γ-process would only be about 0.02. Comparing this to the range of values derived from the Prinzhofer et al. (1989) work one finds that the calculated number is too low by factors of about 10–50 (when allowing for a reasonable time for decay *before* formation of the solar system). Such a discrepancy could put doubts on the origin of ^{146}Sm and ^{144}Sm.

The nuclear reaction rates used in the network calculations play a crucial role in the determination of the ^{146}Sm/^{144}Sm ratio. Therefore, Woosley & Howard (1990) published a reexamination of the ^{146}Sm production with revised photodisintegration rates. They were able to show that the calculated ^{148}Gd(γ,α)^{144}Sm rate would have to be smaller by a factor of about 3 in order to reproduce the ^{146}Sm/^{144}Sm ratio derived from observations.

We recalculated the relevant rates in the statistical model using updated input parameters (masses, optical potentials, level densities, photon transmission functions). As shown in Woosley & Howard (1990) the ratio ^{146}Sm/^{144}Sm is determined almost entirely by the ratio of the neutron- and α-channels of the excited ^{148}Gd nucleus. Thus, the relevant rates are those of ^{148}Gd(γ,n)^{147}Gd and ^{148}Gd(γ,α)^{144}Sm. A minor role is played by the reaction ^{150}Gd(γ,α)^{146}Sm, bypassing the ^{148}Gd nucleus. However, the rate of this reaction is extremely small compared to the other rates and can be neglected.

II. RATE DETERMINATION

In our calculations we made use of the statistical model code SMOKER (Thielemann, Arnould, & Truran 1987) which also includes width fluctuation corrections. In the recalculation we used a folding potential in the α-channel for the real part of the optical potential, which has been applied successfully in many astrophysically relevant reactions before. It is expected to be more suitable than the previously used equivalent square well potentials for which the effective radius parameters are quite uncertain.

In this approach the nuclear target density ρ_{T} (derived from experimental charge distributions or from theory) is folded with an energy and density dependent nucleon-nucleon interaction v_{eff} (Kobos et al. 1984):

$$V(R,E) = \lambda V_{\mathrm{F}}(R,E) = \lambda \int \rho_{\mathrm{T}}(\vec{r}) v_{\mathrm{eff}}(E, \rho_{\mathrm{T}}, |\vec{R}-\vec{r}|) d\vec{r} \quad , \tag{1}$$

with $\vec{R}$ being the separation of the centers of mass of the two colliding nuclei. The normalization factor λ is close to unity and is the only open parameter left for the real part of the optical α-potential. For the imaginary part of the potential we employ a Saxon-Woods form with the radius r_{W} and diffuseness parameter a_{W} taken from a global α-potential (Mann 1978): $r_{\mathrm{W}} = 1.4A^{1/3}$ fm; $a_{\mathrm{W}} = 0.52$ fm.

Volume integrals are used to obtain the strength factor λ and the depth of the Saxon-Woods imaginary part. The strength of a potential is measured by its volume integral per interacting pair of nucleons

$$J(E) = \frac{4\pi}{A_{\mathrm{P}} A_{\mathrm{T}}} \int_0^\infty V(R,E) R^2 \, dR \quad , \tag{2}$$

where A_{P} and A_{T} denote the projectile and target mass numbers, respectively. Volume integrals for the real and imaginary part have been deduced from measurements of light nuclei, but also for intermediate and heavy nuclei (Mohr et al. 1994). From these experimental data a mass and energy dependent parametrization can be found. For the real part (which is only very weakly dependent on the mass for all heavier nuclei) the form

$$\frac{J}{A_{\rm P} A_{\rm T}} = (320 + 0.67 E_{\rm c.m.})\ {\rm MeVfm}^3 \tag{3}$$

is obtained ($E_{\rm c.m.}$ in MeV). As expected, for the imaginary part a strong mass dependence of the volume integral is observed. For ^{144}Sm the value is about 30 MeVfm^3 at a projectile energy of 10 MeV (Mohr et al. 1994). We determined the free parameters by fitting the volume integrals mentioned above. In this manner we find $\lambda = 1.1573$ and for the depth of the Saxon-Woods potential in the imaginary part $W = 10$ MeV.

In our calculations we made use of the most recent mass table (Audi & Wapstra 1993) and the mass formula by Möller et al. (1994) where experimental information was not available.

The level density description gave rise to large uncertainties in previous astrophysical reaction rate calculations (see section 3.4 in Cowan, Thielemann, & Truran 1991). An improved description based on Ignatyuk, Smirenkin, & Tishin 1975 (see also Iljinov et al. 1992; Mengoni & Nakajima 1994), including thermal damping of shell effects, was developed (Rauscher et al. 1995; see also Rauscher & Thielemann 1995). The new description reduces the number of parameters compared to the best global fit as given in Cowan et al. (1991) while lowering the mean deviation from experimental data considerably and is expected to give a similar improvement for the accuracy of level densities for nuclei far from stability. A comparison of the resulting theoretical neutron-capture cross sections for Gd-isotopes to experimental data is given in Section III.

For the remaining properties entering the statistical model calculations we used the same parametrizations and codes as given in Cowan et al. (1991). That means, for the photon transmission function the description of Thielemann & Arnould (1983) is used which satisfactorily reproduces experimental data for spherical and deformed nuclei. The potentials in the neutron and proton channels are the ones given by Jeukenne, Lejeune & Mahaux (1977), based on microscopic calculations, and including the corrections of the imaginary part by Fantoni, Friman, & Pandharipande (1981), and Mahaux (1982). It should be noted that most care was put into ensuring reliable predictions for cross sections of unstable nuclei.

III. PHOTODISINTEGRATION RATES

From the stellar rates of the capture reactions ^{144}Sm(α,γ)^{148}Gd and ^{147}Gd(n,γ)^{148}Gd, calculated in the statistical model, we derived the inverse rates by detailed balance. For a reaction $L(\gamma, j)I$ detailed balance yields the relation (e.g. Woosley et al. 1978)

$$\lambda_{\gamma j} = \frac{G_I}{G_L} \frac{g_I g_j}{g_L} \left(\frac{A_I A_j}{A_L} \right)^{\frac{3}{2}} \left(\frac{m_{\mathrm{u}} kT}{2\pi \hbar^2} \right)^{\frac{3}{2}} < Ij > e^{-Q_{j\gamma}/kT} \tag{4}$$

for the photodisintegration rate $\lambda_{\gamma j}$, with G_I, G_L denoting the temperature-dependent, normalized partition functions. The spin factors $(2J^0 + 1)$, involving the ground state spin J^0, are given by g_I, g_j, and g_L, respectively, and $< Ij >$ is the capture rate. The Q-value for the capture reaction is given by $Q_{j\gamma}$.

Equation (4) is usually derived from the expression for the photodisintegration reaction rate, folding the cross section with a Planck distribution of photons

$$\lambda_{\gamma j} \propto \int_0^\infty \frac{\sigma_{\gamma j}(E_\gamma) E_\gamma^2}{e^{E_\gamma/kT} - 1} \, dE_\gamma \quad . \tag{5}$$

This is compared to the capture rate between two particles obeying a Maxwell-Boltzmann distribution

$$< Ij > \propto \int_0^\infty \frac{\sigma_{Ij}(E) E}{e^{E/kT}} \, dE \quad . \tag{6}$$

One arrives at equation (4) by substituting $\exp(E_\gamma/kT) - 1$ by $\exp(E_\gamma/kT)$ in equation (5) and applying detailed balance (Blatt & Weisskopf 1952).

The substitution mentioned above is justified for reactions with large and positive Q-values because in those cases the integration in equation (5) does not actually start at zero energy but at the energy $Q_{j\gamma}$. For sufficiently large values of $Q_{j\gamma}$ the difference in the denominators of the Maxwell-Boltzmann and the Planck distribution is negligible. Although analytically incorrect, this substitution holds even for negative Q-values (with an error of less than 1%) because of the suppression of the cross section in the integrand by the Coulomb barrier.

Preliminary results on the cross section of ^{144}Sm(α,γ)^{148}Gd have been published in Mohr et al. (1994). For the reaction rate we obtain the values 1.27×10^{-15} cm^3 mole^{-1} s^{-1} at a temperature $T_9 = 2.5$ and 7.56×10^{-13} cm^3 mole^{-1} s^{-1} at $T_9 = 3.0$. (The rates given here and below are always *stellar* rates, since only with those detailed balance can be employed to calculate the photodisintegration rates). This is three times lower than the value for this reaction given by Woosley & Howard (1990). The change in the rate is due to the improved α-potential. By using the folding potential the problem with the ambiguity of the effective radius parameter of the equivalent square well potential (Woosley & Howard 1990) could also be resolved.

In the same paper a network calculation is presented including a variation of the ^{144}Sm(α,γ) rate. It is shown that with such a low rate (see table 1, case C, in Woosley & Howard 1990) the resulting ^{146}Sm/^{144}Sm ratio can be reconciled with the range permitted by observation.

However, in order to treat the rates consistently we also calculated the rate for ^{147}Gd(n,γ)^{148}Gd. Using the global parameter sets described in section II we obtain the values 3.16×10^8 cm^3 mole^{-1} s^{-1} and 3.33×10^8 cm^3 mole^{-1} s^{-1} at $T_9 = 2.5$ and 3.0, respectively. The accuracy of our calculations can be checked by the comparison of the calculated cross sections with recently determined experimental cross sections of Wisshak et al. (1995) (see Table I). As can be seen, our values agree reasonably well with the experimental data, especially for odd targets. It has to be emphasized, however, that we did not intend to adjust any parameters especially to the Gd-region, in order to preserve the reliable predictive power for unstable isotopes from a global fit of the parameters entering the level density description.

Our ^{147}Gd(n,γ)^{148}Gd rate is smaller by about a factor of 0.4 than the rate used by Woosley & Howard (1990). The difference in the rates is mainly due to the different level density treatment involved. This is understandable because Woosley & Howard (1990) employed the level density description and parameters from Holmes et al. (1976). The latter is known to overestimate cross sections and level densities for nuclei close to magic numbers (unless one makes use of experimental level densities, which is not possible for unstable nuclei). This can be illustrated by the behavior of theoretical neutron-capture cross sections at 30 keV in comparison to experimental values (Bao and Käppeler 1987). For example, we find the following values for this ratio with (a) the theoretical description of Holmes et al. (1976), and (b) our treatment, when calculating cross sections for isotopes at magic neutron numbers:

${}^{85}_{36}\mathrm{Kr}_{49}$: $4.19^{(a)}$, $1.44^{(b)}$; ${}^{87}_{38}\mathrm{Sr}_{49}$: $6.18^{(a)}$, $2.5^{(b)}$; ${}^{137}_{56}\mathrm{Ba}_{81}$: $2.27^{(a)}$, $1.74^{(b)}$.

The large discrepancy in case (a) for nuclei close to magic neutron numbers is apparent.

Since the production ratio R of ^{146}Sm/^{144}Sm is determined almost entirely by the ratio of the neutron- and α-separation branches of the ^{148}Gd nucleus (Woosley & Howard 1990) it can be written as

$$R(T) \propto f\left(\frac{\lambda^{148}_{\gamma,\mathrm{n}}(T)}{\lambda^{148}_{\gamma,\alpha}(T)}\right) \quad . \tag{7}$$

(The amount of ^{146}Sm produced by ^{150}Gd(γ,α)^{146}Sm is practically negligible). Our results, which give a reduction by a factor of 0.4 for the (γ,n) rate and a factor of 0.34 for the (γ,α) rate, lead to a total enhancement of this ratio of 1.16 in comparison to Woosley & Howard (1990). Using equation (7) and table 1 in Woosley & Howard (1990), one can determine the ^{146}Sm/^{144}Sm abundance ratio, assuming that the temperature dependence in the range T_9=2.5–3.0 is the same as for the Woosley & Howard (1990) rates. We performed a cubic spline interpolation to the function f in order to compute the production ratio at a given temperature with our rate multiplication factor of 1.16. We obtain a temperature averaged ratio of 0.102, as compared to 0.086 when taking the arithmetic mean of the production values at each temperature given in table 1 in the Woosley & Howard (1990) paper. This is still very close to the lower limit of the range permitted by observations and might argue for short decay periods before the formation of the solar system.

We estimate the error in the ^{147}Gd(n,γ)^{148}Gd cross section arising from the level density description to be about 30%. With a rate enhanced by 30% the temperature averaged ratio would be raised to a value of 0.13. Such a value would also only barely be within the permitted range. (Even with an enhancement of 50% the resulting ratio would only be 0.15).

Summarizing, using improved and consistent input parameters for the statistical model we were able to obtain a ^{146}Sm/^{144}Sm production ratio (barely) consistent with observational limits. A decrease in the ^{144}Sm(α,γ)^{148}Gd cross section was compensated for by an additional decrease in the neutron capture cross section on ^{147}Gd, thus resulting in a similar abundance ratio as found in Woosley & Howard (1990) (table 1, case A). However, only a full network calculation with consistently updated rates for all nuclei involved will be able to give reliable abundances.

ACKNOWLEDGMENTS

This work was supported in part by the Austrian Science Foundation (project S7303-AST), the Scientific-Technical Agreement Austria-Hungary (project A1), and the Swiss Nationalfonds. We want to thank E. Somorjai for discussions and K. Wisshak for the preliminary neutron-capture data. TR is an Alexander von Humboldt fellow.

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TABLES

TABLE I. Maxwellian averaged cross sections $< \sigma >_{30\mathrm{keV}}$ at 30 keV in mbarn for neutron-capture on Gd-isotopes.

Target	Wisshak 1995 (exp.)[1]	this work (calc.)
^{152}Gd	1052±17	870
^{154}Gd	1031±12	622
^{155}Gd	2650±30	2340
^{156}Gd	615±5	455
^{157}Gd	1371±15	1426
^{158}Gd	324±3	265

[1] The common 1.5% uncertainty of the gold standard is not included here, since it cancels out in most applications of relevance for nuclear astrophysics.