Neutron Capture in Dy and Yb Isotopes: Implications for the *s*-Process

K. Wisshak[1], F. Voss[1], C. Arlandini[1], F. Käppeler[1], T. Rauscher[2]

[1] *Forschungszentrum Karlsruhe, Institut für Kernphysik III, Postfach 3640, D-76021 Karlsruhe, Germany*

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

Abstract. The neutron capture cross sections of ^{141}Pr, five Dy and six Yb isotopes were measured in the energy range from 3 to 225 keV at the Karlsruhe Van de Graaff accelerator by means of the time of flight technique. Capture events were registered with the Karlsruhe $4\pi BaF_2$ detector. The overall experimental uncertainty could be reduced to ∼1 – 2%, on average an improvement by factors of five compared to existing data. Stellar neutron capture cross sections were deduced for thermal energies between kT = 8 and 100 keV, and the enhancements under He-burning conditions were calculated. These two sets of new information were used for a detailed analysis of the *s* process in the region of the rare earth isotopes via the classical approach and an AGB star model, which provides new constraints on the *p*-process abundance of ^{160}Dy and for isotopic anomalies in meteoritic material.

1 Motivation

Accurate stellar (n,γ) cross sections of the rare earth isotopes are of interest for s-process studies because of several reasons: They allow to determine the reaction flow and, hence, the produced *s* abundances reliably. Since the solar abundances of these chemically almost identical elements are well known, this mass region is suited for sensitive tests of *s*-process models, either of the traditional classical approach or of stellar models of thermally pulsing AGB stars [3]. Accordingly, the *s*- and *r*-process components can be separated in great detail. Several significant branchings between A=140 and 176 allow to study the physical conditions of He-burning scenarios, such as temperature, neutron density, and electron density [9]. Finally, accurate cross sections are mandatory for an interpretation of isotopic anomalies in meteoritic inclusions [14].

2 Experiment

The neutron capture cross sections of ^{141}Pr, five Dy, and six Yb isotopes were measured in the energy range from 3 to 225 keV at the pulsed Karlsruhe Van de Graaff accelerator, using gold as a standard. Neutrons were produced via the ^{7}Li(p,n)^{7}Be reaction. Capture events were registered with the Karlsruhe $4\pi BaF_2$ detector [13], which consists of 42 hexagonal and pentagonal crystals forming a spherical shell of barium fluoride with 20 cm inner diameter and 15 cm thickness. This detector is characterized by an energy resolution of 14% at 662 keV and 7% at 2.5 MeV, and a time resolution of ∼0.5 ns. The γ-ray efficieny is better than 90% over the entire energy range up to 10 MeV, resulting in typical efficiencies of 97 to 99% for the detection of capture events. Neutron energies are determined by the time of flight (TOF) technique with an overall resolution of 1 ns.

3 Stellar cross sections

From the present results stellar cross sections were derived for thermal energies between kT = 8 and 100 keV. Of these, the 10 and 30 keV values are compared in Table 1 with the evaluated 30 keV data of Bao and Käppeler [1] which are at this energy almost identical with the data of Beer, Voss, and Winters [2]. The last column in this table shows the difference of the evaluated data and the present results. Six of the measured twelve cross sections differ by 15 to 25%, far outside the quoted uncertainties.

Table 1: Stellar neutron capture cross sections of Pr, Dy, and Yb isotopes compared to the evaluation of Ref. [1].[1]

Isotope	$<\sigma>$ (mb) kT=10 keV	$<\sigma>$ (mb) kT=10 keV	Ref.[1]	Δ %
^{160}Dy	1578±27	890±12	772±39	15
^{161}Dy	3891±60	1964±19	2006±60	2
^{162}Dy	796±15	446±4	473±50	6
^{163}Dy	2132±36	1112±11	1140±38	3
^{164}Dy	405±9	212±3	268±27	26
^{141}Pr	247±7	111±1.5	119±15	7
^{170}Yb	1325	768	738±29	4
^{171}Yb	2202	1211	1411±51	17
^{172}Yb	600	341	410±34	20
^{173}Yb	1444	752	865±72	15
^{174}Yb	272	150	176±16	17
^{176}Yb	211	115	111±11	4

[1] The values for the Yb isotopes are yet preliminary but are not expected to change much; final uncertainties will be well below 2%.

4 Cross section calculations

Similar to a number of cases, the experimental (n,γ) data have to be complemented by theoretical calculations in order to arrive at the true stellar rates for the Dy isotopes. At typical *s*-process temperatures the intense photon bath leads to a significant population of low-lying nuclear levels. Accordingly, the effective capture cross section may depend on temperature through neutron reactions on nuclei in excited states, the most important being capture and superelastic scattering. The ratio of the effective stellar cross section derived from model calculations to the cross section measured in the laboratory is denoted as the stellar enhancement factor (SEF).

For the Dy isotopes SEFs were calculated with the statistical model code NON-SMOKER [11] by comparing the cross section for the respective ground state and the effective stellar cross section for thermal energies between kT=10 and 30 keV. The 30 keV results are compared in Fig. 1 with the corresponding values of Harris [5] and Holmes et al. [6]. In general, all results agree within a few % (and even perfectly for ^{160}Dy!), except for a puzzling discrepancy in case of ^{158}Dy.

The discrepancy between the SEF of ^{158}Dy reported in Refs. [5, 6] and the present result has been investigated in some detail, and was found to originate partly from

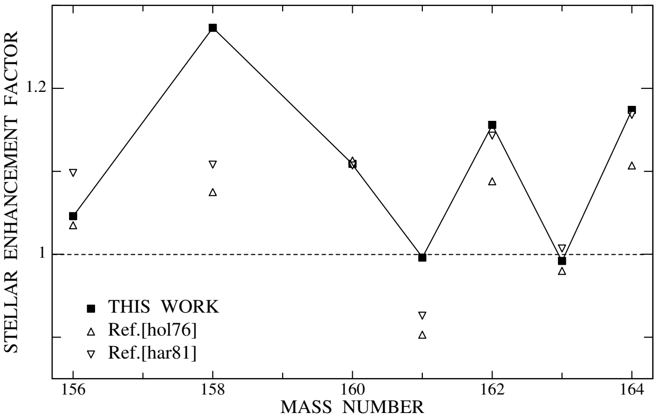

Figure 1: The stellar enhancement factors of the Dy isotopes at a thermal energy of kT=30 keV compared to the values of Refs. [5, 6].

differences in the optical potentials and level densities, whereas mass differences are of minor influence. However, these changes would only cause an 11% variation of the present value. The reason for the remaining discrepancy is yet unclear.

5 Astrophysical implications

The new cross sections have been used for an updated *s*-process analysis. Fig. 2 shows the $N\langle\sigma\rangle$ systematics obtained with the classical approach. The calculated curve (solid line) is normalized at the *s*-only isotope ^{150}Sm. Based on the experimental cross section, the empirical product of ^{160}Dy, the other *s*-only isotope in this region, lies 6% above the curve. If the SEF is considered, this difference increases to 16%. In this calculation the weak branchings at ^{159}Gd and ^{160}Tb, which would further lower the calculated $N\langle\sigma\rangle$ value by 2%, have been neglected. The corresponding differences of 8 to 18% imply that the *s* process does not produce all of ^{160}Dy. In fact, these differences provide evidence for a significant *p*-process contribution to ^{160}Dy, in reasonable agreement with the predictions of model calculations for explosive Ne/O burning in supernovae of type II [10], which give a *p* contribution of ~11%.

The *p* component of ^{160}Dy is significantly reduced if its *s* abundance is calculated within a stellar model for a thermally pulsing AGB star of 1.5 solar masses and with half the solar metallicity. Such a star has been shown to reproduce the main component of the *s*-process abundance distribution and in particular the mass region of the rare earth elements quite well [3]. This model could explain 88% of the observed ^{160}Dy abundance, in good agreement with the estimated *p* component of 11% [10]. Though a full calculation of the *s* abundances within a galactic evolution model did not yet include the new cross sections [4], it can be estimated that it would yield a similar *p*-process component for ^{160}Dy.

Another interesting aspect of the new Dy cross sections concerns the comparison of the isotopic *s* abundances with the Dy abundance pattern in meteoritic inclusions, which in many cases were found to represent pure *s*-process material. The only isotopic anomaly in Dy reported so far [12] exhibits significant differences compared

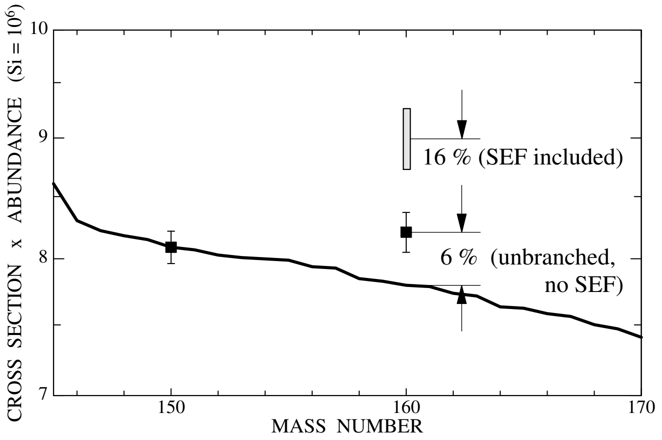

Figure 2: The N$\langle\sigma\rangle$ systematics in the classical approach (solid line) compared to the empirical values (black squares) with and without stellar enhancement factor (SEF).

to the *s*-process pattern inferred from the present data and excludes its interpretation in terms of an *s*-process origin. Nevertheless, a continued search for such a Dy anomaly appears promising since the effect of the branching at ^{163}Dy would be clearly visible in these data. This terrestrially stable nucleus becomes unstable at high temperatures via bound state β-decay, and the resulting branching can be interpreted in terms of the electron or mass density at the *s*-process site [8].

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