Astron. Astrophys. 268, L27–L29 (1993)

ASTRONOMY AND ASTROPHYSICS

*Letter to the Editor*

# Barium isotopes in the very metal-poor star HD 140283*

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Received November 17, accepted November 27, 1992

**Abstract.** The fractions of odd and even isotopes of barium in the metal-poor star HD140283 are determined from an analysis of the profile of the BaII resonance line, taking advantage of the differences in hyperfine structure splitting between the different isotopes. Although one would expect an increased contribution of the r-process in very metal-poor stars (and thus a higher fraction of odd isotopes), it is found that the isotopic ratio ($20 \pm 10\%$ of odd isotopes) is very close to solar.

**Key words:** Stars: abundances – Stars: HD140283 – Stars: Population II – Galaxy: evolution

## 1. Introduction

The elements heavier than the iron peak are mainly produced through neutron capture processes. Two main mechanisms are generally distinguished, the s-process (slow) and the r-process (rapid), depending on the magnitude of the neutron flux available. While the s-process dominates the production of most of these elements in solar system material, it is now generally agreed that the r-process contribution was much higher in the early phases of the galactic evolution. This seems quite natural, as that process is expected to act on time scales much shorter than the s-process, which is believed to take place in the interiors of intermediate or low mass stars.

The suggestion that the r-process is responsible for the production of most (if not all) neutron capture elements in very metal-poor stars dates back to the work of Truran (1981). These ideas were confirmed by the analyses of Sneden and collaborators (Sneden and Parthasarathy 1983, Sneden and Pilachowski 1985, Gilroy et al. 1988) who showed that the heavy elements abundance patterns in very metal-poor giants are in good agreement with expectations from r-process nucleosynthesis and incompatible with the s-process.

On the other hand, as pointed out by Magain (1989), this hypothesis does not seem to agree with the observed variation of relative abundances with metallicity, which show a rise of, e.g., [Ba/Fe] at the lowest metallicities, followed by a more or less constant value for $[Fe/H] > -2$.

However, while all these works deal exclusively with element abundances, most of the neutron capture elements have several isotopes, some of which are primarily or exclusively produced by one process or the other. The information available is thus largely smeared out when element abundances alone are considered. Much stronger constraints would arise from the determination of isotopic ratios as a function of metallicity.

Unfortunately, the heavy elements isotopic ratios are generally not directly measurable, the isotopic shifts being completely negligible compared to the line widths. Nevertheless, some information is available through the fact that the hyperfine structure depends on the nuclear moment and thus on the isotope mass number. This can offer a means of determining the fractions of odd and even isotopes, thus adding one more constraint for each element considered.

A first attempt to estimate the fraction of odd isotopes $R$ was made by Magain and Zhao (1992) in the case of barium. They took advantage of the desaturation provided by the hyperfine structure to determine $R$ by comparing the saturated resonance line of BaII to weaker excited lines. A similar method had been suggested independently by Cowley and Frey (1989). The analysis of Magain and Zhao, carried out for 4 dwarfs with $[Fe/H] \sim -2$, indicated a possible enhancement of the fraction of odd isotopes in these stars as compared to solar system material, in agreement with the expectations.

However, that kind of study, although very easy to implement in practice, requires very accurate data and analysis. In particular, it depends strongly on the line oscillator strengths, on the stellar microturbulence velocity and on possible departures from local thermodynamic equilibrium (LTE) in any of the lines considered. It would thus appear desirable to carry out a more direct determination in at least a few cases, in view of confirming these results. Such an attempt to determine the odd to even isotopic ratio of barium for the well-known halo subgiant HD140283 is described in the following sections.

## 2. Barium isotopes and hyperfine structure

In solar system material, Ba is mainly represented by five stable isotopes, with mass numbers 134 to 138. While the even isotopes are primarily produced by the s-process, the contribution of the r-process to the odd isotopes is very significant (Cameron 1982, Anders and Grevesse 1989). In contrast with the spectral lines of the even isotopes, the lines of the odd iso-

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*Based on observations carried out at the European Southern Observatory, La Silla, Chile

**Chercheur Qualifié au Fonds National Belge de la Recherche Scientifique topes of Ba are affected by hyperfine structure (hereafter HFS). The global effect of HFS on the Ba lines thus depends on the isotopic ratios, and, as a consequence, on the relative contributions of the r and s-processes to the total Ba abundance. This gives a means of estimating the relative contributions of these processes in stars of various metallicities.

The HFS splitting of the resonance line of BaII at 455.4 nm amounts to slightly more then 5 pm for the isotopes 135 and 137 (Rutten 1978). This corresponds to an equivalent broadening velocity of 3.5 km $s^{-1}$, which is comparable to the velocity of the other broadening mechanisms (thermal, microturbulence, macroturbulence, rotational). Depending on the relative contributions of the different broadening mechanisms, the HFS splitting might either be directly discernible or spread out by the convolution with the other broadening profiles. In the latter case, however, it should still be measurable as an additional broadening of the line considered, when compared to other lines not affected by HFS.

Obviously, the spectroscopic observations should be carried out with sufficient resolution to be able to separate the different HFS components. A resolving power of the order of 100000 is thus mandatory.

## 3. Observations and reductions

High resolution spectra were obtained with the Coudé Echelle Spectrometer (CES) fed by the 1.4 m Coudé Auxiliary Telescope at the European Southern Observatory (La Silla, Chile). The observations were carried out in remote control from the ESO headquarters in Garching bei München (FRG), from July 15 to July 18, 1992. The long camera was used. It was for the first time equipped with a 2048 × 2048 pixels Ford CCD, each pixel being of 15 $\mu m^2$ thus corresponding to 1.85 pm in wavelength.

The resolving power, measured from the widths of the thorium lines used for the wavelength calibration, amounts to 100000. Ten spectra, each of one hour exposure time, were obtained. Small wavelengths shifts were applied, so that these spectra were all centered slightly differently on the detector. This ensured that in each exposure, the lines studied fall on different pixels, thus reducing possible systematic errors which might arise from pixel-to-pixel variations. Flat-field and wavelength calibration exposures were obtained for each wavelength setting. Sequences of flat-fields with varying exposure levels were also obtained in order to check the linearity of the CCD, which was found satisfactory.

Specific procedures and programs were written in the MIDAS environment for the reduction of these spectra. These procedures allow for bias, dark, sky and stray light corrections, nonlinearity corrections, flat-fielding, detection of cosmic ray hits, optimal extraction of the spectrum, wavelength calibration, continuum normalization and equivalent width measurement. The continuum was determined by fitting a spline through the mean flux measured in a number of pre-defined continuum windows.

The ten spectra were then averaged, with weights proportional to $\sigma^{-2}$, $\sigma$ being the standard deviation in the normalized continuum. The averaged spectrum has a signal-to-noise ratio (S/N) of 180.

## 4. Line profile analysis

The theoretical line profiles were obtained by solving the radiative transfer equation in a model atmosphere. The model was calculated with the MARCS programme (Gustafsson et al. 1975) and the atmospheric parameters for HD140283 were adopted from Zhao and Magain (1991). The different HFS components were taken explicitly into account as in Table 1. The element abundance was adjusted until the computed equivalent width (EW) was found in agreement with the observed one. Local thermodynamic equilibrium (LTE) was assumed.

**Table 1.** Hyperfine structure model

Even isotopes

| $\delta\lambda$ (pm) | Relative intensity |
|---|---|
| −0.1 | 0.125 |
| +0.0 | 0.875 |

Odd isotopes

| $\delta\lambda$ (pm) | Relative intensity |
|---|---|
| −3.5 | 0.239 |
| −3.2 | 0.133 |
| +1.5 | 0.228 |
| +1.8 | 0.400 |

Before comparing the theoretical profile with the observed one, the broadening profile has to be determined. This includes broadening by stellar phenomena (macroturbulence, rotation) as well as the instrumental profile. The combination of these broadening profiles was determined directly from the comparison of the synthetic profiles to the observed ones for lines not affected by HFS and situated in the same spectral region. Two lines were used: an FeII line at 455.59 nm, which has an EW of 1.59 pm, very similar to the BaII resonance line EW (2.00 pm), and a stronger TiII line at 456.38 nm (EW = 5.03 pm). It was found that a sum of two gaussians could provide an adequate representation of the broadening profile.

The BaII line profile was then computed for various isotopic mixtures and compared to the observations (Figure 1). The isotopic ratio was determined by minimizing the difference between the observed and the synthetic profiles, in the least squares sense. For that purpose, the mean and standard deviation of the observed flux at each wavelength bin were determined from the ten individual spectra, using the appropriate weights. The synthetic spectra, after convolution with the broadening profile, were rebinned on the same grid as the observed spectra and the $\chi^2$ was computed for each value of the isotopic fraction $R$. This last quantity was determined by minimizing the $\chi^2$. A value of $R = 20\%$ was obtained.

In order to estimate the uncertainty on that determination, we repeated that determination on each of the 10 individual spectra. We thus obtained, for each observation, an estimate of $R$. In some cases, we had to extrapolate to (unphysical) negative values of $R$. This is mandatory in order not to introduce a systematic overestimate of the mean value or a systematic underestimate of the scatter. We obtained a mean value of 20%, in agreement with the value determined from the mean spectrum. The one sigma uncertainty on that mean value amounts to 10%.

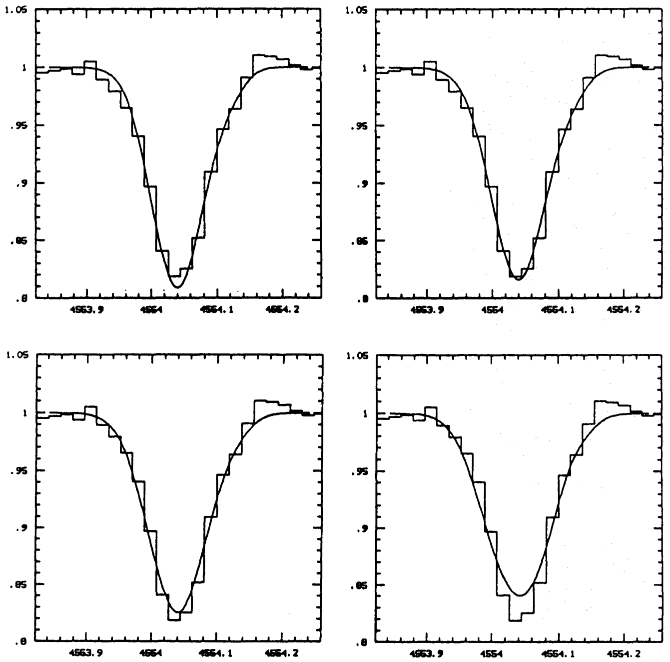


**Fig. 1.** Comparison of the synthetic profile (continuous curve) with the observed one (histogram) for the 455.4 nm resonance line of BaII. The fraction of odd isotopes $R$ used in the computations amounts to 0 (top left), 20% (top right), 50% (bottom left) and 100% (bottom right)

The effect of errors in the stellar atmospheric parameters was estimated by repeating the analysis with different model atmospheres. These errors are negligible: the largest effect comes from the microturbulence velocity, for which a variation of 0.5 km $s^{-1}$ translates into an error of only 4% on the isotopic ratio. Errors on the effective temperature, surface gravity or metal abundances can be completely neglected. This is no surprise since this method compares hyperfine components of the same line, thus having basically the same excitation potential.

As the Ba abundance was determined to fit the observed EW, the present method is independent on the line oscillator strength. On the other hand, the damping constant has some effect on the line profile. The Unsöld formula was used, with no enhancement factor, as indicated by the analysis of the solar line. Multiplying the damping width by a factor 3 (which is certainly an overestimate of the actual uncertainty) would only lead to a 3% reduction of the isotopic ratio.

## 5. Discussion

The isotopic ratio we obtain for HD140283 is in agreement with the solar value ($R_{\odot} = 18\%$). It does not support the hypothesis that the r-process contribution would be larger in metal-poor stars (unless the shift from an r-process dominated barium to an s-process dominated one would preserve the odd-to-even ratio, which appears to be quite an unnatural assumption). However, we should keep in mind that the r-process nucleosynthesis models are still very crude. Thus, one cannot exclude *a priori* such a behaviour which might, for example, be due to a change of the main site of production of r-process barium since the early phases of the galactic evolution.

Another point which must be addressed is the discrepancy with the preliminary results of Magain and Zhao (1992) who found that $R \sim 50\%$ in 4 metal-poor stars. First, one should note that HD140283 is nearly one order of magnitude more metal-poor that these 4 stars. However, we would hardly dare to suggest that the s-process would dominate the very early nucleosynthesis of barium, be then replaced by the r-process and finally become dominant again at high metallicities.

It should be reminded that the results of Magain and Zhao (1992) are quite preliminary and very sensitive to a number of uncertainties. First, the oscillator strength of the weak line at 585.3 nm is still not known with the required accuracy. Secondly, their result is quite dependent on the microturbulence velocity. Although that parameter was carefully determined from a set of CaI lines, the isotopic ratio would be affected by a variation of the microturbulence velocity between the depth at which the CaI lines form and the depth of formation of the BaII lines. Finally, their computations were made in LTE. Any departure from LTE in any of the BaII lines could then change the results. These various points should obviously be investigated in detail, and this is part of our future plans.

The present result, based on only one star, needs confirmation. More stars should be included in the analysis (although it is not obvious to find many stars in which the resonance line of BaII is weak and which can be observed at very high resolution and S/N). Going to higher resolution would allow to improve slightly the accuracy. However, we do not expect a dramatic improvement here as the observed line width is increased by only $\sim 20\%$ due to the instrumental profile. A more promising improvement would be the increase in S/N.

In any case, the present result is, as far as we know, the most direct determination of a heavy element isotopic ratio which has ever been made in a very metal-poor star. It is also maximally insensitive to known sources of uncertainties. We thus feel quite confident in the result, and think it might bring a new stringent constraint on the models of nucleosynthesis and galactic evolution.

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