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Heavy elements in halo stars: the r/s-process controversy*

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Abstract. It has been suggested by Truran (1981) that rapid neutron captures (the r-process) dominate the production of heavy elements in very metal-poor stars. Several spectroscopic works analyzing that hypothesis are reviewed and rediscussed and it is shown that there is, in fact, no secure observational evidence in support of Truran's suggestion.

A method to determine the odd-to-even isotopic ratio of barium, and thus to estimate the relative contributions of the r and s-processes, is presented. It takes advantage of the hyperfine structure affecting the spectral lines of the odd isotopes to distinguish them from the even isotopes.

This method, applied to the classical metal-poor subgiant HD 140283, shows that the barium isotopic ratio in that star is in agreement with a pure s-process production, and excludes any significant enhancement of the r-process contribution, in disagreement with previous works based on elemental abundances.

Key words: stars: abundances – stars: HD 140283 – stars: Population II – Galaxy: evolution – Galaxy: halo – nucleosynthesis

1. Introduction

The elements heavier than the iron peak are mainly produced through neutron capture reactions. Two main mechanisms are generally distinguished: the s-process (slow) and the r-process (rapid), depending on the magnitude of the neutron flux available.

Comparison of the isotopic abundances of these elements in solar system material (mainly meteorites) with the predictions of s-process models allows to determine the contribution of these two processes to the synthesis of the different isotopes (Käppeler et al. 1989). This gives the relative contributions of these processes integrated from the beginning of the Universe to the birth of the solar system. The heavy elements are thus generally classified as r or s-elements, according to the process which dominates their production in solar system material. However, this classification can be very misleading as the relative contribution of these processes may vary with time.

Despite some difficulties in reproducing the detailed solar system abundances, the most popular site for the operation of the s-process is the thermally pulsing helium shell in intermediate-mass asymptotic giant branch (AGB) stars. The site of the r-process is subject to more controversy, but explosive situations, such as those encountered in Type II supernovae, seem to be required.

The r-process abundances are expected to behave in a *primary* way, as neutron captures occur on seed nuclei that were synthesized by the star itself, before operation of the r-process. Thus, synthesis of these elements does not require the presence of seed nuclei at the beginning of the star's life, and can occur in stars of the first generation.

On the other hand, it is generally believed that the s-process elements are *secondary*, which means that their production requires the presence of seed (iron-peak) nuclei in the interstellar gas out of which the star responsible for their synthesis formed. Moreover, these stars, having moderate masses, are also rather long-lived. Thus, the buildup of a significant quantity of s-process is expected to take a rather long time, and these elements should be significantly depleted in the atmospheres of the oldest stars.

As most of the heavy elements can be synthesized to various degrees by both processes, one would expect that the relative contribution of r-process to any of these elements increases with the age of the star being analyzed, and the very oldest stars should show virtually no s-process products.

This suggestion that the r-process is responsible for the production of most (if not all) neutron capture elements in very metal-poor stars was put forward by Truran (1981), following the observational work of Spite & Spite (1978). It explained quite naturally both (1) the observation that the so-called s-process elements are more depleted than the r-process ones in very metal-poor (thus supposedly very old) halo stars and (2) the fact that these so-called s-process elements, although depleted, are present in amounts apparently too important to be explained by a purely secondary s-process, and can be observed in even the most metal-poor stars known.

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This simple idea appeared so clever that it was quite readily accepted, especially after the works of Sneden & collaborators (Sneden & Parthasarathy 1983; Sneden & 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.

However, as pointed out by Magain (1989), this hypothesis does not seem to explain easily 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] $\gtrsim -2$. In this scenario, one would naively expect nearly the reverse behaviour: a quasi-constant value of [Ba/Fe] at the lowest metallicities, when the (primary) r-process is supposed to dominate, followed by a rise when the (secondary) s-process takes the lead.

Moreover, the strength of Truran's arguments is weakened by the fact that recent calculations of galactic chemical enrichment (e.g. Matthews et al. 1992) show that the variation of, e.g., [Ba/Fe] with [Fe/H] can be reproduced by models of the s-process operating in intermediate-mass AGB stars.

Thus, although many experts in the field seem to be convinced that the correctness of Truran's suggestion has been observationally verified, we personally feel that it is not so. In the following section, we will briefly examine the observational evidence provided by the works on metal-poor giants. The rest of the paper will be devoted to the presentation of a new test, based on the determination of the fraction of the odd and even isotopes of barium.

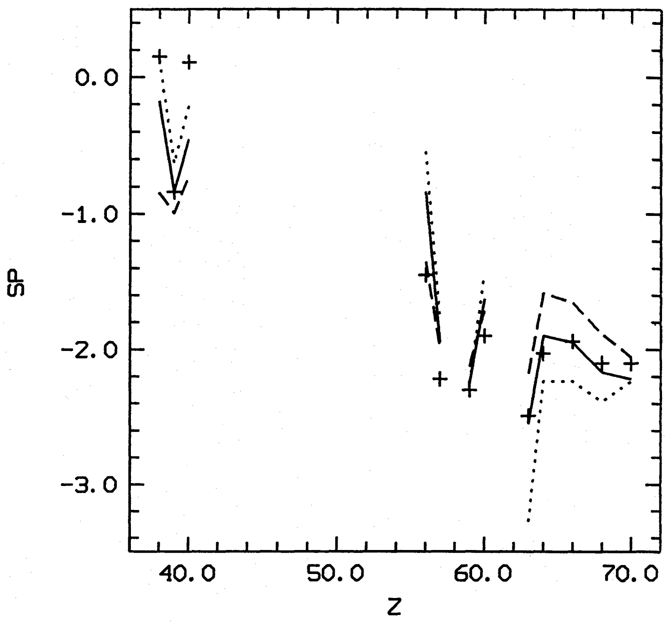

Fig. 1. Comparison of Sneden & Parthasarathy's abundances in HD 122563 (plusses) with three models. Full line: the global meteoritic abundances are scaled; dashed line: the r-process contribution to these meteoritic abundances is scaled; dotted curve: the s-process contribution is scaled. Meteoritic abundances as well as r and s-process contributions are from Cameron (1982). The abundances, in the usual scale ($\log N_H = 12$), are plotted versus the atomic number

2. Abundance analyses

Although most neutron capture elements have several isotopes, with each isotope being synthesized to various degrees by one or the other of the processes, all the past analyses have dealt exclusively with elemental abundances. This is dictated by the fact that the isotopic shifts of the spectral lines are completely negligible for these heavy elements and isotopic abundances therefore virtually out of reach.

Sneden & collaborators thus tried to determine the abundances of as many neutron capture elements as possible. By comparing the distribution of these abundances with model predictions and with solar system s and r-process distributions, they showed that the r-process is the most likely source of neutron capture elements in very metal-poor giants (say, [Fe/H] $\lesssim -2$).

Despite the fact that the chemical composition of their atmospheres might have changed as a result of dredge-up of processed material from the stellar interior, giants were chosen because the spectral lines of most neutron capture elements are too faint to be measured in very metal-poor dwarfs.

2.1. The analysis of Sneden & Parthasarathy (1983)

The first of these analyses is that of Sneden & Parthasarathy (1983), and is devoted to the very metal-poor giant HD 122563. It supports Truran's suggestion by concluding that "*the heavy-element abundances can be understood with nucleosynthesis models in which the progenitors of this star produce mainly r-process isotopes*".

This conclusion was drawn after comparing the abundances of a dozen of neutron capture elements with scaled distributions of the r and s-process contributions to the solar system abundances as well as with theoretical s and r-process distributions.

Such an exercise is shown in Fig. 1, where the abundances in HD 122563 are compared to scaled meteoritic abundances, for three cases: (1) only the s-process contribution to the solar-system abundances is scaled; (2) same for the r-process contribution and (3) the global solar system abundances are scaled down. The scaling factor is determined so that the best overall fit is obtained, in the least squares sense. The meteoritic abundances are taken from Cameron (1982), the same source as used by Sneden & Parthasarathy. Taking these abundances from a more recent source, such as Anders & Grevesse (1989), does not alter the conclusion.

Contrary to Sneden & Parthasarathy's conclusion, Fig. 1 shows that the best fit is obtained by scaling the full solar system abundances, neither the r nor the s-process distributions producing acceptable fits. This is confirmed by a computation of the least squares scatter between the observations and the scaled solar system distributions. While the scatter amounts to 0.29 dex when the global solar system abundances are considered, it increases to 0.45 dex when either the r or the s-process distributions are considered. If we take the meteoritic abundances from Anders and Grevesse (1989), the scatters amount to 0.30 dex for the global solar system abundances, to 0.50 dex for the r-process distribution and to 0.51 dex for the s-process.

Thus, our examination of their data does not support Sneden & Parthasarathy's conclusion that the r-process is responsible for the production of the heavy elements in HD 122563. It rather suggests that the mix of r and s-process material is comparable to that found in the solar system.

More recent analyses of the same star are less extensive in the sense that a smaller number of heavy elements is considered (e.g., Gilroy et al. 1988; Gratton & Sneden 1994). Nevertheless, playing the same game with these data gives basically the same conclusion. As an example, if, in order to reduce the observational errors, we consider the mean abundance from these three analyses for the six elements in common (Y, Zr, Ba, La, Nd and Eu), we obtain a scatter of 0.39 dex for the global solar system abundance, 0.56 dex for the r-process distribution and 0.65 dex for the s-process. In all cases, the solar system mix is preferred.

2.2. The analysis of Gilroy et al. (1988)

A more comprehensive analysis from the same team was published in 1988 (Gilroy et al. 1988). Abundances of neutron capture elements were determined in a sample of 20 metal-poor stars, mostly giants. That sample includes HD 122563, the star considered in the 1983 paper, as well as HD 110184, another giant studied by Sneden & Pilachowski (1985) who found overabundances of r-process elements in its atmosphere.

Gilroy et al. (1988) compared their average abundance results with scaled solar system distributions as well as with r and s-process model predictions and concluded, in agreement with the previous studies, that "*below stellar metallicities of* [Fe/H] ~ -2 *there is consistency in the heavy element abundance patterns: all indicate the presence of r-process synthesis events*".

The same exercise as in Sect. 2.1 is now in agreement with Gilroy et al.'s conclusion: while the scaled solar system s-process distribution does not fit the mean abundances in a satisfactory way (scatter = 0.66 dex), the fit is significantly improved if the r-process distribution is used, with a scatter of 0.29 dex. However, the global solar system distribution gives a fit which is nearly as good, with a scatter of 0.36 dex.

There is thus some disagreement between our reanalyzes of the 1983 and 1988 papers, a roughly solar mix being clearly indicated by the 1983 data, while the 1988 data favor an r-process distribution.

We suggest that this disagreement is due to the low quality of the Gilroy et al. data. This poor quality is illustrated in Fig. 2, which shows the comparison between the equivalent widths (EWs) of two lines of Y II, originating from levels with nearly the same excitation potential. In principle, such similar lines should behave in similar ways, so that there should be a good correlation between the EWs of the two lines measured on spectra of different stars. The scatter thus reflects the measurement uncertainties. Figure 2 shows that there are cases where Gilroy et al. find nearly the same value for the EWs of the first line in

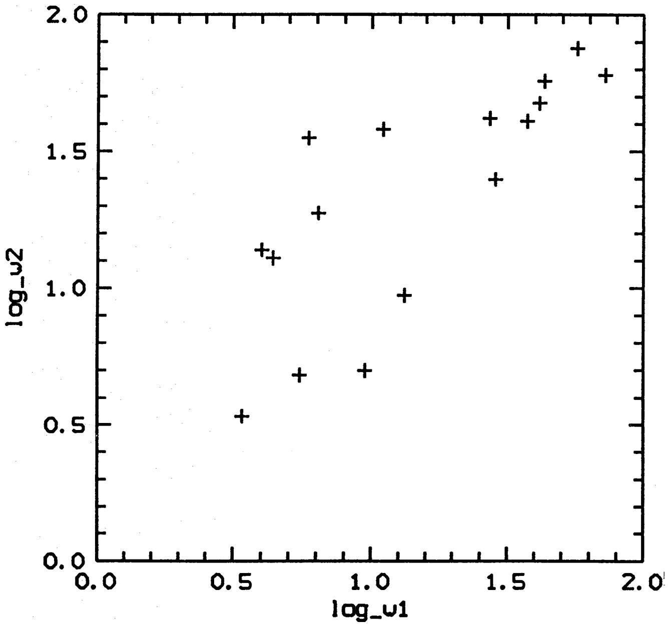

Fig. 2. The logarithms of the EWs of two lines of Y II as measured in different stars by Gilroy et al. (1988) are plotted against each other

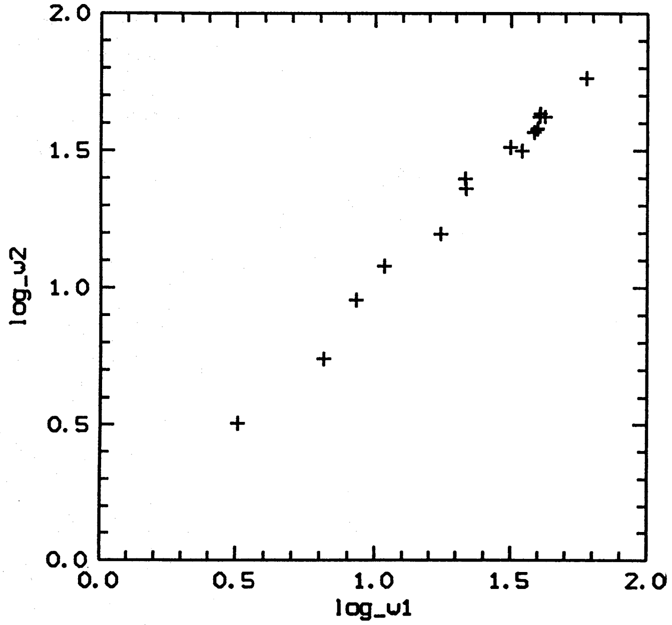

Fig. 3. Same as Fig. 2 but with the data of Zhao & Magain (1991)

two different stars and, at the same time, measure an order of magnitude difference in the EWs of the second line. What this plot should look like if the data were of good quality is shown in Fig. 3, which is the same as Fig. 2, but using the data of Zhao & Magain (1991).

This poor quality of the Gilroy et al. data is confirmed by Sneden himself, who writes, in a recent paper with Gratton (Gratton & Sneden 1994) that "*many lines of these elements* (i.e. La, Ce, Pr, Nd and Sm) *are near the detection limits of the spectra used in these studies* (Luck & Bond 1985; Gilroy et al. 1988), *and the resulting abundances are therefore subject to large uncertainties*".

Noting that, especially for the most metal-poor stars, their abundances for La, Ce, Pr, Nd and Sm are systematically lower than those of Gilroy et al. (as well as those of Luck & Bond 1985); Gratton & Sneden (1994) conclude: "*we attribute this fact to systematic errors in the measure of very weak features at the noise level in these previous investigations*".

We can go a little further, if we note that the lines of the elements which, in the solar system, are dominated by the r-process, are systematically weaker in the solar spectrum than those of the elements dominated by the s-process. This reflects simply the fact that the s-process elements are more abundant than the r-process ones in the solar system. Indeed, for the 7 elements in the paper of Gilroy et al. which are dominated by the s-process, the typical solar EW is of the order of 50 mÅ (for the lines considered by Gilroy et al.). On the other hand, for the 5 elements dominated by the r-process, the typical solar EW is only 15 mÅ.

It is well known that EWs of lines near the detection limit tend to be overestimated (because the line will be taken into account if it is reinforced by the noise, while it will be dropped if it is weakened by the noise). Thus, the lines of the r-process elements, being weaker on the average, will reach the detection limit in metal-poor stars before the lines of the s-process elements. **Therefore, one expects a stronger overestimate of the abundance of these elements which are dominated by the r-process**. The enhancement of the r-process contribution found by Gilroy et al. might thus be, at least partly, caused by these systematic errors.

2.3. The analysis of Gratton & Sneden (1994)

The same question was attacked in a very recent paper by Gratton & Sneden (1994), who consider a smaller number of elements, but with higher quality spectra.

They find that the s-process elements are more depleted than the r-process ones, but not so much as if the r-process alone contributed to the abundances. Indeed, when they compare their heavy elements abundance distribution with a scaled solar system r-process distribution, they find an excess of the elements which are mainly produced by the s-process.

The most obvious interpretation of their results is thus that the contribution of the s-process is smaller in the metal-poor stars than in the solar system, but that it is not negligible at all, even in stars as metal-poor as [Fe/H] ~ -2.5. Both processes would thus contribute to the heavy elements synthesis, even at these low metallicities.

3. Isotopic abundances: the case of barium

The observational situation is thus largely unclear. Truran's (1981) suggestion that this is the r-process which produced the heavy elements seen in the atmospheres of very metal-poor stars can by no means be considered proven observationally. All we can say is that there is a hint that, in very metal-poor stars, the elements produced preferentially by the r-process are slightly less depleted than those attributed to the s-process.

However, all the works considered in Sect. 2 deal exclusively with element abundances, while 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 (HFS) 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.

Barium is particularly well suited for this kind of analysis since its even isotopes are mostly produced by the s-process, while the r-process contribution dominates for the odd isotopes, at least in solar-system material (e.g. Anders & Grevesse 1989; Käppeler et al. 1989). The odd-to-even isotopic ratio is thus a measure of the relative importance of both processes in the production of barium.

A first attempt to estimate the fraction of odd isotopes of barium $f_{\rm odd}$ was made by Magain & Zhao (1993a). They took advantage of the desaturation provided by the HFS to determine $f_{\rm odd}$ by comparing the saturated resonance line of Ba II to weaker excited lines. Their analysis, carried out for 4 dwarfs with [Fe/H] ~ -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 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 thus appears desirable to carry out a more direct determination.

Such a direct determination can be based on the analysis of the profile of the resonance line of Ba II at 4554 Å. This line, when produced by the even isotopes of barium (mass numbers 134, 136 and 138), has no HFS. On the other hand, the resonance line of the odd isotopes (135 and 137) has several HFS components, with a total splitting of slightly more than 50 mÅ. 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). This HFS splitting is thus measurable with a spectrograph of sufficient resolving power (at least 100 000).

If the s-process dominates, the line will be narrow, as it is barely affected by HFS. The larger the r-process contribution, the larger the fraction of odd isotopes, and the broader the spectral line will be. The width of the line is thus a measure of the isotopic ratio and, thus, of the r-process contribution.

An important advantage of that method is that it is largely independent of the parameters of the stellar atmosphere (effective temperature, surface gravity, chemical composition) since it only requires the comparison of different HFS components of the **same line**. It should also be minimally sensitive to non-LTE effects.

On the other hand, it requires very good spectra and precise knowledge of the other broadening mechanisms. However, the contribution of these other broadening mechanisms can be determined from the profile of other spectral lines (not affected by HFS) in the same spectral region.

4. Observations and reductions

High resolution spectra of the classical metal-poor subgiant HD 140283 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 April 24 to 30, 1993. The long camera was used. It was for the first time equipped with a 2048 × 2048 pixels Ford CCD, each 15 μm^2 pixel corresponding to 18.5 mÅ in wavelength.

The entrance slit width was chosen so that the resolving power, as measured from the widths of the thorium lines used for the wavelength calibration, amounts to 100 000. This corresponds to a full width at half maximum (FWHM) of the spectral lines of 2.3 pixels and is thus close to the maximum resolving power permitted by the sampling theorem.

Thirty spectra were obtained, with exposure times varying between 30 minutes and 1 hour, corresponding to a total exposure time of 20 hours. Small wavelength shifts (up to a few Å) were applied, so that these spectra were all centered differently on the detector. This ensured that in each exposure, the lines studied fall on different regions of the detector, thus reducing possible systematic errors which might arise from pixel-to-pixel variations and allowing a better sampling of the spectral lines.

Several flat-field exposures were obtained for each wavelength setting. Thorium spectra for wavelength calibration were obtained immediately before and after each stellar exposure.

Sequences of flat-fields with varying exposure levels were also secured in order to check the linearity of the CCD, which was found satisfactory at the 1% level.

The individual spectra were reduced with the MIDAS package, using the following procedure. The bias was first subtracted, then division by an average flat-field (normalized to a mean level of unity) was performed. Cosmic ray hits were detected and spectra with such a event contaminating an important spectral line were rejected. This is this selection which led us with a total number of 30 spectra. The spectra were then optimally extracted with a procedure similar to that described by Robertson (1986).

The wavelength calibration was determined by fitting a third-order polynomial through the positions of the thorium lines, as determined by gaussian fitting on the sum of the calibrating spectra, taken immediately before and after the stellar exposure. The wavelength corresponding to the center of each pixel was then computed but the spectra were not rebinned to a constant wavelength step, as this introduces interpolation errors as well as some degradation of the resolution and correlations between the errors on neighboring pixels. Rather, MIDAS tables were created, with two columns, the first containing the pixel wavelengths and the second the pixel intensities.

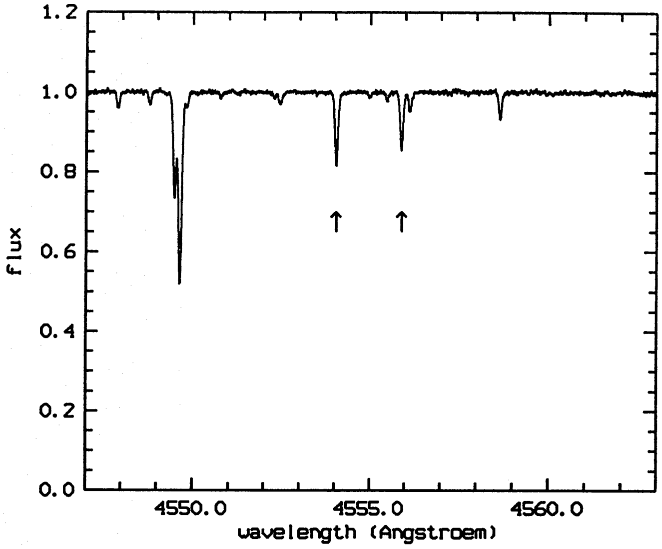

Fig. 4. Central portion of the average of the 30 spectra of HD 140283 used in the present analysis. The resonance line of Ba II and the Fe II line used for the broadening profile determination are indicated by arrows

The continuum was determined in the following way. A number of continuum windows were selected by inspection of the Liège solar atlas (Delbouille et al. 1973). The average level was determined in each window and a third order spline was fitted through these points. Visual inspection helped to reject deviating points (e.g. affected by cosmic ray hits) and to choose the Spline smoothing factor. The spectra were then divided by the continuum, and the normalized spectra stored in the MIDAS table.

The uncertainty on the relative flux measurements were determined from an estimate of the signal-to-noise ratio (S/N) in each spectrum. The S/N was measured in a number of continuum windows and averaged. All the data in a given normalized spectrum were then assigned a common one sigma uncertainty equal to the inverse S/N of that spectrum. This approximation of a given uncertainty for all the data points in a given spectrum is allowed by the facts that the spectral lines considered are quite weak and that the slope of the original spectra (caused by the blase of the Echelle grating) is moderate.

The subsequent analysis is based on the individual data. However, for the purpose of illustration, we computed an average spectrum in the classical way, by rebinning the individual spectra to constant wavelength steps. The central part of the resulting spectrum is shown in Fig. 4. Its S/N, estimated from 12 continuum windows extracted from the spectrum and considered together, is about 400 in the region of the barium line. Note that this way of computing the S/N takes into account not only

Table 1. Hyperfine structure model

Even isotopes

$\delta\lambda$ (Å)	Relative intensity
−0.002	0.030
−0.001	0.095
+0.000	0.875

Odd isotopes

$\delta\lambda$ (Å)	Relative intensity
−0.036	0.099
−0.034	0.099
−0.033	0.097
−0.031	0.080
+0.014	0.161
+0.017	0.334
+0.018	0.011
+0.020	0.099
+0.021	0.020

the photon statistics, but also the errors in the determination of the continuum level.

5. Line profile analysis

The theoretical line profiles were obtained by solving the radiative transfer equation in a model atmosphere, assuming LTE. The model was calculated with the MARCS programme (Gustafsson et al. 1975) and the atmospheric parameters for HD 140283 were adopted from Zhao & Magain (1991). The different HFS components were taken explicitly into account as in Table 1 (based on Biehl 1976).

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 with the observed ones for lines not affected by HFS and situated in the same spectral region.

The main line chosen for the broadening profile determination is the Fe II line at 4555.9 Å, which has an EW very similar to the Ba II resonance line. It was found that a sum of two gaussians could provide an adequate representation of the broadening profile: a main gaussian, plus a weaker secondary component centered on the long wavelength side of the main component. This assymetry may be due to turbulent motions in the atmosphere of the star. It corresponds to C-shaped line bisectors.

Small wavelength shifts had to be applied to the line centers in order to produce the best fit between the model and data. These shifts amount to 5 mÅ and 1 mÅ for the Fe II and Ba II line, respectively. They may also reflect motions in the stellar atmosphere, but should also include some contribution from the uncertainty in the wavelength calibration of the spectra, as well as in the nominal wavelengths of the spectral lines.

Once the broadening profile is determined, it is used to convolve the synthetic profiles of the Ba II line, before comparing it to the data. The odd-to-even isotopic ratio $f_{\rm odd}$ is then varied until the best fit is obtained.

As already mentioned, the synthetic line profiles are compared to the individual data points, not to a mean spectrum. Each point is considered, together with its uncertainty, estimated as decribed in the previous section. The chi-squared (χ^2) is computed and the model adjusted in order to find the minimum χ^2.

This method allows to preserve the full resolution of the data and to take explicitly into account the uncertainty on each individual observation. So, it should be as free as possible from biases, which might be introduced by combining the individual spectra. However, if it produces the best value of the isotopic ratio, it does not easily allow to estimate the uncertainty on that determination, which would require the uncertainty on each data point to be known to unrealistic accuracy.

In order to estimate the uncertainty on the isotopic ratio, we used a second fitting method. Instead of fitting the model to the individual data points, we computed a mean spectrum and compared the model to that spectrum. The full resolution of the data was preserved by the following procedure.

Each point in the mean spectrum is the combination of 30 individual data points, taken in a wavelength interval whose size corresponds to one pixel of the detector. However, taking the mean of the data points in such a given interval would introduce a smearing of the data, as the points are scattered through the interval. We thus have to displace these measurements to the center of the interval. The problem is to find a suitable function to compute the flux at the center of the interval, given the flux at some other point. We found that a very good function for that purpose is the model itself that we are fitting to the data (i.e. the synthetic profile convolved by the broadening profile).

So, the procedure is the following. We compute the difference between the data point and the fitting function at the wavelength of the data point considered. We repeat this for the 30 data points in the given interval. We then compute the weighted mean of these 30 differences, as well as the uncertainty on that mean value, with weights corresponding to the uncertainties on the individual data points. We then add the mean difference to the value of the fitting function at the center of the interval. This gives the weighted average of the 30 observations at the center of the interval. We then compute the χ^2, using the mean differences and their uncertainties.

Having 30 data points in each interval, the uncertainty on the mean value can be computed quite reliably, and thus the χ^2 obtained can be used to estimate the uncertainty on the determination of the isotopic ratio.

This procedure also gives a determination of the isotopic ratio. Although we prefer the value determined from the fit on the individual data points, it should be pointed out that the two values differ by less than 1%, which is a testimony to the validity of the interpolation method.

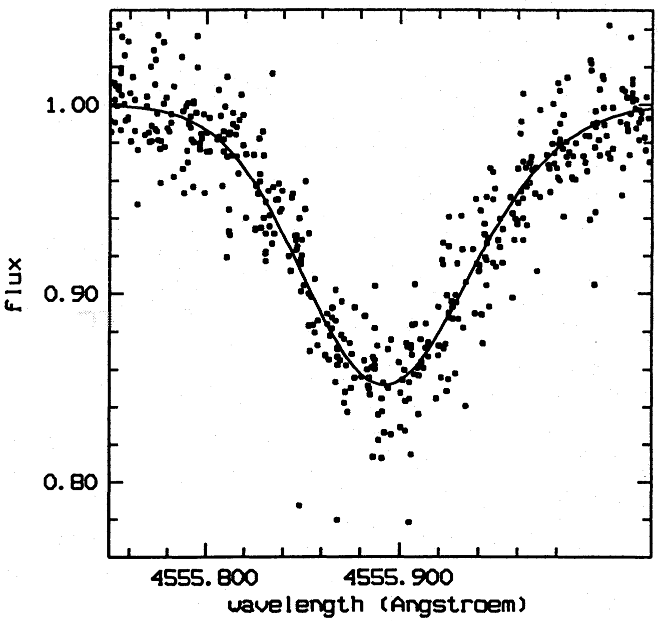

Fig. 5. Comparison of the synthetic profile of the Fe II line at 4555.9 Å (curve) with the observations (dots)

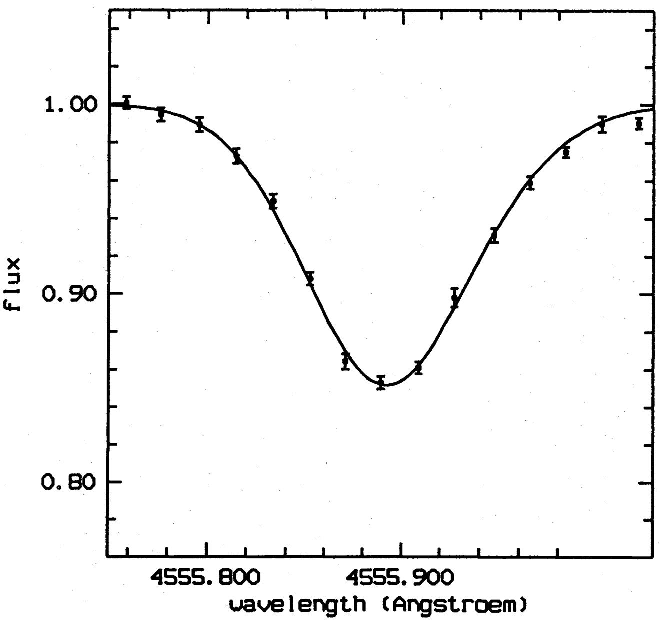

Fig. 6. Comparison of the synthetic profile of the Fe II line at 4555.9 Å (curve) with the average data (see text for details). 1σ error bars are indicated

6. Results

The best fit of the Fe II line used for the broadening profile determination is shown in Fig. 5, while the same profile is compared in Fig. 6 to the average values, determined as explained in the previous section. Figures 7 and 8 provide the same comparison for the Ba II line, while Fig. 9 shows the comparison of the average spectrum to the synthetic Ba II profiles computed with various isotopic mixtures: $f_{\rm odd} = 0.0, 0.5, 1.0$. It can immediately be seen that large quantities of odd isotopes are excluded by the observations.

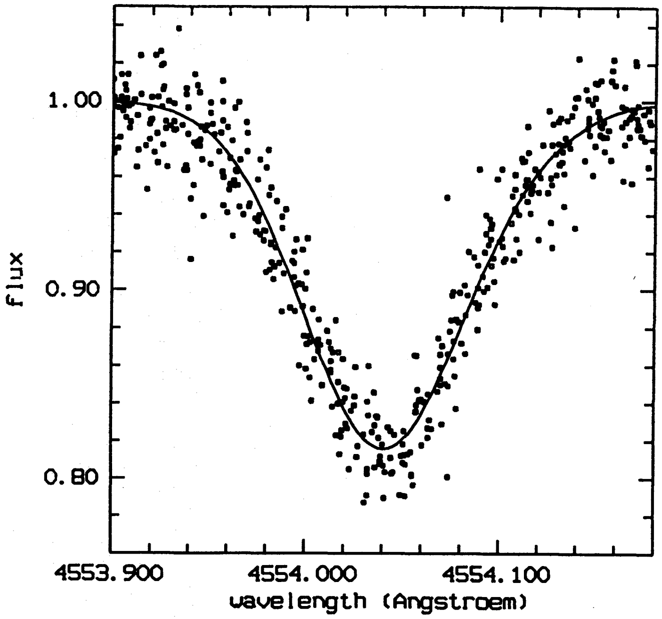

Fig. 7. Comparison of the synthetic profile of the Ba II line at 4554.0 Å (curve) with the observations (dots)

The best fit value is

$$f_{\rm odd} = 0.08(\pm 0.06)$$

in agreement with the value of $0.2(\pm 0.1)$ obtained by Magain & Zhao (1993b) from a preliminary analysis of 10 spectra of the same star. Note that these 10 spectra were not included in the present analysis.

The quoted uncertainty is the one sigma uncertainty as determined from the fit on the average spectrum.

The equivalent widths of the lines, determined from the same fits, amount to 16.2 mÅ for the Fe II line and 19.8 mÅ for the Ba II line.

As expected, the errors on the model atmosphere parameters have quite a negligible effect on the determination of the isotopic ratio. The main uncertainty comes from the microturbulent velocity, for which an error of 0.5 km s^{-1} corresponds to an error of 0.01 only on the isotopic ratio. The effect is so small because the same value of the microturbulent velocity is used to compute the Fe II as well as the Ba II line, resulting in a nearly perfect cancellation of the effect as the two lines have similar EWs. Varying the microturbulent velocity used to compute the Ba II line, letting the Fe II line unchanged, would result in a error of 0.21 on $f_{\rm odd}$.

Another parameter which has some influence on the result is the damping constant. We used the value computed from the Unsöld formula for the Ba II line and a multiplication factor of 1.2 for the Fe II line. However, changing the multiplication factor from 1 to 2 for the Ba II line would result in a change of the isotopic ratio of 0.016 only.

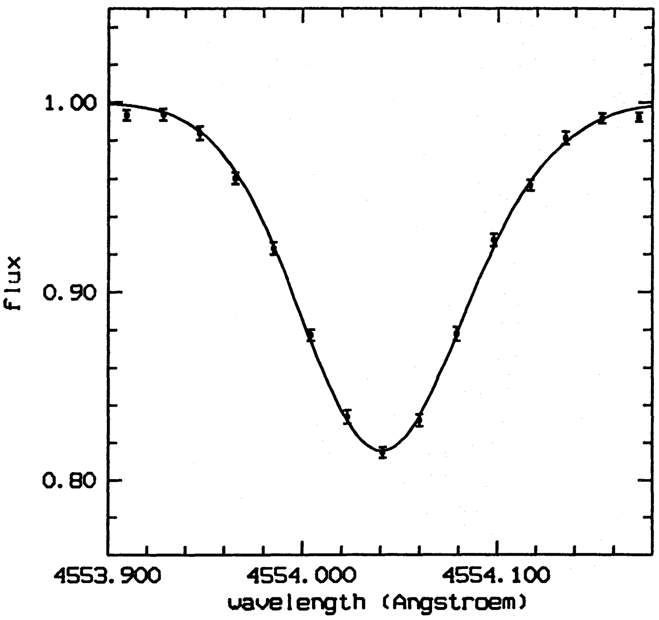

Fig. 8. Comparison of the synthetic profile of the Ba II line at 4554.0 Å computed with an isotopic fraction $f_{\mathrm{odd}} = 0.08$ (curve) with the average data (see text for details). 1σ error bars are indicated

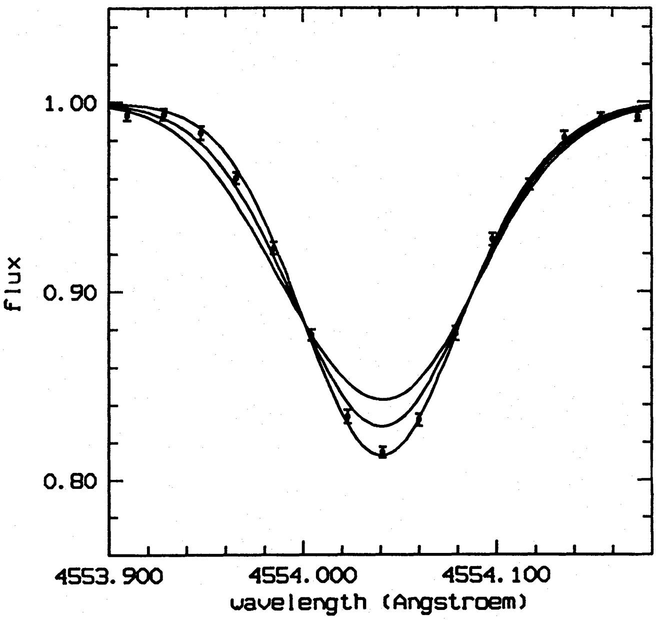

Fig. 9. Synthetic Ba II line profiles computed with $f_{\mathrm{odd}} = 1.0$, 0.5 and 0.0 (curves) compared with the average data

Of course, it would be desirable to test the present method on the only star for which the barium isotopic composition is known: the Sun. Unfortunately, the resonance line of Ba II is saturated in the solar spectrum, with an equivalent width of about 180 mÅ. Thus, it cannot provide a reliable test of the method since HFS primarily affects the line core, which is saturated and, moreover, formed in very outer layers, where the model atmosphere is subject to rather large uncertainties and where non-LTE effects might be quite important.

Nevertheless, comparison of the synthetic profiles computed for the center of the solar disk with the observed solar spectrum (Delbouille et al. 1973) allows to exclude extreme values of f_{odd} and shows that the solar line profile, given the uncertainties mentioned above, is compatible with the isotopic ratio determined from meteoritic studies ($f_{odd,\odot} = 0.18$).

The uncertainties related to errors on the atmospheric and atomic parameters are thus quite small and their global effect should not exceed 0.02 or 0.03. The main uncertainty therefore comes from the observational errors (photon statistics, continuum level, small blends, broadening profile determination). The best way to reduce the uncertainty coming from the observational errors is obviously to increase the spectral resolution. Spectra taken at 200 000 resolving power with a S/N of 500 would be quite well suited for such a program. However, HD 140283, with its visual magnitude of 7.2, being the brightest star for which such an analysis can be carried out, a large telescope is obviously required.

7. Discussion

The isotopic ratio we obtain for HD 140283 is even smaller than the solar value ($f_{odd,\odot} = 0.18$). The analyses of meteoritic data predict an isotopic ratio $f_{\mathrm{odd}} = 0.11(\pm 0.02)$ for a pure s-process production of barium and a value $f_{\mathrm{odd}} > 0.52$ for a pure r-process production. Our result for HD 140283 is thus in perfect agreement with a pure s-process production of barium and excludes any significant enhancement of the r-process, as compared to solar system material.

This result therefore does not support Truran's suggestion of an r-process nucleosynthesis for the heavy elements in very metal-poor stars. Together with our reexamination of Sneden and collaborators' analyses, and with the results of Gratton & Sneden (1994), it shows that the situation is far less obvious than previously thought.

Of course, the present result is based on one star only, and one would like to repeat this analysis for a fair sample of very metal-poor stars. This is, however, at the limit of the present possibilities, and one may have to wait until a 10 m class telescope is equipped with a very high resolution spectrograph to be able to get the barium isotopic ratio for a large sample of stars.

In any case, the present result is, as far as we know, the most direct and most precise 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 hope that it will open new insights into the stellar nucleosynthetic processes and shed more light on the the early phases of the chemical evolution of the Galaxy.

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