Barium even-to-odd isotope abundance ratios in thick disk and thin disk stars *

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Abstract. We present the Ba even-to-odd isotope abundance ratios in 25 cool dwarf stars with the metallicity [Fe/H] ranging between 0.25 and −1.35. Our method takes advantage of the hyperfine structure (HFS) affecting the Ba resonance line of the odd isotopes. The fractional abundance of the odd isotopes of Ba is derived from a requirement that Ba abundances from the resonance line λ4554 and subordinate lines λ5853 and λ6496 must be equal. The results are based on NLTE line formation and analysis of high resolution (R ∼ 60000) high signal-to-noise (S/N ≥ 200) observed spectra. We find that the fraction of the odd isotopes of Ba grows toward the lower Ba abundance (or metallicity) and the mean value in the thick disk stars equals 33 ± 4%. This indicates the higher contribution of the $r$–process to barium in the thick disk stars compared to the solar system matter. The obtained fraction increases with the [Eu/Ba] abundance ratio growth in agreement with expectations. A significant fraction of the “even” isotopes of Ba found in old Galactic stars (the thick disk stars), ~ 67%, is in contrast to the prediction of the “classical” model of the $s$–process and favors the value predicted by the “stellar” models of Arlandini et al. (1999) and Travaglio et al. (1999).

Key words. Line: formation – Nuclear reactions, nucleosynthesis, abundances – Stars: abundances – Stars: late-type – Galaxy: evolution

1. Introduction

The elements heavier than the iron peak are mainly produced through neutron capture reactions in two main processes, the $s$–process (slow) and $r$–process (rapid). As supported by many observational and theoretical results (Travaglio et al. 1999 and references therein), $s$–nuclei are mainly synthesized during the thermally pulsing asymptotic giant branch phase of low-mass stars (2 - 4 $M_{\odot}$). The $r$–process is associated with explosive conditions in SNeII (see Thielemann et al. 2002 for a general review). Following the pioneering observational study of Spite & Spite (1978), Truran (1981) has put forward the suggestion that most (if not all) neutron capture elements in very metal-poor stars are of $r$–process origin. Much observational effort was invested in testing this idea (for review, see Truran et al. 2002). To understand the relative importance of the two neutron capture synthesis mechanisms throughout the Galaxy history, stellar element abundance comparisons are made between elements whose solar system isotopic abundances are dominated by the $s$–process and those due mainly to the $r$–process. The europium-to-barium abundance ratio is particularly sensitive to whether nucleosynthesis of the heavy elements occurred by the $s$– or $r$–process. Other important indicators are the [Eu/La] and [Nd/Ba] abundance ratios. The most recent determinations of the [Eu/Ba] abundance ratios in the samples of metal-poor stars were made by McWilliam (1998), Burris et al. (2000), Fulbright (2000), Mashonkina & Gehren (2000, 2003), Mishenina & Kovtyukh (2001) and Bensby et al. (2005). The [Eu/La] abundance ratios in 159 giant and dwarf stars have been measured by Simmerer et al. (2004): the [Nd/Ba] abundance ratios in 46 stars have been derived by Mashonkina et al. (2004). Stellar element abundance ratios have to be compared with theoretical predictions. However, at present, the nucleosynthesis theory is not able to predict the yields of the $r$–process. Based on the hypothesis that the $r$–contributions in the solar system are of primary origin, the $r$–process abundance fractions are obtained by subtracting the $s$–contributions at the epoch of solar formation, estimated with the use of reliable $s$–model, from the solar abundances. One refers to them as $r$–residuals. Two approaches are used to cal-

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culate the \( s \)-process abundance fractions. The "classical" approach relies upon reproducing the product of \( n \)-capture cross-section and \( s \)-process abundance (the "\( \sigma N \)" curve). "Stellar" \( s \)-process models are based on nucleosynthesis computations in low- and intermediate-mass AGB stars. The recent "classical" (Arlandini et al. [1999]) and "stellar" (Arlandini et al. [1999]) Travaglio et al. [1999] models give consistent results within the respective uncertainties for the \( s \)-process contributions to the most abundant Ba and Eu isotopes in the solar system matter, with the only exception being \(^{138}\)Ba. Its \( r \)-residual equals 14\% to 16\% in the "stellar" models and 0\% in the "classical" model. Since \(^{138}\)Ba is the most abundant solar Ba isotope, the \( r \)-residual of total Ba is larger in the "stellar" model by a factor of 2.4 than in the "classical" one. As a result, the "stellar" and "classical" models lead to significantly different values of the solar abundance ratio of Eu to Ba contributed by the \( r \)-process: taken relative to the total abundances, [Eu/Ba], = 0.69 and [Eu/Ba], = 1.06, respectively. The "stellar" model predicts the isotope abundance ratio \(^{135}\)Ba : \(^{137}\)Ba : \(^{138}\)Ba = 26 : 20 : 54 in a pure \( r \)-process nucleosynthesis, while no Ba even isotope is predicted in the "classical" model.

To reconstruct the evolutionary history of neutron-rich elements in the Galaxy it is, thus, very important to disentangle the fractions of Ba even and odd isotopes and inspect their abundance as a function of Galactic age. Isotopic shifts of the barium lines are negligible compared to the line width. A determination of the Ba even-to-odd isotope abundance ratio in stars becomes possible due to the significant hyperfine structure (HFS) affecting the Ba \( \Pi \) resonance lines of the odd isotopes. In total, the resonance line \( \lambda 4554 \) has 15 components spread over 58 mA. The larger the fraction of the odd isotopes, the stronger the HFS broadening of \( \lambda 4554 \) and the larger the energy absorbed in this line. The total width of the patterns of the Ba \( \Pi \) subordinate lines, \( \lambda 5853, \lambda 6141, \) and \( \lambda 6496 \), is much smaller, 8 mA, 8 mA, and 23 Å, correspondingly.

Cowley & Frey [1989] pointed out the importance of accounting for HFS in Ba abundance determinations; however, the first attempt to estimate the fraction of the odd isotopes of Ba in four metal-poor stars was made by Magain & Zhao [1993]. They used the Ba \( \Pi \) subordinate lines, \( \lambda 5853 \) and \( \lambda 6496 \), to derive the total Ba abundance. The Ba abundance was then deduced from the \( \lambda 4554 \) line for various isotopic mixtures, the proportion of the odd isotopes being changed until agreement with the subordinate lines was obtained. Magain & Zhao found an enhancement of the odd isotopes in these stars as compared to solar system matter, in agreement with the expectations. Using the same approach, Mashonkina et al. [1999] did not find significant deviation of the Ba isotopic mixture in the halo star G24-38 ([Fe/H] = −2.20) from the solar one. In their recent study, Mashonkina et al. [2003] show a distinction between the different Galactic stellar populations with respect to the Ba even-to-odd isotope ratio. The halo stars reveal, on average, equal amounts of the odd and even isotopes of Ba; a mean ratio 65 : 35 (±10\%) was obtained for the sample of thick disk stars, whereas the solar ratio 82 : 18 (Anders & Grevesse 1989) adjusts to observations of the Ba \( \Pi \) lines in the sample of thin disk stars.

Magain & Zhao [1993] and Magain [1995] have suggested a different method based on measuring the broadening of the Ba \( \Pi \lambda 4554 \) line. They have applied it to the extremely metal-poor star HD 140283 and found the low fraction of the odd isotopes, 8\%, that is consistent with a pure \( s \)-process production of barium. Using the same method and new high resolution (\( R \approx 200000 \)), high signal-to-noise ratio (S/N ≈ 550) spectra of HD 140283, Lambert & Allende Prieto [2002] draw the opposite conclusion. They find that the \( r \)-process mixture of the Ba isotopes predicted by the "stellar" model of Arlandini et al. [1999] provides a fair fit to the observed Ba \( \Pi \lambda 4554 \) profile.

This study is intended to inspect a history of Ba isotopic fractions in the Galaxy and, thus, a relative importance of the \( r \)- and \( s \)-process in heavy element production through the Galaxy evolution. We determine the abundance ratios of even to odd isotopes of Ba in the 25 selected stars representing the older ( thick disk) and younger ( thinner disk) Galactic stellar populations. We use the method applied in our previous papers. The results are based on the high resolution ( \( \approx 60000 \) high signal-to-noise ratio (S/N \( \geq 200 \) ) spectra and non-local thermodynamical equilibrium (NLTE) line formation.

The paper is organized as follows. In Sect. 2 we discuss an accuracy of the used atomic parameters, oscillator strengths and van de Waals damping constants \( C_\circ \), and check the investigated Ba \( \Pi \) lines with respect to blending lines. We test our method on solar Ba \( \Pi \) lines. Stellar sample, observations, and stellar parameters are described in Sect. 3. In Sect. 4 we present the obtained Ba even-to-odd isotope ratio in stars and investigate their errors caused by uncertainties of atomic data and stellar parameters. In Sect. 5 stellar fractions of the odd isotopes of Ba are inspected as indicators of the \( r/s \)-process nucleosynthesis, and conclusions are given. At the end, the outlook for a determination of Ba isotopic fractions in very metal-poor stars is estimated.

2. Method of calculations

Homogeneous blanketed model atmospheres computed with the MAFAGS code (Fuhrmann et al. 1997) are used in the analysis of both solar and stellar spectra.

2.1. Atomic parameters

In the metallicity range of our stellar sample, not only the resonance line, but also one or both of the used subordinate lines either lie on the damping part of the curve of growth or are saturated. In the first turn, our analysis requires very accurate atomic parameters.

As in our previous analysis, in this study we use the absolute oscillator strengths from Reader et al. [1980]:

\[
\log g f(\lambda 4554) = 0.162, \quad \log g f(\lambda 5853) = -1.0, \quad \text{and} \quad \log g f(\lambda 6496) = -0.377.
\]

The most recent measurements of Davidson et al. [1992] give \( \log g f(\lambda 4554) = 0.140, \log g f(\lambda 5853) = -0.91, \) and \( \log g f(\lambda 6496) = -0.407. \) We show below that applying the data of Davidson et al., we cannot agree when fitting parameters of the solar Ba \( \Pi \lambda 6496 \) and \( \lambda 5853 \) lines. We do not use the third line of the Ba \( \Pi \lambda 5d - 6p \)
multiplet, \( \lambda 6141 \) which is blended with the strong Fe I line (Fig. 1).

In our previous studies, we used the data on hyperfine structure components of the Ba II \( \lambda 4554 \) calculated by Biehl (1976) on the base of Brix & Kopfermann (1952) measurements. Having reviewed the literature for more recent data, we found that the new fine structure constants of \(^{135}\text{Ba} \) and \(^{137}\text{Ba} \) obtained by Blatt & Werth (1982) and Becker & Werth (1983) lead to a negligible change of the wavelength separations by more than 1% for the HFS components of the resonance line. In order to have common input data with other authors we prefer to search for atomic parameters of blending atomic lines. The line profiles computed with the data of Biehl and McWilliam become identical after their relative shift by 0.001 Å. Table 1 contains the list of the HFS components of the Ba II \( \lambda 4554 \). The product of \( f_i \) and fractional isotope abundance \( \epsilon \) is given for the Ba isotope mixture in the solar system matter. \(^{134}\text{Ba} :^{135}\text{Ba} :^{136}\text{Ba} :^{137}\text{Ba} :^{138}\text{Ba} = 2.4 : 6.6 : 7.9 : 11.2 : 71.8 \) (Anders & Grevesse 1989) and that for a pure \( r \)-process production of Ba, \(^{135}\text{Ba} :^{137}\text{Ba} :^{138}\text{Ba} = 26 : 20 : 54 \) (Arlandini et al. 1999). Total \( f_i \) = 0.727. The 23 mÅ wide patterns of the \( \lambda 6496 \) line are considered as a four component model according to Rutten (1978). Variation in fractional isotope abundances between the solar and pure \( r \)-process cases has negligible effect on the \( \lambda 6496 \) line profile, and we use \( f \times \epsilon \) computed for the solar mixture of Ba isotopes. We neglect the hyperfine structure of \( \lambda 5853 \).

The investigated Ba II lines are strongly affected by van der Waals damping. We apply the van der Waals damping constant \( C_6 = -31.65 \) to \( \lambda 4554 \). If \( C_6 \) is fixed, solar Ba abundance is immediately determined from the fitting of the solar \( \lambda 4554 \) line wings. Using the MAFAGS solar model atmosphere, we find \( \log C_{6,\text{Ba}} = 2.21 \) \(^1\). This value agrees within error bars with the meteoritic Ba abundance given by Anders & Grevesse (1989) \( \log C_{6,\text{met,Ba}} = 2.21 \pm 0.03 \) \(^1\) and Grevesse et al. (1996) \( \log C_{6,\text{met,Ba}} = 2.22 \pm 0.02 \). Recent determinations by Asplund et al. (2005) lead to the smaller meteoritic \( \log C_{6,\text{met,Ba}} = 2.16 \pm 0.03 \) and solar \( \log C_{6,\text{Ba}} = 2.17 \pm 0.07 \) Ba abundance. For comments, see Note added in proofs.

The Van der Waals damping constant \( C_6 \) of the subordinate lines was obtained empirically from the fitting of the solar line profiles under the requirement that unique set of fitting parameters (Ba abundance, microturbulence value, and \( C_6 \) value) must adjust observations of the spectral lines belonging to the same multiplet, \( \Delta d - \Delta p \). Far wings of \( \lambda 6496 \) impose the upper limit of \( \log C_6 \), provided that solar Ba abundance is given. We adopt \( \log C_{6,\text{Ba}} = 2.21 \). In this case, \( \log C_6 \) of \( \lambda 6496 \) cannot be larger than \(-31.3 \). Applying this value to \( \lambda 5853 \) and based on NLTE analysis we obtain a microturbulence value \( V_{\text{mic}} = 0.85 \text{ km s}^{-1} \). The best fit of each line of the multiplet \( 5\Delta - \Delta p \) is achieved at \( \log C_6 = 2.21 \), \( \log C_6 = -31.3 \), and \( V_{\text{mic}} = 0.85 \text{ km s}^{-1} \) (Fig. 1). In Sect. 3 we will discuss an effect of variation in \( \log C_6 \) on Ba isotope ratio in stars. Analysis of the solar \( \lambda 6496 \) and \( \lambda 5853 \) line profiles was also performed with the oscillator strengths from Davidson et al. (1992). Solar Ba abundance was fixed at \( \log C_{6,\text{Ba}} = 2.21 \). Fitting parameters of two lines turn out to be different: \( \lambda 6496 \) gives \( \log C_6 = -31.2 \) and \( V_{\text{mic}} = 0.9 \text{ km s}^{-1} \), while the significantly lower microturbulence value \( V_{\text{mic}} = 0.7 \text{ km s}^{-1} \) is required to fit the \( \lambda 5853 \) line profile using \( \log C_6 = -31.2 \).

The Ba II \( \lambda 4554.034 \) Å line is blended by the Cr I \( \lambda 4553.945 \) and Zr II \( \lambda 4553.934 \) lines in the blue line wing and by the CH molecular line at 4554.142 Å in the red line wing (Fig. 2). We have requested the Vienna Atomic Line Data base (VALD, Kupka et al. 1999) and the NIST atomic spectra database (http://physics.nist.gov/PhysRefData) to search for atomic parameters of blending atomic lines. The same value \( \log g_f = -0.73 \) based on measurements of Wujec & Weniger (1981) is given in NIST and VALD for the Cr I \( \lambda 4553.945 \). NIST does not contain the Zr II \( \lambda 4553.934 \) line, but VALD provides \( \log g_f = -0.57 \), taken from Cowley & Corliss (1983), for this line. The oscillator strength of the CH \( \lambda 5454.142 \) molecular line was fitted to reproduce the observed blend profile; we have obtained \( \log g_f = -3.2 \). The Ba II \( \lambda 5853.675 \) Å line is blended by the Fe I \( \lambda 5853.682 \) line (Fig. 1). Based on calculations of Kurucz & Bell (1995), VALD gives \( \log g_f \) (Fe I \( \lambda 5853.682 \)) = -2.148. Recently, Kurucz (http://cfaku5.cfa.harvard.edu) calculated the new value \( \log g_f = -2.371 \) for this line. We note that the predicted oscillator strength of Fe I \( \lambda 5853.682 \) has been reduced by a factor of 2.3, compared to the first estimate of Kurucz & Peytremann (1975).

### Table 1. Atomic data for the HFS components of the Ba II \( \lambda 4554 \).

| \( \lambda, \text{Å} \) | \( I \) | \( f \times \epsilon \) | \( \text{solar} \) | \( r \)-process |
|---|---|---|---|---|
| \(^{134}\text{Ba} \) | 4554.032 | 1.000 | 0.0176 | - |
| \(^{135}\text{Ba} \) | 4554.003 | 0.1562 | 0.0075 | 0.0292 |
| \(^{137}\text{Ba} \) | 4554.004 | 0.1562 | 0.0075 | 0.0292 |
| \(^{138}\text{Ba} \) | 4554.005 | 0.0625 | 0.0030 | 0.0117 |
| \(^{136}\text{Ba} \) | 4554.051 | 0.4375 | 0.0209 | 0.0818 |
| \(^{135}\text{Ba} \) | 4554.054 | 0.1562 | 0.0075 | 0.0292 |
| \(^{136}\text{Ba} \) | 4554.055 | 0.0313 | 0.0015 | 0.0058 |
| \(^{137}\text{Ba} \) | 4554.033 | 1.000 | 0.0568 | - |
| \(^{138}\text{Ba} \) | 4553.999 | 0.1562 | 0.0129 | 0.0232 |
| \(^{134}\text{Ba} \) | 4554.001 | 0.1562 | 0.0129 | 0.0232 |
| \(^{135}\text{Ba} \) | 4554.002 | 0.0625 | 0.0052 | 0.0093 |
| \(^{137}\text{Ba} \) | 4554.054 | 0.4375 | 0.0360 | 0.0650 |
| \(^{138}\text{Ba} \) | 4554.056 | 0.1562 | 0.0129 | 0.0232 |
| \(^{136}\text{Ba} \) | 4554.057 | 0.0313 | 0.0025 | 0.0046 |
| \(^{137}\text{Ba} \) | 4554.034 | 1.000 | 0.521 | 0.392 |

\(^1\) We refer to abundances on the usual scale where \( \log \epsilon = 12 \).
log \(gf\) = -2.0. This line is absent in the NIST database. The \(\text{Ba} \, \lambda 6141.713\,\text{Å}\) is strongly blended by the \(\text{Fe I} \, \lambda 6141.732\) line and not used in further analysis of stellar spectra. With log \(gf\) (Fe \(\lambda 6141\)) = -1.61 taken from the NIST database, we can achieve a good fitting of the solar blend profile (Fig. 1). VALD gives the larger oscillator strength, log \(gf\) = -1.459, for Fe \(\lambda 6141\). The contribution of blending lines is treated using the LTE assumption. The chemical abundances are taken from Anders & Grevesse (1989) in the solar case, and we assume that in the investigated stars, Cr abundance follows the iron one with [Cr/Fe] = 0, and Zr abundance follows the barium one with [Zr/Ba] = 0.

### 2.2. NLTE line formation

Our results are based on NLTE line formation for \(\text{Ba II}\). The method of NLTE calculations was developed and described earlier (Mashonkina & Bikmaev 1996, Mashonkina et al. 1999). We use a revised version of the DETAIL program (Butler & Giddings 1985) based on the accelerated lambda iteration method to solve the coupled radiative transfer and statistical equilibrium equations and the SIU code (www.usm.uni-muenchen.de/people/reetz/siu.html) to compute the synthetic line profiles.

In Fig. 1 we present the best fits of the observed \(\text{Ba II}\) subordinate line profiles in the solar flux atlas of Kurucz et al. (1984) achieved using the NLTE approach and LTE assumption. We emphasize that the unique value of Ba abundance, log \(\epsilon_{\text{Ba}}\) = 2.21, adjusts observations of all these lines. The same value, log \(C_0\) = -31.3, is used for each line in both the NLTE and LTE calculations. The same microturbulence value, \(V_{\text{mic}}\) = 0.85 km s\(^{-1}\), is required when the NLTE approach is applied while different values in the LTE case are used: \(V_{\text{mic}}\) = 0.95 km s\(^{-1}\) for \(\lambda 5853\), \(V_{\text{mic}}\) = 1.05 km s\(^{-1}\) for \(\lambda 6496\), and \(V_{\text{mic}}\) = 1 km s\(^{-1}\) for \(\lambda 6141\). Our synthetic flux profiles are convolved with a profile that combines a rotational broadening of 1.8 km s\(^{-1}\) and broadening by macroturbulence with a radial-tangential profile. The macroturbulence values \(V_{\text{mac}}\) = 3.1 km s\(^{-1}\) and 3.0 km s\(^{-1}\) are required for \(\lambda 5853\) in the NLTE and LTE cases, respectively. The corresponding values for \(\lambda 6496\) are 2.3 km s\(^{-1}\) and 2.1 km s\(^{-1}\) and for \(\lambda 6141\), in both cases, \(V_{\text{mac}}\) = 2.9 km s\(^{-1}\).

### 2.3. Can we derive the solar Ba isotope abundance ratio?

Assuming the solar system matter Ba isotopic fractions \(^{134}\text{Ba} : ^{135}\text{Ba} : ^{136}\text{Ba} : ^{138}\text{Ba} = 2.4 : 6.6 : 7.9 : 11.2 : 71.8\), total Ba abundance log \(\epsilon_{\text{Ba}}\) = 2.21, log \(C_0\) = -31.65, and using \(V_{\text{mic}}\) = 1 km s\(^{-1}\), we can achieve a good fitting of the solar \(\lambda 4554\) profile. In Fig. 2 we show the best fit obtained by applying \(V_{\text{mac}}\) = 3.5 km s\(^{-1}\).

The value \(V_{\text{mic}}\) = 1 km s\(^{-1}\) obtained from the resonance line does not agree with the value \(V_{\text{mic}}\) = 0.85 km s\(^{-1}\) found from the subordinate lines. We are aware that a phenomenological description of the velocity field using a microturbulence value is a rough approximation and that it fails to treat spectral lines formed over a wide range of depths. The \(\lambda 4554\) line core is formed in very outer layers near log \(\tau_{5000}\) = -4.7, while radiation of the subordinate lines comes from the deeper layers, below log \(\tau_{5000}\) = -2.8 for \(\lambda 6496\) and below log \(\tau_{5000}\) = -1.9 for \(\lambda 5853\). We have tried to answer the question of whether we are able to derive a solar atmosphere Ba isotope abundance ratio from the HFS affecting the \(\lambda 4554\) line profile without a reference to the subordinate lines. In addition to the even-to-odd iso-
Fig. 2. Synthetic NLTE flux profile of the Ba II resonance line corresponding to the Ba even-to-odd isotope ratio of 82 : 18 (continuous line) compared with the solar flux profile (bold dots, Kurucz et al. 1984). The differences between observed and calculated spectra, (O - C), multiplied by a factor of 5, are shown for various even-to-odd isotope ratios in the lower part of figure. Blending lines are shown by a dash-dotted line. See text for more details.

We conclude from these results that a precise determination of the proportion of the even and odd isotopes of Ba in the solar atmosphere matter requires a correct treatment of the atmospheric velocity field that is only possible on the basis of hydrodynamic calculations. In metal-poor stars, the λ 4554 line forms in the deeper atmospheric layers compared to the Sun and in smaller extension is expected to be affected by hydrodynamic phenomena of the very surface layers.

3. Stellar sample, observations, and stellar parameters

All the 25 stars were selected from Fuhrmann’s (2004) list. Each star was observed with a resolution of ∼ 60 000, at least twice, and for each star both the Ba II subordinate lines, λ 5853 and λ6496, are available in its spectra. Spectra were obtained by Klaus Fuhrmann using the fiber optics Cassegrain echelle spectrograph FOCES at the 2.2m telescope of the Calar Alto Observatory in 1997 - 2000. The signal-to-noise ratio is 200 or higher in the spectral range λ > 4500 Å. Typical line profiles are seen in Figs. 4 and 5.

The list of stars under investigation is given in Table 2. Stellar parameters have been determined spectroscopically by Fuhrmann (2004). Their errors are estimated as ΔTeff = 80 K, Δlog g = 0.1, Δ[Fe/H] = 0.1 dex, and ΔVmic = 0.2 km s−1. We use also his identification of a membership of individual stars in the particular stellar population that is based on the star’s kinematics, metallicity, α−enhancement, and age. Our sample includes 15 thick disk stars, 9 thin disk stars, and one halo star.

4. Results

4.1. Stellar total Ba abundances

Ba abundances were derived from the Ba II λ 5853 and λ 6496 line profile fitting, and then the average value was calculated. The [Ba/H] values calculated using solar Ba abundance log εBa H = 2.21 are presented in Table 2. We note that in this paper we revise our earlier determinations (Mashonkina & Gehren 2001) of Ba abundance in the investigated stars. Contrary to the previous analysis, we use the same value log C6 for both subordinate lines and treat the λ 5853 blend taking into account both the Ba II and Fe I lines (see Sect. 2.1). A reduction of the van der Waals damping constant from log C6 = −30.6 for λ 5853 and log C6 = −31.2 for λ 6496 used in 2001 to our present estimate log C6 = −31.3 (Sect. 2.1) leads to an increase of derived Ba abundance, while accounting for absorption by the blending of the Fe I line leads to a decrease of Ba abundance from the λ 5853 blend. As a result, in the two most metal-poor stars of our sample (HD 103095 and HD 64606), the revised Ba abundance is smaller (van der Waals broadening of the subordinate lines is weak and blending of Ba II λ 5853 prevails) by 0.01 dex compared to our previous data. Also in the remaining stars, the revised Ba abundance has become larger by 0.02 - 0.04 dex, with the only exception being that HD 117176 now reveals Ba abundance that is higher by 0.06 dex. The latter star shows the largest discrepancy in log εBa derived from the λ 5853 and λ 6496 lines.
Table 2. Stellar parameters, Ba abundances, and the fractions of the odd isotopes of Ba (column \textit{odd}, in \%) of the selected sample. The column \textit{low - up} contains the lower and upper limits of that fraction. In the column “Note”, the notations 0, 1, and 2 refer to the thin disk, thick disk, and halo stars, respectively. $V_{\text{mic}}$ is given in km s$^{-1}$.

| HD  | $T_{\text{eff}}$ | log g | $V_{\text{mic}}$ | [Fe/H] | [Ba/H] | odd | low - up | Note |
|-----|-----------------|-------|-----------------|--------|--------|------|----------|------|
| 3795 | 5370            | 3.82   | -0.64           | -0.58  | 39     | 34 - 44 | 1       |
| 4614 | 5940            | 4.33   | -0.30           | -0.23  | 24     | 17 - 31 | 0       |
| 9407 | 5660            | 4.42   | 0.03            | -0.01  | 13     | 7 - 18  | 0       |
| 10519 | 5710          | 4.00   | -0.64           | -0.69  | 42     | 38 - 46 | 1       |
| 10697 | 5610           | 3.96   | 0.10            | 0.14   | 11     | 4 - 17  | 0       |
| 18757 | 5710           | 4.34   | -0.28           | -0.38  | 31     | 26 - 36 | 1       |
| 22879 | 5820           | 4.27   | 0.12            | -0.06  | 26     | 24 - 34 | 1       |
| 30649 | 5820           | 4.28   | -0.47           | -0.57  | 30     | 27 - 33 | 1       |
| 37124 | 5610           | 4.44   | -0.44           | -0.55  | 29     | 25 - 34 | 1       |
| 52711 | 5890           | 4.31   | -0.16           | -0.09  | 16     | 11 - 22 | 0       |
| 55575 | 5890           | 4.25   | -0.36           | -0.39  | 23     | 20 - 26 | 0       |
| 62301 | 5940           | 4.18   | -0.69           | -0.75  | 32     | 28 - 36 | 1       |
| 64606 | 5320           | 4.54   | -0.89           | -1.00  | 35     | 30 - 40 | 1       |
| 65583 | 5320           | 4.55   | -0.73           | -0.77  | 39     | 34 - 44 | 1       |
| 68017 | 5630           | 4.45   | -0.40           | -0.50  | 33     | 25 - 38 | 1       |
| 69611 | 5820           | 4.18   | -0.60           | -0.72  | 28     | 24 - 32 | 1       |
| 101258 | 5760          | 4.24   | -0.46           | -0.59  | 35     | 29 - 43 | 1       |
| 103095 | 5110          | 4.66   | -1.35           | -1.41  | 42     | 36 - 46 | 2       |
| 112758 | 5240          | 4.62   | -0.43           | -0.53  | 27     | 16 - 37 | 1       |
| 114762 | 5930          | 4.11   | -1.71           | -0.83  | 37     | 31 - 42 | 1       |
| 117176 | 5480          | 3.83   | -0.11           | -0.09  | 25     | 11 - 38 | 0       |
| 121560 | 6140          | 4.27   | -0.43           | -0.35  | 27     | 22 - 32 | 0       |
| 132142 | 5240          | 4.58   | -0.39           | -0.46  | 33     | 29 - 37 | 1       |
| 134987 | 5740          | 4.25   | 0.25            | 0.17   | 18     | 13 - 21 | 0       |
| 168009 | 5785          | 4.23   | -0.03           | -0.07  | 16     | 12 - 21 | 0       |

Ba abundance determined from the $\lambda$5853 line turns out to be systematically lower than that from the second line; the Ba abundance is lower by $-0.03 \pm 0.02$ dex in the stars with [Ba/H] $\geq -0.35$, by $-0.01 \pm 0.03$ dex in the more Ba-poor stars, and by $-0.02 \pm 0.03$ dex for the whole sample (Fig. 4 top panel). The abundance difference log $\varepsilon(\lambda5853) - \log \varepsilon(\lambda6496)$ shows no correlation with $T_{\text{eff}}$ (Fig. 4 bottom panel). Ba abundance from the $\lambda$5853 line can be underestimated due to overestimation of the oscillator strength of the blending Fe I $\lambda$5853 line. Using log $g_f = -2.371$ calculated recently by Kurucz (\url{http://cfaku5.cfa.harvard.edu}), we derive the larger Ba abundance from the $\lambda$5853 blend: it is larger by 0.01 dex in HD 9407 ([Ba/H] = $-0.01$) and by 0.02 dex in HD 68017 ([Ba/H] = $-0.50$) and HD 64606 ([Ba/H] = $-1.00$). Another source of the obtained discrepancy between the two Ba lines is the uncertainty of the van der Waals damping constant of 0.05 – 0.18 dex according to Barklem (2006). In the next subsection, we will discuss an effect of total Ba abundance error on the Ba even-to-odd isotope ratio in stars.

Fig. 3. Synthetic NLTE (continuous line) flux profiles of the Ba II subordinate lines compared with the observed FOCES spectra (bold dots) of HD 10519. The same value [Ba/H] = $-0.69$ is obtained from both lines.

Fig. 4. NLTE abundance differences log $\varepsilon(\lambda5853) - \log \varepsilon(\lambda6496)$ versus total Ba abundance [Ba/H] (top panel) and $T_{\text{eff}}$ (bottom panel).

4.2. Ba even-to-odd isotope ratio in stars

The fraction of the odd isotopes of Ba is derived from the requirement that Ba abundances derived from the Ba II resonance line and the subordinate lines must be equal. We emphasize that absolute Ba abundance log $\varepsilon_{\text{Ba}}$ is used in this procedure,
and, thus, the obtained fraction does not depend on the adopted value of solar Ba abundance.

Figure 5 illustrates a determination procedure for one of the stars of our sample, HD 10519. The same Ba abundance, \( \log \varepsilon_{\text{Ba}} = 1.52 \), is obtained from both subordinate lines. The \( \lambda \) 4554 line gives \( \log \varepsilon_{\text{Ba}} = 1.64 \) at the assumption of the isotopic mixture in solar system matter and \( \log \varepsilon_{\text{Ba}} = 1.51 \) for the pure \( r \)-process yields predicted by Arlandini et al. (1999). As noted above, the synthetic \( \lambda \) 4554 line profile depends on the total fractional abundance of the odd isotopes rather than on the exact abundance of each odd isotope. Therefore, we vary the even-to-odd isotope ratio (from here on, “the isotope ratio”) in calculations of \( \lambda \) 4554 until the obtained Ba abundance agrees with that from the subordinate lines. The required Ba abundance \( \log \varepsilon_{\text{Ba}} = 1.52 \) is achieved from \( \lambda \) 4554 when the isotope ratio equals 58 : 42. The following points should be noted.

- When we go from the isotope ratio 82 : 18 to 54 : 46, the relative shift of the observed profile by 0.001 Å is required to achieve the best fit.
- We define the best fit from a requirement of the minimum \( \text{rms} \) difference between observed and calculated spectra. The equivalent width difference corresponding to the best fit may be different for different isotope ratios, e.g., in our calculations for HD 10519, the equivalent width measured over the same spectral interval, 4553.8 Å - 4554.3 Å, \( W(\lambda 4554) = 154.1 \text{ mÅ} \) for the isotope ratio 82 : 18 and 152.2 mÅ for 54 : 46. This can be understood. The smaller fraction of the odd isotopes that the larger Ba abundance is required to fit, in the observed line profile, and the calculated line wings, which never perfectly fit the observed ones (Fig. 5), contribute to \( W_i \) in the greater extension, when compared to the case of the larger fraction of the odd isotopes with the smaller Ba abundance.
- The macroturbulence value was allowed to be free because we have no arguments to fix it. An increase of the fraction of the odd isotopes cancels, in part, a saturation of \( \lambda 4554 \), and the line formation depth shifts downward; e.g., in our calculations for HD 10519, a macroturbulence value grows from 4.25 km s\(^{-1}\) to 4.5 km s\(^{-1}\) when the isotope ratio changes from 82 : 18 to 54 : 46.

**Uncertainty of the fractional abundance of the odd isotopes of Ba in stars.** Random errors of a desirable fraction are due to total Ba abundance error and the uncertainty of stellar parameters, \( T_{\text{eff}} \), \( \log g \), and macroturbulence value. Systematical errors are caused by the uncertainty of the Ba \( \lambda 4554 \) atomic parameters, namely, \( f_{ij} \) and \( C_6 \) values. Varying all mentioned parameters, we have performed the test calculations for the three representative stars of our sample with different values of \([\text{Ba}/H] \), HD 9407 (\([\text{Ba}/H] = -0.01 \)), HD 68017 (\([\text{Ba}/H] = -0.50 \)), and HD 64606 (\([\text{Ba}/H] = -1.00 \)). The effect on the Ba odd isotope fraction in these stars is shown in Table 3.

The most important source of total Ba abundance error in the stars with metallicity close to solar one is the uncertainty of the van der Waals damping constant of the subordinate lines. A variation in \( \log C_6 \) of 0.1 translates to the 0.03 dex variation in \( \log \varepsilon_{\text{Ba}} \). When \( \lambda 4554 \) is saturated, a reduction of Ba abundance obtained from the subordinate lines by 0.01 dex requires an increase of the fractional abundance of the odd isotopes by \( \sim 2\% \) to \( \sim 3\% \) depending on the resonance line strength. A variation of 80 K in \( T_{\text{eff}} \) translates to the uncertainty of the obtained fraction of 3% to 4%. In the stars with \([\text{Ba}/H] \leq -0.5 \), a variation in \( V_{\text{mic}} \) has nearly the same effect on both the resonance and subordinate lines, and no change of the Ba odd isotope fraction is required. In the stars with metallicity close to solar one, the resonance line lies on the damping part of the curve of growth and is weakly sensitive to \( V_{\text{mic}} \) variations, while this is not the case for the subordinate lines. The uncertainties of total Ba abundance, \( T_{\text{eff}} \), \( \log g \), and \( V_{\text{mic}} \), in total, result in a random error of the obtained fraction of 7%, 9%, and 10% in the stars with \([\text{Ba}/H] = 0, -0.5, \) and \(-1 \), correspondingly. There can be also a systematical difference of 4% to 5% between the thick disk and thin disk stars, due to a discrepancy in the mean value \( \log \varepsilon_{\text{Ba}}(\lambda 5853) - \log \varepsilon_{\text{Ba}}(\lambda 6496) \) between the samples of thick disk and thin disk stars.

Table 3. Effect on the Ba odd isotope fraction (in %) caused by uncertainties of atomic data and stellar parameters

| Input parameter | Input error | | \([\text{Ba}/H]\) |
|-----------------|-------------|-----------------|-----------------|
| \(\log C_6(5d-6p)\) | +0.1 | +6 | +3.8 | +1.4 |
| \(\log \varepsilon_{\text{Ba}}\) | -0.02 | +4 | +5 | +5.6 |
| \(T_{\text{eff}}(\text{K})\) | +80 | +3 | +4 | +4 |
| \(\log g\) | -0.1 | < 1 | -1 | +3 |
| \(V_{\text{mic}}(\text{km s}^{-1})\) | +0.1 | +5 | < 1 | < 1 |
| \(\log g f(\lambda 4554)\) | -0.02 | +4 | +5 | +5.6 |
| \(\log C_6(\lambda 4554)\) | +0.1 | -7 | -8 | -8 |
A variation of 0.1 dex in the van der Waals damping constant of the λ4554 line produces a strong effect, 7% to 8% of the derived fraction of the odd isotopes of Ba; however, this is a systematical effect. It depends only weakly on Ba/H and therefore will not affect a difference in the fraction of the odd isotopes between different stars.

We suppose that in each individual star, the spread of Ba abundance derived from two subordinate lines fully reflects both random and systematical errors of total Ba abundance, including effects of the uncertainties of atomic parameters (gf and Cv values), microturbulence value, and NLTE treatment. It is worth while to remember that due to different strengths of the Ba II λ6496 and λ5853 lines (f(λ6496)/f(λ5853) ≃ 4), they lie in each star on different parts of the curve of growth. The uncertainty of a desirable fraction in each star is evaluated, taking into account its individual Ba abundance error and uncertainty of the λ4554 line profile fitting. In terms of Ba abundance, the latter value is estimated to be 0.01 dex, based on the analysis of the (O - C) values. For example, in HD 10519, both subordinate lines give the same log εBa, and the lower and upper limits of the odd isotope fraction are calculated taking into account only the uncertainty of the λ4554 line profile fitting (0.01 dex). In the range of the odd isotope fraction between 35% and 46%, characteristic of this star, a Ba abundance variation of 0.01 dex produces the 4% variation in the fractional abundance of the odd isotopes. Therefore, our estimate of the fraction of the odd isotopes of Ba in this star is 42 ± 4%.

The obtained fraction of the odd isotopes, with its lower and upper limits in the stars of our sample, are presented in Table 2.

5. Stellar Ba odd isotopes as an indicator of the r/s-process nucleosynthesis

In Fig. 5, we plot the fractional abundance of the odd isotopes of Ba versus the total Ba abundance and the [Eu/Ba] and [Eu/Fe] abundance ratios. Based on the spread of Ba abundance in each star (Fig. 4), error bars of the [Ba/H] value do not exceed 0.1 dex. The [Eu/Fe] abundance ratios are taken from our earlier determinations (Mashonkina & Gehren 2001), where their errors are estimated as Δ[Eu/Fe] = 0.05 dex. We note that both Eu and Fe abundances are derived from weak spectral lines of the dominant ionization stage, Eu II and Fe II, respectively, and the uncertainty of stellar parameters has a negligible effect on the derived Eu/Fe abundance ratio. Error bars of the [Eu/Ba] value are mainly defined by errors of Ba abundance.

It is clearly seen that the obtained fraction grows towards the lower Ba abundance. Its value in the thick disk stars ranges between 27% and 42%, with the mean value 33 ± 4%. This indicates the higher contribution of the r-process to barium in the thick disk stars compared to the solar system matter in agreement with our expectations. Analysis of the [α/Fe] abundance ratios (we cite here only the first such studies: Gratton et al. 1996, 2000; Fuhrmann 1998; Prochaska et al. 2000) suggests that the thick disk stellar population is nearly the same age as the Galactic halo one. This conclusion was confirmed from an analysis of Eu/Ba and Nd/Ba abundance ratios (Mashonkina & Gehren 2000; Mashonkina et al. 2004; Bensby et al. 2005). The significant overabundance of Eu and Nd relative to Ba found in the thick disk stars at [Fe/H] ≤ −0.3 says that these stars formed in the early Galaxy when SNeII dominated the synthesis of heavy elements.

Both the [Eu/Ba] abundance ratio and the fractional abundance of the odd isotopes of Ba are sensitive to the relative con-
tribution of the \(r\)-process to heavy element synthesis, and it is natural to expect their correlation. Figure 4 shows that such correlation really exists. It is more clearly seen in the plane *fractional abundance of the odd isotopes of Ba* - *[Eu/Fe]* because the range of *[Eu/Fe]* values in the thick disk stars is larger than that of *[Eu/Ba]*, and errors of the *[Eu/Fe]* values are smaller than that of *[Eu/Ba]*.

The obtained data provide observational constraints to models of the \(s\)- and \(r\)-process nucleosynthesis. The "classical" model of the \(s\)-process based on the newest accurate measurements of the stellar \(n\)-capture cross-sections (Arlandini et al. 1999) predicts a pure \(s\)-process origin of solar even isotopes of Ba. In this model, no even isotope of Ba appears in stars formed in the early Galaxy before the onset of the \(s\)-process in AGB stars. In contrast to this prediction, we find a significant fraction of the even isotopes of Ba, \(\sim 67\%\), in old Galactic stars, the thick disk stars. The "stellar" models of Arlandini et al. (1999), based on stellar AGB models of 1.5 *M*\(_{\odot}\) and 3 *M*\(_{\odot}\) with half solar metal abundance, and Travaglio et al. (1999), who integrate \(s\)-abundances from different generations of AGB stars, i.e., consider the whole range of Galactic metallicities, both predict that solar abundance of isotope \(^{138}\)Ba is contributed to by the \(s\)-process only in part: 86\% and 84\%, respectively. As a result, in the oldest stars of the Galaxy, formed at the epoch of SNeII dominance in nucleosynthesis, a fraction of the even isotopes of Ba is expected to be at the level of 54\%. Ba isotopic fractions found in the thick disk stars favor the "stellar" model of heavy element synthesis.

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**Appendix A: The outlook for a determination of Ba isotopic fractions in very metal-poor stars**

It would be very important to extend our study to the older and more metal-poor stars revealing a pure \(r\)-process nucleosynthesis and to determine from observations the relative yields of the even and odd isotopes of Ba in the \(r\)-process. At *[Ba/H]* < −2, our method fails to give a reliable value of the fractional abundance of the odd isotopes of Ba due to (i) less sensitivity of the \(\lambda\,4554\) line to its variation, and (ii) less accuracy of total Ba abundance. An increase of the fraction of the odd isotopes of Ba from 18\% to 46\% leads to a decrease of Ba abundance derived from \(\lambda\,4554\) by 0.07 dex at *[Ba/H]* = −2 and by only 0.02 dex at *[Ba/H]* = −3.3. At the same time, the weaker subordinate line \(\lambda\,5853\) becomes, in fact, unmeasurable in stellar spectra.

Can we determine a desirable fraction based on only the HFS broadening of the \(\lambda\,4554\) line without knowing total Ba abundance? Let’s imagine that we have a perfect observed profile of \(\lambda\,4554\). Then we fit it varying the fractional abundance of the odd isotopes of Ba. We have modelled such situation for two "stars" using two model atmospheres.

"Star" 1: \(T_{\text{eff}} = 5710\) K, \(\log g = 4.00\), \([\text{M/H}] = -0.64\), \(V_{\text{mic}} = 1.1\) km s\(^{-1}\), \([\text{Ba/H}] = -0.69\). The theoretical line profile of \(\lambda\,4554\) calculated assuming the Ba odd isotope fraction of 42\% and convolved with the Gaussian of 4 km s\(^{-1}\) and radial-tangential profile of \(V_{\text{mac}} = 4.5\) km s\(^{-1}\) will serve as the "observed" line profile. Its \(W_{\lambda} = 152\) mÅ.

"Star" 2: \(T_{\text{eff}} = 6350\) K, \(\log g = 4.03\), \([\text{M/H}] = -2.07\), \(V_{\text{mic}} = 1.7\) km s\(^{-1}\), \([\text{Ba/H}] = -2.14\). The "observed" profile of \(\lambda\,4554\) was obtained assuming the Ba odd isotope fraction of 46\% and applying the Gaussian of 2 km s\(^{-1}\) and \(V_{\text{mac}} = 4.7\) km s\(^{-1}\). Its \(W_{\lambda} = 50\) mÅ.

Assuming the fraction of the odd isotope of Ba, \(odd = 18\%\) and then 35\%, we obtained the best fits for each case and for both "stars". Ba abundance and \(V_{\text{mac}}\) value were allowed to vary. The Gaussian was fixed. In practice, the \(V_{\text{mac}}\) values turn out to be within the uncertainty of determination: \(V_{\text{mac}} = 4.25\) km s\(^{-1}\) when \(odd = 18\%\) and 4.4 km s\(^{-1}\) when \(odd = 35\%\) in "star" 1; \(V_{\text{mac}} = 5.1\) km s\(^{-1}\) when \(odd = 18\%\) and 5.0 km s\(^{-1}\) when \(odd = 35\%\) in "star" 2. The ("O" - C) differences are shown in Fig. A.1.

It can be seen from Fig. A.1 that an accuracy of line profile measurements has to be much higher than 0.05\% if one wishes to determine a desirable fraction within the uncertainty of 10\%.

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Note added in proofs.

For $\lambda 4554$, the van der Waals damping constant based on theoretical predictions of Barklem & O’Mara (1998) is equal to log $C_0 = -31.46$ with the uncertainty of 0.05 – 0.18 dex according to Barklem & Asplund-Johansson (2005) and Barklem (2006). Using this value and the MAFAGS solar model atmosphere, we find solar Ba abundance log $\varepsilon_{\text{Ba}} = 2.17$, in well agreement with the recent determinations of the meteoritic log $\varepsilon_{\text{met,Ba}} = 2.16 \pm 0.03$ and solar log $\varepsilon_{\text{Ba}} = 2.17 \pm 0.07$ Ba abundance by Asplund et al. (2005). Assuming log $C_0 = -31.46$ for $\lambda 4554$, we checked other stars of our sample with stellar parameters close to solar ones, HD 9407, HD 10697, HD 134987, and HD 168009 (see Sect. 3), and found systematically lower Ba abundance from the Ba$^+$ resonance line compared to that from the subordinate lines, by 0.06 dex to 0.10 dex. Variation of stellar parameters and microturbulence value does not help to achieve agreement between different lines, and the only way out is to reduce collisional broadening of the resonance line. Therefore, we apply in this study the value log $C_0 = -31.65$ for $\lambda 4554$. For the Ba$^+$ multiplet $5d-6p$, the van der Waals damping constant log $C_0 = -31.3$ found empirically in Sect. 2.1 is very close to log $C_0 = -31.28$ based on the theory of Barklem & O’Mara (1998) and accessible via the Vienna Atomic Line Data base (VALD, Kupka et al. 1999).