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Mg, Ba and Eu abundances in thick disk and halo stars*

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Abstract. Our sample of cool dwarf stars from previous papers (Mashonkina & Gehren 2000, 2001) is extended in this study including 15 moderately metal-deficient stars. The samples of halo and thick disk stars have overlapping metallicities with [Fe/H] in the region from −0.9 to −1.5, and we compare chemical properties of these two kinematically different stellar populations independent of their metallicity. We present barium, europium and magnesium abundances for the new sample of stars. The results are based on NLTE line formation obtained in differential model atmosphere analyses of high resolution spectra observed mainly using the UVES spectrograph at the VLT of the European Southern Observatory. We confirm the overabundance of Eu relative to Mg in halo stars as reported in our previous papers. Eight halo stars show [Eu/Mg] values between 0.23 and 0.41, whereas stars in the thick and thin disk display a solar europium to magnesium ratio. The [Eu/Ba] values found in the thick disk stars to lie between 0.35 and 0.57 suggest that during thick disk formation evolved low-mass stars started to enrich the interstellar gas by *s*-nuclei of Ba, and the *s*-process contribution to barium thus varies from 30% to 50%. Based on these results, and using the chemical evolution calculations by Travaglio et al. (1999), we estimate that the thick disk stellar population formed on a timescale between 1.1 to 1.6 Gyr from the beginning of the protogalactic collapse. In the halo stars the [Eu/Ba] values are found mostly between 0.40 and 0.67, which suggests a duration of the halo formation of about 1.5 Gyr. For the whole sample of stars we present the even-to-odd Ba isotope ratios as determined from hyperfine structure seen in the Ba II resonance line λ 4554. As expected, the solar ratio 82:18 (Cameron 1982) adjusts to observations of the Ba II lines in the thin disk stars. In our halo stars the even-to-odd Ba isotope ratios are close to the pure *r*-process ratio 54:46 (Arlandini et al. 1999), and in the thick disk stars the isotope ratio is around 65:35 (±10%). Based on these data we deduce for thick disk stars the ratio of the *s*/*r*-process contribution to barium as 30:70 (±30%), in agreement with the results obtained from the [Eu/Ba] values.

Key words. line: formation – nuclear reactions, nucleosynthesis, abundances – stars: abundances – stars: late-type – Galaxy: evolution

1. Introduction

In this paper we continue our study of element abundances in cool dwarf stars, which gives useful information about nucleosynthesis in the Galaxy and also for some important parameters of Galactic evolution. In our previous studies (Mashonkina & Gehren 2000, 2001, hereafter Papers I and II) strong evidence for a distinct chemical history of the thick and thin disk was found from analyses of the Eu/Fe and Eu/Ba ratios: europium is overabundant relative to iron and barium in the *thick disk* stars, and there is a step-like decrease in the [Eu/Ba] and [Eu/Fe] values at the thick to thin disk *transition*. The europium to barium abundance ratio is particularly sensitive to whether nucleosynthesis of the heavy elements occurred in the *s*- or *r*-process. For solar system matter $\log \varepsilon_{\rm Eu,\odot} - \log \varepsilon_{\rm Ba,\odot} = -1.67$ (Grevesse et al. 1996). The contributions of the *s*- and *r*-process to the solar Ba abundance consist of 81% and 19% according to the recent data of Arlandini et al. (1999), whereas 94% of the solar europium originated from the *r*-process. This result has been obtained by Arlandini et al. (1999) as the best-fit to the solar *main s*-component using stellar AGB models of 1.5 $M_\odot$ and 3 $M_\odot$ with half solar metallicity. A very similar result for Ba and Eu has been obtained by Travaglio et al. (1999) by the integration of *s*-abundances from different generations of AGB stars, i.e. considering the whole range of Galactic metallicities. Thus, the solar abundance ratio of Eu to Ba contributed by the *r*-process relative to the total abundances, $[{\rm Eu/Ba}]_r$, equals 0.70. In several studies Sneden et al. (1996, 2000), Cowan et al. (1999, 2002), and Hill et al. (2002) have presented arguments

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supporting constant relative *r*-process element abundances during the history of the Galaxy (at least, where $Z < 70$). Due to the delay in the onset of main *s*-process nucleosynthesis during the thermally pulsing asymptotic giant branch (AGB) phase of low-mass stars ($2 \ldots 4\ M_{\odot}$) compared with the production of *r*-nuclei in SNe II, the oldest stars in the Galaxy are expected to carry a significant Eu overabundance of about 0.7 dex relative to barium. A clear break in the run of [Eu/Ba] values with overall metallicity therefore should signal the onset of the contribution to barium coming from AGB stars. Our data obtained in Paper II suggest a dominance of the *r*-process in heavy element production at the epoch of the halo and thick disk formation. Abrupt changes in [Eu/Fe] and [Eu/Ba] clearly indicate a hiatus in star formation before the early stage of the thin disk developed, when europium enrichment from SN II events had come to an end, but iron and barium continued to be produced in evolved stars of lower mass.

In this paper we add 15 newly observed stars. For the sample of thick disk stars the range of metallicities is now extended to [Fe/H] = −1.49, and we first determine Eu and Ba abundances in the "metal-weak thick disk" stars. The sample of halo stars with both Ba and Eu abundance available includes 10 stars with metal abundances from −0.90 to −1.71. These new data improve the statistical significance of our earlier conclusions. We use the obtained [Eu/Ba] abundance ratios to evaluate the ratio of the s/r-process contribution to the barium isotopes. Based on chemical evolution calculations of Travaglio et al. (1999) we then estimate the timescale for the halo and thick disk formation.

The s/r-process ratio can be found in an independent way from analysis of the Ba II lines. The idea is based on the fact that the larger the *r*-process contribution is, the larger the fraction of odd isotopes must be, and the stronger the hyperfine structure (HFS) broadening of the Ba II resonance line, λ 4554. The even-to-odd Ba isotope ratio is determined from the requirement that Ba abundances derived from the Ba II subordinate lines (which are free of HFS effect) and the resonance line must be equal. In this study the even-to-odd Ba isotope ratios are derived for the samples of halo, thick and thin disk stars. They reveal a distinction between the different Galactic stellar populations. The solar ratio 82:18 (Cameron 1982) adjusts to observations of the Ba II lines in *thin disk* stars. A mean ratio 65:35 (±10%) is obtained for *thick disk* stars, whereas halo stars are observed with values close to the pure *r*-process ratio 54:46 (Arlandini et al. 1999).

In Paper I we first reported an overabundance of europium relative to magnesium of more than 0.2 dex in two halo stars. The knowledge of Eu/Mg abundance ratios in the oldest stars of the Galaxy is of great importance for understanding nucleosynthesis in the early Galaxy. One commonly believes that Mg and Eu are mainly produced in SN II explosions, but the question remains whether α- and *r*-process occur in a common site. Theoretical predictions of SN II element yields show that [α/Fe] increases with increasing progenitor mass (Arnett 1991). Most theoretical models of *r*-process nucleosynthesis are based on low mass ($8 \ldots 12\ M_{\odot}$) supernovae (Wheeler et al. 1998; Tsujimoto & Shigeyama 1998). However, even the lowest mass SN II progenitors have very short evolution times of less than 20 million years. Thus, if mixing of the interstellar gas in the early Galaxy was sufficient, the Eu/Mg ratios in stars born after 20 million years from the beginning of protogalactic collapse would be expected to be close to solar. Stars born earlier should reveal an underabundance and, certainly, not an overabundance of Eu relative to Mg. This problem remained unsolved in Papers I and II because our sample of halo stars was limited to 3 stars.

Here we determine the [Eu/Mg] abundance ratios for an extended sample of halo stars. Eight of the ten stars show an overabundance of europium relative to magnesium with a mean value of 0.31 ± 0.06 dex, whereas in both the thick and thin disk stars europium follows magnesium. This observational result points at different sites for the *r*-process and α-process, respectively, and it poses problems on some aspects of Galactic chemical evolution such as mixing of the interstellar matter during the halo formation phase, additional sources of Galactic magnesium in stars with $M < 8\ M_{\odot}$, and the astrophysical site (or sites?) for the *r*-process.

Our results are based on high-resolution (~60 000) spectra observed using the UVES echelle spectrograph at the ESO VLT2 telescope and the FOCES echelle spectrograph at the 2.2 m telescope at Calar Alto Observatory. Stellar parameters of the newly included stars are derived with the same methods as applied to the remaining stars of our sample which were selected from Fuhrmann's (1998, 2000) lists. Effective temperatures $T_{\rm eff}$ are from Balmer line profile fitting, surface gravities $\log g$ from Hipparcos parallaxes and modelling the line wings of the Mg Ib triplet; metal abundances [Fe/H] and microturbulence values $V_{\rm mic}$ from profile fitting of Fe II lines. As in our previous studies barium and europium abundances are based on non-local thermodynamical equilibrium (NLTE) line formation for Ba II and Eu II. NLTE magnesium abundances are determined from the Mg I lines using NLTE abundance corrections calculated by Zhao & Gehren (2000).

The paper is organized as follows. Observations and data reduction are described in Sect. 2. In Sect. 3 we determine stellar parameters and identify the membership of individual stars in particular stellar populations of the Galaxy. NLTE magnesium, barium and europium abundances are derived in Sect. 4 and the even-to-odd Ba isotope ratios in Sect. 5. In Sect. 6 we discuss the element abundance ratios and their implications for nucleosynthesis and the evolution of the Galaxy.

2. Observations and data reduction

Our sample of 63 stars from Paper II is extended in this study by including 15 newly observed stars. For the three brightest stars, HD 25329, HD 148816 and HD 193901, spectra were observed by Klaus Fuhrmann with a resolution of ~60 000 and for BD +18°3423 by one of the authors (TG) at $R \sim 40\,000$ using the fiber optics Cassegrain echelle spectrograph FOCES at the 2.2 m telescope of the Calar Alto Observatory in August and October 2001. The signal-to-noise ratio is 200 or higher in the spectral range $\lambda > 4500$ Å, but smaller in the blue, where $S/N \sim 30$ near the Eu line at $\lambda = 4130$ Å. The data cover an approximate spectral range of 4000–7000 Å.

For metal-poor stars with fainter magnitudes it is necessary to observe with a larger telescope because only this guarantees simultaneously high resolution *and* high signal-to-noise ratio, both needed to detect and model the extremely faint Eu and Ba lines. In April 2001 therefore 14 metal-poor stars were observed using the Ultraviolet and Visual Echelle Spectrograph UVES (Dekker et al. 2000) at the 8 m ESO VLT2 telescope on Cerro Paranal. As usual, at least two exposures were obtained for each star to keep the influence of hot pixels at a minimum. Data extraction followed a full multi-exposure echelle analysis originally developed for the FOCES spectrograph and taking advantage of data redundancy. This turned out to be much more reliable than standard optimal extraction. Finally, the resulting order spectra were rectified with the help of spectral continua in neighbouring orders. Typical line profiles are seen in Fig. 1. In spite of the considerable efforts both in observing and in extracting the spectra, three of the stars could not be used in our present analysis. HD 140283 is so metal-poor that even with the high S/N ratio the Ba II λ 5853, λ 6496 and Eu II λ 4129 lines cannot be extracted from noise. BD −3°2525 and CD 52°2174, turn out to show double-lined spectra.

3. Stellar parameters

For the three stars marked with an asterisk in Table 1, we use stellar parameters determined spectroscopically by Fuhrmann (2002b). Effective temperatures $T_{\rm eff}$ are found from Balmer line profile fitting, surface gravities $\log g$ from analysis of the line wings of the Mg Ib triplet; metal abundances [Fe/H] and microturbulence velocities $V_{\rm mic}$ are derived from Fe II line profile fitting. For the remaining stars listed in Table 1 stellar parameters are determined using the same methods, with $\log g$ calculated from the Hipparcos parallaxes. Our analyses are all based on the same type of model atmospheres. In stellar parameter determinations we use the MAFAGS line-blanketed LTE model atmospheres generated and discussed by Fuhrmann et al. (1997).

Effective temperatures: Theoretical H_α and H_β line profiles are calculated according to the description given by Fuhrmann et al. (1993). For each star the difference of effective temperatures obtained from H_α and H_β is less than 100 K, and for 12 stars the mean value $\Delta T_{\rm eff}(H_\alpha–H_\beta) = -20 \pm 60$ K. We adopt the average value of $T_{\rm eff}(H_\alpha)$ and $T_{\rm eff}(H_\beta)$ as final effective temperature and estimate a statistical error of $T_{\rm eff} \sim 60$ K.

Surface gravities: Nearly all stars investigated here have Hipparcos parallaxes (ESA 1997) with an accuracy $\sigma(\pi)/\pi < 0.2$ (the only exception being BD −4°3208 with $\sigma(\pi)/\pi = 0.27$). The well-known relation between g, stellar mass M, radius R and $T_{\rm eff}$ is used to calculate $\log g$ (Hip), where square brackets denote the logarithmic ratio with respect to the solar value,

$$[g] = [M] + 4[T_{\rm eff}] + 0.4(M_{\rm bol} - M_{\rm bol,\odot}).$$

Here, $M_{\rm bol}$ is the absolute bolometric magnitude, with bolometric corrections taken from Alonso et al. (1995). For the Sun, an absolute visual magnitude $M_{V,\odot} = 4.83$ and bolometric correction $BC_\odot = -0.12$ (Allen 1973) are adopted. The mass is obtained by interpolating in the $M_{\rm bol}$ vs. $\log T_{\rm eff}$ diagram between the α-element enhanced isochrones of 12 Gyr and 16 Gyr calculated by VandenBerg et al. (2000). The internal precision of the mass is estimated to be better than $\pm 0.05\ M_\odot$.

The error of the surface gravity $\log g$ (Hip) derived from Hipparcos parallaxes is dominated by the error of π, where $\sigma(\pi)/\pi = 0.20$ transforms to $\sigma(\log g) = \pm 0.16$ dex. Column 4 of Table 1 lists $\log g$ (Hip) and the errors obtained from adding the squared errors of parallax and mass.

Table 1. Stellar parameters of the new sample.

HD/BD	$T_{\rm eff}$ [K]	Mass [$M_\odot$]	$\log g$ (Hip)	$\log g$ (Mg I)	[Fe/H]	$V_{\rm mic}$ [km s^{-1}]
25329*	4800			4.66	–1.84	0.6
29907	5500	0.7	4.64 ± 0.06	4.67	–1.55	0.6
31128	5980	0.8	4.49 ± 0.07	4.42	–1.49	1.2
34328	5955	0.8	4.54 ± 0.07	4.44	–1.61	1.2
59392	6010	0.85	4.02 ± 0.15	3.90	–1.59	1.4
74000	6225	0.85	4.16 ± 0.16	4.28	–2.00	1.4
97320	6110	0.8	4.27 ± 0.05	4.27	–1.18	1.4
99383	6100	0.8	4.22 ± 0.12	4.37	–1.54	1.4
102200	6115	0.8	4.20 ± 0.08	4.24	–1.24	1.4
122196	6000	0.9	3.99 ± 0.12	3.94	–1.71	1.5
148816*	5880			4.07	–0.78	1.2
193901*	5780			4.46	–1.08	0.9
298986	6130	0.8	4.30 ± 0.16	4.22	–1.34	1.4
−4°3208	6280	0.9	4.08 ± 0.24	4.03	–2.23	1.6
18°3423	6070	0.8	4.28 ± 0.15	4.14	–0.90	1.4

* Stellar parameters from Fuhrmann (2002b).

In addition, the surface gravities were determined by an independent method based on the Mg I λ 5172 and λ 5183 line wing fitting. First the magnesium abundance is obtained from the weaker Mg I λ 5528 and λ 5711 lines, which are not strong enough to develop significant line wings. Then the damping of the Mg Ib lines is used as an indicator of surface gravity. LTE was assumed both in line wing fitting and in deriving the abundance. Since we use a differential analysis with respect to the Sun, atomic parameters of the Mg I lines are improved empirically from analyses of the *solar* line profiles (Kurucz et al. 1984) on the base of the MAFAGS solar model atmosphere and assuming $V_{\rm mic} = 1$ km s^{-1}. The values of $\log gf\varepsilon_\odot$ and $\log C_6$ obtained for the solar spectrum are given in Table 2. We note that using the meteoritic value $\log \varepsilon_{\rm Mg} = 7.58$ (Grevesse et al. 1996) as the solar photospheric Mg abundance the empirically determined values of $\log gf$ coincide within 0.05 dex with the corresponding oscillator strengths from Opacity Project calculations (Butler et al. 1993). For λ 5172 and λ 5183 the $\log C_6$ values in Table 2 are in agreement with $\log C_6 = -30.69$ based on Anstee & O'Mara's (1995) calculations. For λ 5528 our value of $\log C_6$ is smaller by 0.15 dex compared with $\log C_6 = -29.94$ based on the calculations of Barklem & O'Mara (1997). We refer to abundances on the usual scale where $\log \varepsilon_{\rm H} = 12$.

Column 5 of Table 1 lists $\log g$ (Mg I). It is obvious that for most of the stars surface gravities obtained from the Hipparcos parallax and Mg Ib lines agree within error bars

Table 2. Atomic data obtained from solar line profile fitting for the Mg I and Fe II lines used in stellar parameter determinations.

λ (Å)	$E_{\rm low}$(eV)	$\log gf\varepsilon_{\odot}$	$\log C_6$
	Mg I lines		
5528.41	4.33	7.03	–30.10
5711.09	4.33	5.86	–30.18
5172.70	2.70	7.13	–30.69
5183.62	2.70	7.35	–30.75
	Fe II lines		
4923.93	2.88	6.00	–31.91
5018.45	2.88	6.22	–32.11
5264.81	3.22	4.43	–32.19
5425.26	3.19	4.24	–32.19
5325.56	3.21	4.30	–32.19
5234.63	3.21	5.19	–31.89
5197.58	3.22	5.19	–31.89
6456.38	3.89	5.40	–32.18
6247.56	3.87	5.16	–32.18

of $\log g$ (Hip). For HD 34328 and HD 99383 the difference $\log g$ (Hip) $-$ $\log g$ (Mg I) only slightly exceeds 1 σ. For 12 stars this difference equals, on average, 0.02 ± 0.09 dex. Based on the data for ∼100 stars Fuhrmann (2000) has found a systematic deviation of the surface gravities based on Hipparcos parallaxes from those based on Mg Ib spectroscopy of 0.02 ± 0.04 dex. Since both methods give very similar results, we adopt $\log g$ (Hip) as final values for the investigated stars.

Fe abundance and microturbulence: from comparison of the spectra of typical program stars with the solar spectrum 9 unblended Fe II lines were selected to determine the Fe abundance and microturbulence velocities $V_{\rm mic}$ by the requirement that the derived [Fe/H] abundances should not depend on line strength. We assume LTE in the analyses of the Fe II lines as verified in our recent NLTE calculations for Fe I and II (Gehren et al. 2001) which have shown neglegible NLTE effects for Fe II. Van der Waals damping constants C_6 were taken from Kurucz's (1992) line list. Similar to the Mg I lines the values $\log gf\varepsilon_{\odot}$ for Fe II were obtained from solar line profile fitting. They are given in Table 2. Using $\log \varepsilon_{\rm Fe} = 7.51$ as solar iron abundance the obtained values $\log gf$ for 6 Fe II lines coincide within 0.11 dex with the corresponding oscillator strengths from Raassen & Uylings (1998), and the mean difference equals 0.06 ± 0.06.

For each star the line-to-line scatter of [Fe/H] does not exceed 0.13 dex, and the mean value is calculated with a mean square error of no more than 0.04 dex. We estimate that the error of $V_{\rm mic}$ is about 0.1 km s^{-1}. The uncertainties in $T_{\rm eff}$ (60 K) and $\log g$ (0.1 dex) correspond to errors of ≤0.02 dex and 0.05 dex in [Fe/H]. Altogether, the error of [Fe/H] is of the order of 0.1 dex except for the most distant star BD −4°3208 with a maximum uncertainty in $\log g$ roughly twice as large.

Membership in Galactic stellar population: all the stars have [Fe/H] ≤ −0.90, and they can be expected *not* to belong to the thin disk. We follow Fuhrmann (2000, 2002a) and use the stellar kinematics to discriminate between halo and thick disk stars. The kinematic data were taken from the Hipparcos catalogue (ESA 1997) and the catalogue of radial velocities of Barbier-Brossat & Figon (2000). For three stars with halo-type metal abundances, HD 31128 ([Fe/H] = −1.49), HD 97320 ([Fe/H] = −1.18) and HD 102200 ([Fe/H] = −1.24), the peculiar space velocities $V_{\rm pec}$ = 117 km s^{-1}, 85 km s^{-1} and 157 km s^{-1}, respectively, favour a thick disk membership. This assumption is supported by their small W space velocity components. Possibly, these stars represent the so-called "metal-weak thick-disk" discussed in the literature by Norris et al. (1985) and Fuhrmann (2002a). The lowest metal abundance of −1.84 in our sample of thick disk stars was found by Fuhrmann (2002a) for HD 25329. For the remaining stars $V_{\rm pec}$ is between 224 km s^{-1} and 440 km s^{-1}, and we refer to them as halo stars.

4. Element abundances

For each star line-blanketed LTE model atmospheres have been generated using the MAFAGS code at given values of $T_{\rm eff}$, $\log g$, [Fe/H] (Table 1) and [α/Fe], where [α/Fe] is the relative abundance of the most abundant α-process elements O, Mg and Si, of which the last two contribute in significant amounts to the electron pressure in cool stellar atmospheres. We assume that oxygen and silicon abundances follow magnesium and adopt [α/Fe] = [Mg/Fe].

4.1. Mg abundances

Magnesium abundances were derived in this study from profile fitting of the Mg I λ 5528 and λ 5711 lines, originally assuming LTE. NLTE abundance corrections $\Delta_{\rm NLTE}$ from Zhao & Gehren (2000) were then added to obtain NLTE abundances. NLTE effects tend to weaken the Mg I lines due to photoionization. For both lines this implies *positive* corrections $\Delta_{\rm NLTE}$ which are only slightly different by value. Relative to the solar values $\Delta_{\rm NLTE}(\lambda 5528)$ = 0.02 dex and $\Delta_{\rm NLTE}(\lambda 5711)$ = 0.05 dex NLTE abundance corrections for the investigated stars are therefore mostly between 0.06 dex and 0.10 dex. For 11 stars the difference between NLTE abundances obtained from λ 5528 and λ 5711 does not exceed 0.07 dex, with a mean value of 0.04 ± 0.02 dex. Only for HD 99383 the corresponding difference of 0.10 dex is slightly larger. The final Mg abundance is obtained as the average value. The [Mg I/Fe II] ratios are presented in Table 3.

4.2. Ba and Eu abundances

We use the same method as in Papers I and II to derive Ba and Eu abundances for the stars. The synthetic line profiles are computed using the departure coefficients of the Ba II and Eu II levels from the code NONLTE3 (Sakhibullin 1983) and the LTE assumption for other atoms. The line list is extracted from Kurucz' (1994) compilation, and it includes all the relevant atomic and molecular lines. A differential analysis with respect to the Sun is performed. Solar barium and europium abundances, $\log \varepsilon_{\rm Ba,\odot}$ = 2.21 and $\log \varepsilon_{\rm Eu,\odot}$ = 0.53, and van der Waals damping constants C_6 for the Ba II and Eu II lines were determined in Paper I from solar line profile fitting. The methods of NLTE calculations for Ba II and Eu II were

Table 3. Element abundances of the new sample.

HD/BD	[Fe/H]	[Mg/Fe]	[Ba/Fe]	[Eu/Fe]	Note
25329*	–1.84	0.42	0.33	0.24	*N*-rich
29907	–1.55	0.29	–0.02	0.63	
31128	–1.49	0.34	0.02	0.44	
34328	–1.61	0.38	0.20	0.27	?
59392	–1.59	0.27	0.19	0.68	
74000	–2.00	0.35	0.24	0.16 :	*N*-rich
97320	–1.18	0.36	0.02	0.40	
99383	–1.54	0.37	0.07	0.40	SB
102200	–1.24	0.30	–0.01	0.57	
122196	–1.71	0.16	–0.07	0.24	
148816*	–0.78	0.41	–0.13	0.30	
193901*	–1.08	0.18	–0.04	0.44	
298986	–1.34	0.16	–0.03	0.54	
−4°3208	–2.23	0.34	–0.14	–	
18°3423	–0.90	0.12	–0.02	0.42 :	

* [Fe/H] and [Mg/Fe] are from Fuhrmann (2002b).

developed earlier (Mashonkina & Bikmaev 1996; Mashonkina et al. 1999; Mashonkina 2000; Paper I). Some examples of the Ba II and Eu II line profile fitting are given in Fig. 1.

Altogether, uncertainties in $T_{\rm eff}$ (60 K), $\log g$ (0.1 dex) and $V_{\rm mic}$ (0.1 km s^{-1}) cause Ba abundance errors up to 0.08 dex in the range of metal abundances between −0.9 and −1.5 and up to 0.05 dex for the more metal-poor stars. For europium abundances the corresponding values are 0.06 dex and 0.05 dex. However, the ratios [Ba II/Fe II] and [Eu II/Fe II] are much less affected by possible errors of stellar parameters. Test calculations for BD +18°3423 ([Fe/H] = −0.90) have shown that varying $\log g$ by 0.15 dex leads to Δ[Ba/Fe] = 0.04 dex and Δ[Eu/Fe] = 0.02 dex. The effect is even smaller (∼0.01 . . . 0.02 dex) at [Fe/H] ∼ −1.5.

Barium abundances are obtained from the two Ba II subordinate lines, λ 5853 and λ 6496, nearly free of hyperfine structure. In three stars λ 6496 could not be used because of blends with telluric lines. In the spectrum of BD −4°3208, λ 5853 is too weak and could not be extracted from noise.

As discussed in a previous paper (Mashonkina et al. 1999), NLTE effects for Ba II depend on the Ba abundance, which correlates with the overall metal abundance of the atmospheric model. Thus, NLTE leads to stronger Ba II lines compared with LTE in stars of normal or moderately deficient metal abundances, but changes to the opposite effect in very metal-poor stars. $\Delta_{\rm NLTE}$ changes its sign at [Fe/H] between −1.2 and −1.9 depending on $T_{\rm eff}$ and $\log g$. As most stars of our new sample have [Fe/H] in this metallicity range, NLTE abundance corrections have different signs in different stars: $\Delta_{\rm NLTE}(\lambda\,6496)$ varies from −0.14 dex to 0.15 dex and $\Delta_{\rm NLTE}(\lambda\,5853)$ from −0.01 dex to 0.10 dex. For 3 stars NLTE effects are opposite for λ 6496 and λ 5853 (see, for example, Fig. 1). For 12 stars the mean value of the difference between NLTE abundances derived from λ 6496 and λ 5853 equals −0.01 ± 0.02 dex, while under the assumption of LTE Ba abundances from the first line are systematically overestimated relative to $\log \varepsilon_{\rm LTE}(\lambda\,5853)$, with a mean difference of 0.05 ± 0.05 dex. Taking into account the uncertainties of the stellar parameters we estimate the total statistical error of [Ba/Fe] to be ±0.05 dex.

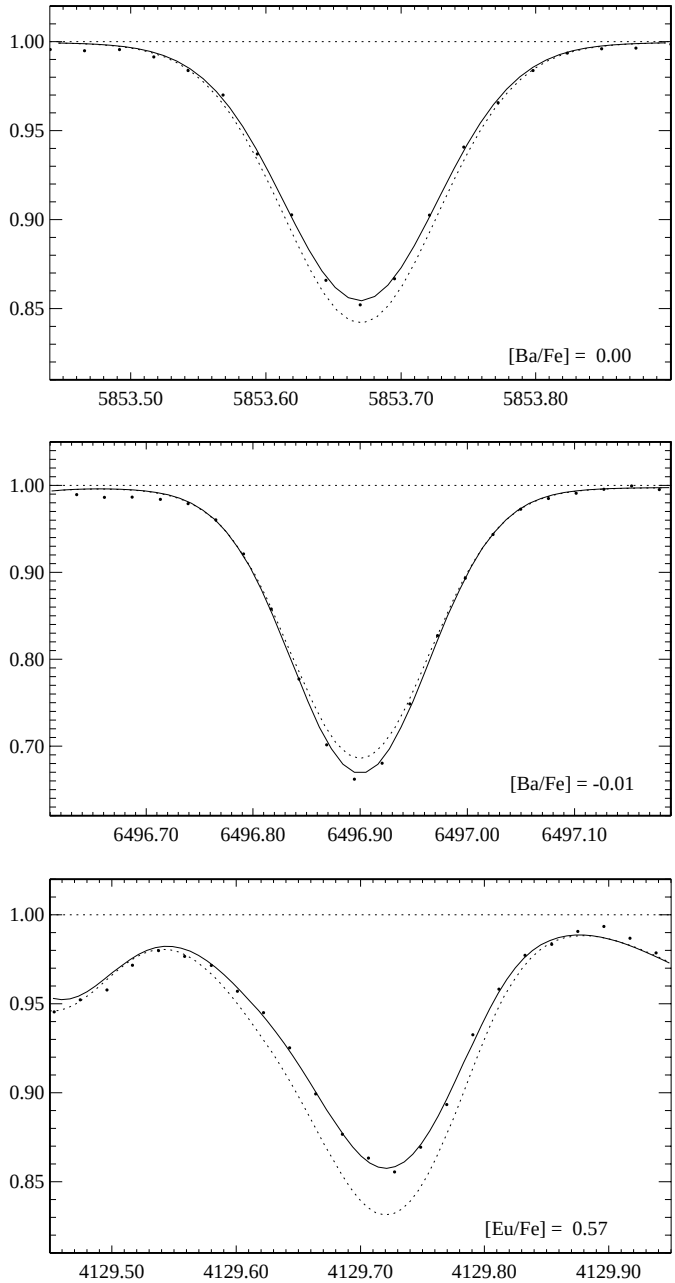

Fig. 1. Synthetic NLTE (continuous line) and LTE (dotted line) flux profiles of Ba and Eu lines compared with the observed UVES spectra (bold dots) of HD 102200 ([Fe/H] = −1.24).

Europium abundances have been derived for 14 stars of our new sample from the Eu II line, λ 4129. In the spectrum of BD −4°3208 this line was again too weak, and could not be extracted from noise; therefore, only an upper limit of ∼0.4 dex for the [Eu/Fe] value was estimated. The λ 4129 line is located in a crowded spectral range and the uncertainty in determining the local continuum may cause Eu abundance errors up to 0.05 dex for the spectra observed with UVES, and up to 0.10 dex for the FOCES spectra.

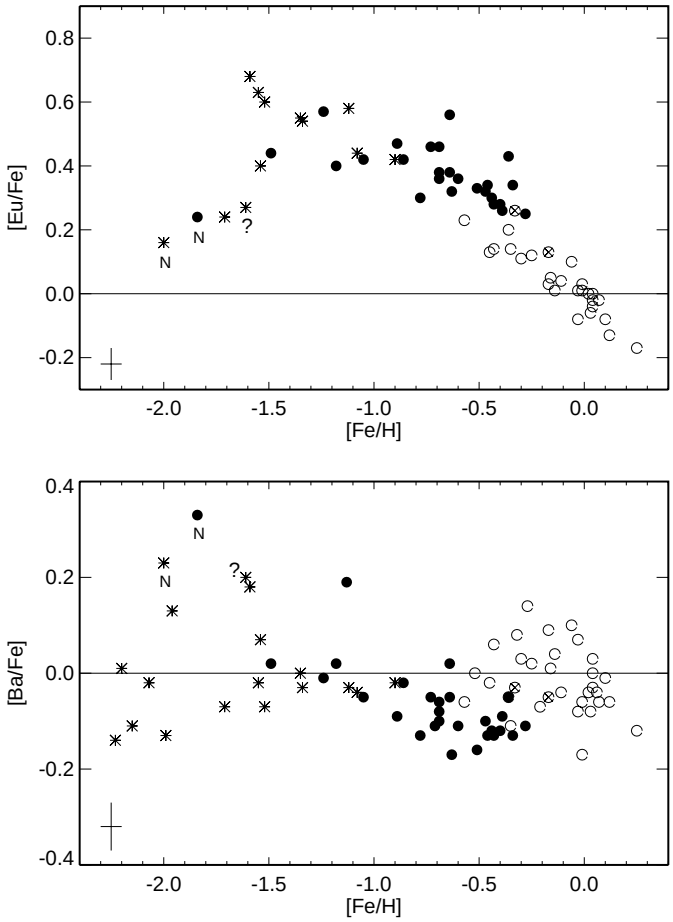

Fig. 2. The run of [Eu/Fe] (top panel) and [Ba/Fe] (bottom panel) with [Fe/H]. Symbols correspond to thin disk (open circles), thick disk (filled circles), and halo stars (asterisks). The two stars indicated by a cross in an open circle are transition stars between thin and thick disk according to Fuhrmann (1998). The N-rich stars are marked by "N" and HD 34328 with similar chemistry by "?". Error bars are indicated at the lower left.

Atomic data for hyperfine structure and isotopic shift were described in detail in Paper I for λ 4129. As discussed there, NLTE effects weaken the Eu II λ 4129 line compared with the LTE case, and NLTE abundance corrections are therefore positive. For our stars $\Delta_{\rm NLTE}$ ranges from 0.05 dex to 0.11 dex.

The results are presented in Table 3. [Ba/Fe] and [Eu/Fe] values for the whole sample of stars are shown in Fig. 2. We comment on a few stars which reveal different element abundances compared with other stars of similar metal abundances.

HD 25329 and HD 74000 are known as nitrogen-rich stars (Carbon et al. 1987) with [N/Fe] = 0.5 and 0.9, respectively. For the typical halo star HD 103095 the same authors give [N/Fe] = −1.0. Our data show for both stars overabundances of barium (Table 3) and strontium (preliminary result) relative to iron of more than 0.2 dex, whereas in the remaining metal-poor stars Ba and Sr are slightly *underabundant*. The most surprising result is presented by their low Eu abundances, with [Eu/Fe] = 0.24 and 0.16 for HD 25329 and HD 74000, respectively. The [Eu/Ba] values (−0.09 and −0.08) are close to solar, and they suggest a dominance of the *s*-process contribution to barium in contrast to other halo and thick disk stars, which show a significant contribution of the *r*-process. Simultaneously, both stars have an overabundance of Mg relative to iron of ∼0.4 dex, typical for the halo and the thick disk. High *N* and *s*-process element abundances could be explained by contamination of the surface layers with products of nucleosynthesis during the AGB phase of an evolved primary component. However, neither our spectra nor any publication suggests that these stars are binaries. Nevertheless, we suppose that *N*-rich stars do not represent *normal* chemical evolution of Galactic matter, and we exclude HD 25329 and HD 74000 from further analysis.

HD 34328 was not studied with respect to its *N* abundance but the [Ba/Fe], [Sr/Fe], [Eu/Fe] and [Mg/Fe] values in this star turn out to be very close to the corresponding values in the two *N*-rich stars. Most probably, similar nucleosynthesis processes are responsible for the chemical peculiarity of *N*-rich stars and also HD 34328, and we exclude the latter from further analysis.

HD 122196 shows low overabundances not only of europium but also of magnesium relative to iron of the order of 0.2 dex. Kinematically ($V_{\rm pec}$ = 224 km s^{-1}), according to metal abundance ([Fe/H] = −1.71) and our age estimate (∼12 Gyr) it is a member of the halo population.

HD 99383 is noted by Nissen et al. (2002) as spectroscopic binary. Our UVES spectrum of this star does not show double lines. However, we have already mentioned slightly larger uncertainties of the surface gravity and Mg abundance compared with the other stars. Thus larger errors of Ba and Eu abundances may be expected.

The important results of our previous studies (Papers I and II) were based on element abundance ratios related to the Eu abundance. In this paper our sample of halo stars with Eu abundances available is extended to 10 stars with [Fe/H] ranging between −0.90 and −1.71 and for the sample of thick disk stars the range of metallicity is extended down to −1.49. Our new data improve the significance of the results obtained in Papers I and II. We summarize them as follows.

- In halo stars europium is overabundant relative to iron with [Eu/Fe] values between 0.40 and 0.67 (HD 122196 is the only exception) and there is a marginal trend of increasing [Eu/Fe] with decreasing metal abundance. The [Ba/Fe] values are mostly between 0.12 and −0.14. The relatively large value [Ba/Fe] = 0.18 found for HD 59392 is accompanied by high Eu abundance with [Eu/Fe] = 0.67 which may reflect a local inhomogeneity of the interstellar matter.
- In thick disk stars europium is overabundant relative to iron with a clear decline of the [Eu/Fe] abundance ratios from about 0.50 at [Fe/H] = −1.5 to 0.25 at [Fe/H] = −0.3. The decline of [Ba/Fe] values with increasing metal abundance noted in Paper II for thick disk stars becomes more evident for our extended sample of stars.
- In the region of overlapping metallicities (from −0.9 to −1.5) both the [Ba/Fe] and [Eu/Fe] values do *not* reveal a distinction between the halo and thick disk stars, in contrast to the thick-to-thin disk transition where a step-like change of the [Eu/Fe] and [Ba/Fe] values occurs.

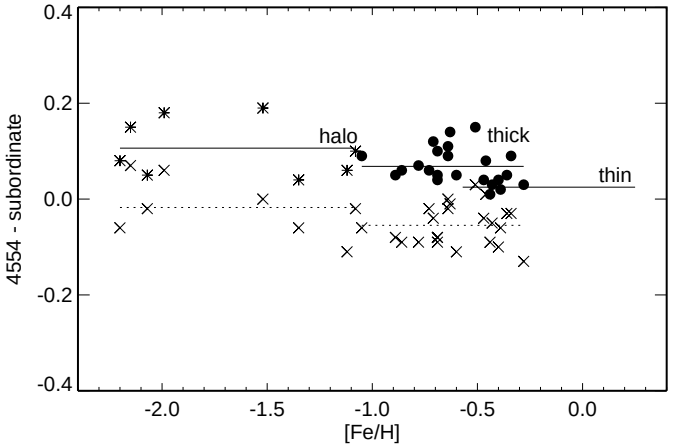

Fig. 3. Comparison of barium abundances derived from the Ba II λ 4554 and subordinate lines. The data obtained with the solar Ba isotope mixture are shown by filled circles (thick disk stars) and by asterisks (halo stars). The solid line for each stellar population indicates the mean value of abundance difference. Dotted lines correspond to similar values obtained with the *r*-process Ba isotope mixture and crosses for the thick disk and halo stars.

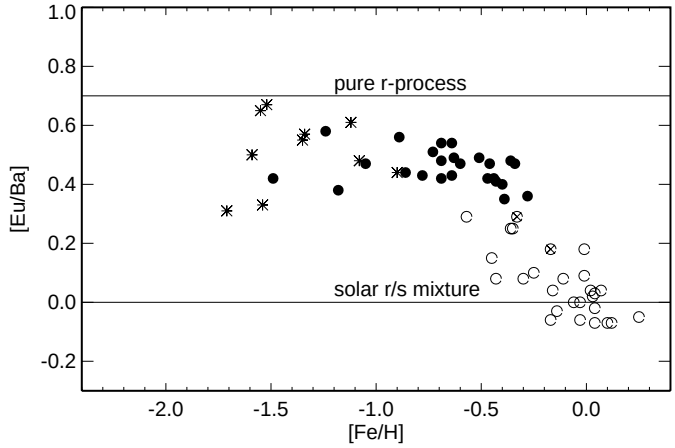

Fig. 4. The run of [Eu/Ba] with [Fe/H]. Compare the values for the thick disk and thin disk stars in the region of overlapping metallicities. Symbols are the same as in Fig. 2.

5. Even-to-odd Ba isotope ratios

Previously (Mashonkina et al. 1999) we suggested a direct method for the evaluation of even-to-odd Ba isotope ratios from the Ba II resonance line λ 4554, provided that the Ba *abundance* can be determined from the Ba II subordinate lines. The resonance line of the odd isotopes has several HFS components and this leads to an additional broadening of the line. HFS components of each odd isotope appear in two groups shifted relative to the resonance line of even isotopes by 18 and −34 mÅ, respectively. Our test calculations for both solar metal abundance and metal-poor stars have shown that the 3-component simplification suggested by Rutten (1978) is sufficiently precise and we accept it in this study. The relative strengths of the components depend on the even-to-odd isotopic ratio. Oscillator strengths of the separate components corresponding to the solar ratio of 82:18 (Cameron 1982) and the *r*-process ratio of 54:46 (Arlandini et al. 1999) are as follows:

even-to-odd	82:18	54:46
$\log gf$ (4554.000) =	−1.011	−0.609
$\log gf$ (4554.034) =	0.077	−0.097
$\log gf$ (4554.052) =	−0.790	−0.389.

The absolute oscillator strength of λ 4554, $\log gf = 0.162$, is taken from Wiese & Martin (1980).

For all stars with both the resonance and subordinate Ba II lines available barium abundances were derived from λ 4554 assuming a solar Ba isotope mixture. For the thin disk stars $\log\varepsilon$ (4554) coincides, on average, with $\log\varepsilon$ (subordinate lines), with the mean value of abundance difference equal to 0.02 ± 0.04 dex. As expected, the even-to-odd Ba isotope ratio in these stars is close to solar. For thick disk and halo stars values of $\log\varepsilon$ (4554) have been obtained assuming the *r*-process Ba isotope mixture, too. In Fig. 3 the differences $\log\varepsilon$ (4554) − $\log\varepsilon$ (subordinate lines) are shown for both cases. At the even-to-odd Ba isotope ratio of 54:46 the resonance and subordinate lines in the halo stars give, on average, the same abundances with the mean abundance difference of −0.02 ± 0.06. This suggests a dominance of the *r*-process contribution to barium. For the thick disk stars this assumption results in underestimating $\log\varepsilon$ (4554) compared with $\log\varepsilon$ (subordinate lines) by −0.05 ± 0.04 dex. For 3 representative thick disk stars, HD 18757 ([Fe/H] = −0.28), HD 3795 ([Fe/H] = −0.64) and HD 22879 ([Fe/H] = −0.86) we have calculated $\log\varepsilon$ (4554) for a number of Ba isotope ratios. Using these results, i.e. $\log\varepsilon$ (4554) − $\log\varepsilon$ (subordinate lines) vs. even-to-odd Ba isotope ratio, we estimate that a fraction of the odd Ba isotopes of ∼35 ± 10% should be adopted to put the abundances from different lines on a common scale. From this value the *s*-process contribution to Ba in thick disk stars is obtained as 30 ± 30%.

6. Discussion

6.1. Abundance ratios [Eu/Ba] and a timescale for the formation of Galactic stellar populations

[Eu/Ba] abundance ratios are shown in Fig. 4. The solar abundance ratio of Eu to Ba contributed by the *r*-process (Arlandini et al. 1999) relative to the total abundances, $[\mathrm{Eu/Ba}]_r = 0.70$, is indicated in Fig. 4 by solid line. The new data confirm in general and improve in statistical sense the conclusions drawn in Paper II; they also provide a fundament for new conclusions.

Europium is significantly overabundant relative to barium in the halo and thick disk stars, and in the region of overlapping metallicities the [Eu/Ba] values do not reveal a clear distinction between these stellar populations. According to the deviation of observed values of [Eu/Ba] from $[\mathrm{Eu/Ba}]_r = 0.70$ we can estimate the *s*-process contribution to barium. For the thick disk stars the [Eu/Ba] values are all between 0.35 and 0.57. This suggests that during the active phase of thick disk formation evolved low mass stars enriched the interstellar gas by *s*-nuclei of Ba with an *s*-process contribution to barium from 30% to 50%. This agrees with the estimate of the s/r-process ratio of 30:70 (±30%) obtained above from our analyses of the even-to-odd Ba isotope ratios in the thick disk stars. According to

the chemical evolution calculations of Travaglio et al. (1999) *s*-nuclei of Ba appear after about 0.5 Gyr from the beginning of the protogalactic collapse; in another ~0.6 Gyr the *s*/*r*-process ratio reaches 30:70, and in further 0.5 Gyr arrives at 50:50. Thus, *the thick disk population formed in the early Galaxy during an interval of ~1.1 Gyr to 1.6 Gyr after the beginning of the protogalactic collapse*.

For the halo stars the spread in the [Eu/Ba] values between 0.31 and 0.67 is rather large. The values close to $[\mathrm{Eu/Ba}]_r = 0.70$ favour the dominance of the *r*-process in heavy element production; under such circumstances the star formation epoch is related to the first 0.5 Gyr after the beginning of the protogalactic collapse. The [Eu/Ba] values of ~0.4 give arguments for a duration of the halo formation of ~1.5 Gyr. Thus, both the oldest stars of the Galaxy and the "late halo" stars are found among the moderate metal-deficient halo stars ([Fe/H] ≥ -1.71). This suggests that the metallicity of halo stars does not correlate with the stellar age.

From analyses of the [Fe/O] and [Mg/Fe] values Gratton et al. (2000) estimate that the formation of stars in *the halo and the thick disk* was fast (a few 10^8 yr), i.e. shorter than the typical timescale of evolution for the progenitors of type Ia SNe. Our data on the [Eu/Ba] values suggest a longer duration of the *halo formation phase* of ~1.5 Gyr and a delay of the thick disk formation of about 1 Gyr. Such discrepancy may be connected with problems of the *r*-process and α-process element abundances in metal-poor stars. We discuss these problems below.

6.2. Europium versus magnesium in halo stars and nucleosynthesis in the early Galaxy

In Fig. 5 [Eu/Fe] values are plotted against [Mg/Fe] values. As expected, the Eu abundance follows the Mg abundance in thin and thick disk stars. An exception is found in two thick disk stars, HD 3795 and HD 102200, that show an overabundance of Eu relative to Mg with [Eu/Mg] = 0.27 and 0.23, respectively. In 8 out of 10 halo stars europium is overabundant relative to magnesium with a mean value [Eu/Mg] = 0.31 ± 0.06. The observed values of [Eu/Mg] are independent of stellar metallicity (between −0.90 and −1.59), effective temperature (from 5110 K to 6130 K), surface gravity (from 3.12 to 4.66) and Mg enhancement (from 0.12 to 0.37). This gives reason to exclude an influence of possible methodical errors of the [Eu/Mg] value, connected with the treatment of NLTE effects or with the use of 1-D model atmospheres. The remaining two stars were discussed above as spectroscopic binary (HD 99383) and a star with low Eu and Mg abundance. They have the [Eu/Mg] values close to 0. Thus, 5 halo stars added in this study confirm the observational finding reported earlier in respect to an overabundance of Eu relative to Mg in the halo. This gives strong evidence for different sites of Eu and Mg production.

The following hypotheses could explain that overabundance.

1. After the epoch of SN II dominance in nucleosynthesis additional production of Galactic magnesium occurred, and it was connected with stars of $M < 8\ M_\odot$. An argument for that can be found from inspection of the variation of the [Eu/Fe] and

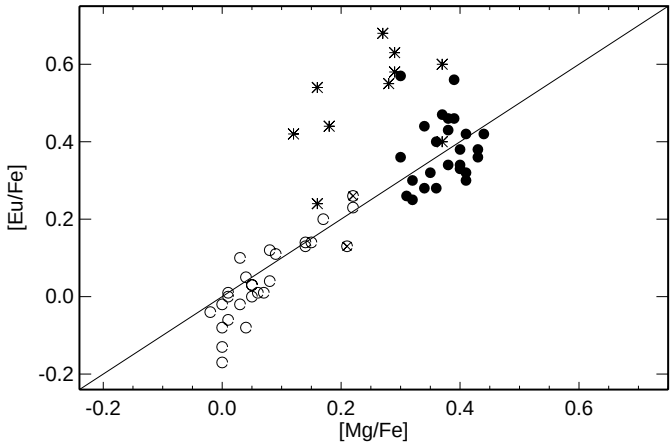

Fig. 5. The run of [Eu/Fe] with [Mg/Fe]. Compare the values for the thick disk and halo stars. Symbols are the same as in Fig. 2.

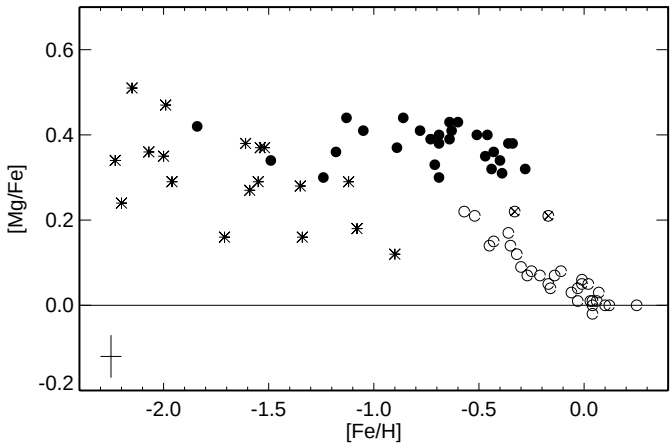

Fig. 6. The run of [Mg/Fe] with [Fe/H]. Compare the spread of data for the thick disk and halo stars. Symbols are the same as in Fig. 2.

[Mg/Fe] values with overall metallicity for the thick disk stars. At [Fe/H] > -1.0 our data show a clear decline of the [Eu/Fe] abundance ratios with increasing metallicity of the order

$$[\mathrm{Eu/Fe}] = 0.22\ (\pm 0.04) - 0.25\ (\pm 0.07)\ [\mathrm{Fe/H}].$$

This supports the notion that during the thick disk formation phase iron starts to be produced in SNe I and its production rate is higher than that for Eu. If SNe II are the main source of Galactic magnesium, a similar decline is expected for the [Mg/Fe] values. In Fig. 6 the run of [Mg/Fe] with [Fe/H] is shown. For our sample of 26 thick disk stars the [Mg/Fe] values taken mostly from the work of Fuhrmann (1998, 2000) are all between 0.30 and 0.44, and only a marginal decline of these ratios with increasing metal abundance can be detected. About 20 thick disk stars of the Gratton et al. sample (2000, their Fig. 4) show [Mg/Fe] values between 0.24 and 0.44, and there is only a hint of a small decline of this ratio with increasing metallicity. Prochaska et al. (2000) suggest a small decline of the [α/Fe] values for their sample of 10 thick disk stars. Thus, the production rate of Mg during the thick disk formation phase seems to be higher compared with that for Eu.

Another way to check the hypothesis of an additional source of Galactic magnesium is to compare Eu abundances

with oxygen abundances because one commonly believes that O is mostly produced in SNe II. However, the data on the [O/Fe] values available in the literature are confusing (see, for example, the data collected by Melendez et al. 2001, their Table 10). Nissen et al. (2002) discuss in detail possible sources of inconsistencies in O abundances determined from the different methods and show that careful analyses of the ultraviolet OH, the forbidden [O I] λ 6300 lines and the O I triplet at 7774 Å using 1-D model atmospheres give consistent O abundances for metal-poor dwarfs and subgiants. For two stars in common, HD 97320 and HD 298986, we use their data on the [O/Fe] values based on the [O I] λ 6300 line and 1-D model atmospheres, [O/Fe] = 0.33 and 0.38, respectively. Differences in adopted model atmosphere parameters are small. $\Delta T_{\rm eff}$ (this work – Nissen et al. 2002) = 130 K and 60 K, $\Delta \log g$ = 0.11 and 0.09, Δ[Fe/H] = 0.03 and 0.01, respectively. We obtain [Eu/O] = 0.07 for HD 97320 and [Eu/O] = 0.16 for HD 298986. When a correction of −0.10 dex (from Table 6 of Nissen et al. 2002) is applied accounting for the influence of granulation on the O abundance, the [Eu/O] values become larger, 0.17 and 0.26. Both the [O I] λ 6300 and Eu II λ 4129 lines originate from the ground state of the dominant ionization stage of the corresponding atoms, and their intensities are essentially insensitive to temperature variations in a 3-D model atmosphere. However, Nissen et al. (2002) point out that the effect of 3-D granulation on the [O I] line comes from differences in the continuous opacities between 3-D and 1-D models. This effect should be much smaller for the Eu II line because it is much stronger compared with the [O I] line.

Oxygen abundances based on the [O I] λ 6300 line are found in the literature also for the halo star HD 103095. Israelian et al. (1998), Balachandran & Carney (1996) and Spite & Spite (1991) give [O/Fe] = 0.37, 0.33 and 0.48, respectively. Using a mean value [O/Fe] = 0.39 we arrive at [Eu/O] = 0.16. Thus, at least, in 2 halo stars europium is overabundant not only relative to magnesium but also relative to oxygen. This does not exclude with certainty the existence of an additional source of Galactic magnesium.

2. Current theoretical models of the *r*-process are valid, but Eu is mostly produced in low-mass SNe II while Mg is synthesized in larger amounts in the higher mass stars. However, mixing of the interstellar matter was insufficient in the early Galaxy up to the epoch with [Fe/H] ~ -1.0. In this case there should be stars with an overabundance of Mg relative to Eu, which were born near exploded high-mass stars, and stars with [Eu/Mg] > 0.0 born near low-mass SNe II. Due to an unknown selection effect we observe stars with high Eu abundance (resulting in [Eu/Mg] > 0.0) and do not observe stars with low Eu abundance.

Out of 6 halo stars with no europium abundance available two stars, HD 84937 ([Fe/H] = −2.07, [Mg/Fe] = 0.36) and BD −4°3208 ([Fe/H] = −2.23, [Mg/Fe] = 0.34), could be candidates for the "high Mg/low Eu abundance" sample. Their Eu II λ 4129 line can not be extracted from noise, and the upper limit of the [Eu/Fe] value is estimated as 0.4 dex. Two stars, BD +66°268 ([Fe/H] = −2.20, [Mg/Fe] = 0.24) and BD +34°2476 ([Fe/H] = −1.96, [Mg/Fe] = 0.29), are more likely "low Mg/high Eu abundance" stars because for both of them the upper limit of the [Eu/Fe] value is higher (0.5 dex) and the [Mg/Fe] value is lower. For the remaining two halo stars spectra of λ 4129 have not been observed. Thus, in total, 10 halo stars of our sample can be related to "low Mg/high Eu abundance" stars and 4 stars to a "high Mg/low Eu abundance" sample.

The large spread of the [Mg/Fe] values in the halo stars seen in Fig. 6 can serve as an argument for this hypothesis. The 16 halo stars of our sample have [Mg/Fe] ratios between 0.12 and 0.51 with no correlation to metallicity. Such a spread can not be caused by errors of Mg abundance determinations because in the region of overlapping metallicities the thick disk stars show a much narrower range of [Mg/Fe] values of 0.30 to 0.44.

We have inspected the recent work of Fulbright (2000), where Eu and Mg abundances are presented for stars in the metallicity range covered in this study. Fulbright does not identify the membership of individual stars in particular stellar populations of the Galaxy, and we have selected from his sample 17 halo stars with $\log g \geq 3.0$, based on their metallicities ([Fe/H] ≤ -0.9). Seven of the stars with relatively low Mg abundance (the [Mg/Fe] value is between 0.06 and 0.29) reveal overabundances of Eu relative to Mg with a mean value [Eu/Mg] = 0.39 ± 0.12 while the remaining 10 stars with [Mg/Fe] between 0.35 and 0.55 have the [Eu/Mg] values from −0.38 to 0.18 with the mean value [Eu/Mg] = −0.06 ± 0.21. Both samples of stars have the same range of metallicity, i.e. from −0.92 to −1.60. Thus, a hypothesis of *insufficient mixing* of the interstellar matter during the halo formation phase seems to be reasonable.

7. Concluding remarks

In the literature moderately metal-deficient halo stars with [Fe/H] from −1.5 to −1.0 are often referred as "late halo" stars and attention is mainly focused on extremely metal-poor stars when problems of the early Galaxy are studied. In this paper we have demonstrated that moderate metal-deficient stars give useful information about nucleosynthesis in the Galaxy (the *s*/*r*-process ratio, different sites of Mg and Eu production), about mixing of the interstellar matter, and about the timescale for the *formation* of the Galactic halo and thick disk.

After the work of Gilmore & Reid (1983) who offered the evidence for the existence of the thick disk stellar population[1] the key question is how it is related to the thin disk and halo in terms of the Galaxy's chemical and dynamical evolution. Clear evidence of chemical distinction of the thick from thin disk was given by Gratton et al. (1996) and Fuhrmann (1998) from analyses of the [O/Fe] and [Mg/Fe] abundance ratios and by our previous studies (Papers I and II) from analyses of the [Eu/Ba] values. A step-like decrease in α/Fe and Eu/Ba ratios at the thick to thin disk transition indicates a phase of nearly ceased star formation before the earliest stars of the thin disk

[1] Marsakov & Suchkov (1977) were probably the first who suggested the existence of the "intermediate halo" stellar population with the kinematics and metallicity corresponding to the stellar population now named "thick disk".

developed. In this paper we have compared chemical properties of the thick disk and halo stars, and it is important that they have, in part, overlapping metallicities. Surprisingly good correlations of various chemical elements found in the thick disk stars ([Mg/Fe] between 0.30 and 0.44; [Eu/Ba] between 0.35 and 0.57 with the hint of a decline with increasing metal abundance; a clear decline of the [Eu/Fe] values with increasing metal abundance) suggest that the thick disk stellar population formed from well mixed gas during a short time interval of ~0.5 Gyr, according to our estimate. We note that strong support to the present conclusion that the thick disk is a homogeneous, chemically old population comes from the results of Nissen & Schuster (1997), Fuhrmann (1998) and Gratton et al. (2000); they found that the thick disk stars have low [Fe/Mg] and [Fe/O] values (equal or even lower than those found for halo stars of similar metal abundance), with very small intrinsic scatter. In opposite, the large spread in element abundance ratios found in halo stars with metal abundances up to [Fe/H] = −0.9 points at insufficient mixing of the interstellar matter during the halo formation phase. Most probably, metal abundance did not correlate with time during the evolution of the Galactic halo. All the thick disk stars investigated here reveal an *s*-process element enrichment with a fraction of the *s*-process contribution to barium from 30% to 50%. We conclude that the thick disk stellar population must have formed on a timescale of between 1.1 and 1.6 Gyr after the beginning of the protogalactic collapse. In this paper we study only a few "metal-weak thick disk" stars. It would be important to extend a sample of such stars. Among the moderately metal-deficient halo stars we see also an enrichment of *s*-process elements. This suggests that the phases of halo and thick disk formation overlapped in time.

Further theoretical and observational work is required to understand the problem of the Eu overabundance relative to Mg in halo stars. It would be important to detect not only Eu/Mg but also Eu/α abundance ratios in halo stars and to extend the sample of stars both in number and metallicity.

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