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Even-to-odd Barium Isotope Ratios in Thick Disk and Halo Stars as a Constraint to r- and s-process Nucleosynthesis

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Abstract. We present the even-to-odd Ba isotope ratios in 16 thick disk and 3 halo stars as determined from hyperfine structure (HFS) seen in the Ba II resonance line λ 4554. We find in our stars a higher fraction of the odd Ba isotopes compared with the solar one 18% (Cameron 1982): 35% in the halo stars and between 25% and 53% in the thick disk stars. There is a hint of increasing this value with the Eu/Fe abundance ratio growth. Based on the r-process even-to-odd Ba isotope ratio 54 : 46 (Arlandini, Käppeler, Wisshak, *et al.* 1999) we deduce the ratio of the s/r-process contribution to barium in the thick disk stars as 30 : 70 ($\pm$24%).

Keywords. Nuclear reactions, nucleosynthesis, abundances, stars: abundances

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The [Eu/Ba] and [Nd/Ba] values found in the thick disk stars suggest that during thick disk formation the r-process dominated production of heavy elements, however, evolved low-mass stars started to enrich the interstellar gas by s-nuclei of Ba, and the s-process contribution to barium varies from 30% to 50% (Mashonkina *et al.* 2000; 2003; 2004).

The s/r-process ratio can be found in an independent way from the analysis of Ba II lines. The larger the r-process contribution is, the larger the fraction of odd Ba isotopes must be. The even-to-odd isotope ratio equals 82 : 18 for the solar system matter (Cameron 1982) and predicts as 54 : 46 for the r-process production of barium (Arlandini, Käppeler, Wisshak, *et al.* 1999). The larger the fraction of odd isotopes is, the stronger the HFS broadening of the Ba II resonance line, λ 4554, is, while HFS effect is neglegible for the Ba II subordinate lines λ6496 and λ5853. The even-to-odd Ba isotope ratio is determined from the requirement that Ba abundances derived from the Ba II subordinate lines and the resonance line must be equal.

Observations and stellar parameters. We selected from Fuhrmann's (2004) list the stars which (i) belong to the thick disk or halo; (ii) were observed with a resolution of $\sim 60\,000$, $S/N > 200$ at least twice; (iii) have both the Ba II λ5853 and λ6496 subordinate lines in their spectra. Spectra of most stars were obtained by Klaus Fuhrmann with the echelle spectrograph FOCES at the 2.2m telescope of the Calar Alto Observatory in 1997–2000. Two stars, HD 84937 and HD 122563, were observed by Gang Zhao, Masahide Takada-Hidai, Wako Aoki and Kunio Noguchi with the Subaru/HDS in 2002 at $R \sim 90\,000$ and $S/N \sim 300$. For most stars stellar parameters (Table 1) and identification of the stellar population are taken from Fuhrmann (2004). For HD 122563 we use the infrared flux method temperature; $\log g$ based on the *Hipparcos* parallax; [Fe/H] from LTE analysis of Fe II lines and $V_{\rm mic}$ from NLTE analysis of Ca I lines.

Even-to-odd Ba isotope ratios. Our results are based on NLTE line formation for Ba II. Atomic data of the Ba II lines are from our previous study (Mashonkina & Gehren

Table 1. Stellar parameters and Ba abundance of the selected sample. The column *odd* contains the fraction (in %) of the odd Ba isotopes. $V_{\rm mic}$ is a microturbulence value

HD	$T_{\rm eff}$	log g	$V_{\rm mic}$	[Fe/H]	[Ba/Fe]	*odd*	HD	$T_{\rm eff}$	log g	$V_{\rm mic}$	[Fe/H]	[Ba/Fe]	*odd*
3795	5370	3.82	1.0	–0.64	0.01	53	10519	5710	4.00	1.1	–0.64	–0.09	43
18757	5710	4.34	1.0	–0.28	–0.14	33	84937	6350	4.03	1.7	–2.07	–0.06	35
22879	5870	4.27	1.2	–0.86	–0.05	33	102158	5760	4.24	1.1	–0.46	–0.15	28
30649	5820	4.28	1.2	–0.47	–0.13	31	103095	5110	4.66	0.8	–1.35	–0.05	35
37124	5610	4.44	0.9	–0.44	–0.14	22	114762	5930	4.11	1.2	–0.71	–0.14	35
62301	5940	4.18	1.2	–0.69	–0.11	35	122563	4570	1.50	1.5	–2.51	–0.98	35
64606	5320	4.54	1.0	–0.89	–0.12	25	132142	5240	4.58	0.7	–0.39	–0.11	35
65583	5320	4.55	0.8	–0.73	–0.08	42	157214	5735	4.24	1.0	–0.34	–0.16	41
68017	5630	4.45	0.9	–0.40	–0.14	33	222794	5620	3.94	1.2	–0.69	–0.13	27
69611	5820	4.18	1.2	–0.60	–0.16	31							

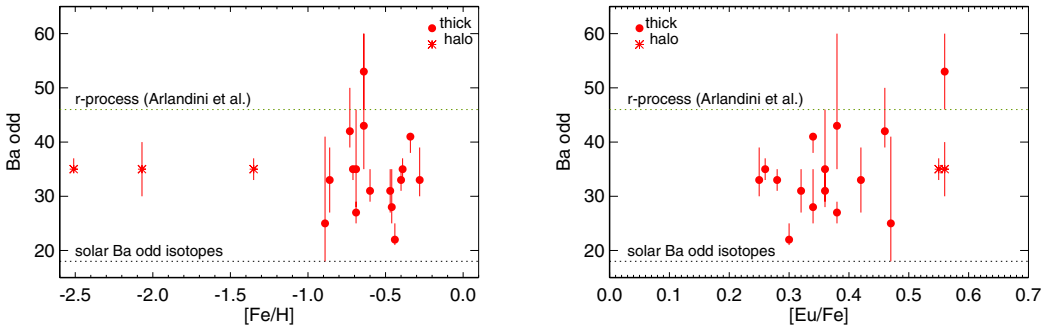

Figure 1. The fraction of the odd Ba isotopes along [Fe/H] and [Eu/Fe]. The uncertainty of individual values is shown by vertical lines. It corresponds to a spread of Ba abundance determined from λ6496 and λ5853. The r-process fraction of the odd Ba isotopes predicted by Arlandini, Käppeler, Wisshak, *et al.* (1999), 46%, is indicated by dotted line.

2000). Ba abundance and the fraction of odd isotopes in the stars of our sample are presented in Table 1 and Figure 1. The three halo stars show the same even-to-odd Ba isotope ratio 65 : 35. No correlation with metallicity can be seen for the thick disk stars and the mean fraction of the odd isotopes equals 34±8%. Based on these data the s/r-process contribution to barium is calculated as 30 : 70 (±24%), in agreement with the results obtained from the [Eu/Ba] and [Nd/Ba] values (Mashonkina *et al.* 2003; 2004). The run of the odd isotope fraction along [Eu/Fe] gives a hint of its decline in the thick disk stars with a decrease of the [Eu/Fe] value. This indicates an increasing contribution of the s-process to Ba synthesis with time.

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