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Lead abundance in the uranium star CS 31082-001*

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Abstract. In a previous paper we were able to measure the abundance of uranium and thorium in the very-metal poor halo giant BPS CS 31082-001, but only obtained an upper limit for the abundance of lead (Pb). We have got from ESO 17 h of additional exposure on this star in order to secure a detection of the minimum amount of lead expected to be present in CS 31082-001, the amount arising from the decay of the original content of Th and U in the star. We report here this successful detection. We find an LTE abundance log (Pb/H) + 12 = −0.55 ± 0.15 dex, one dex below the upper limits given by other authors for the similar stars CS 22892-052 and BD +17° 3248, also enhanced in *r*-process elements. From the observed present abundances of Th and U in the star, the expected amount of Pb produced by the decay of ^{232}Th, and ^{238}U alone, over 12–15 Gyr is −0.73±0.17 dex. The decay of ^{235}U is more difficult to estimate, but is probably slightly below the contribution of ^{238}U, making the contribution of the 3 actinides only slightly below, or even equal to, the measured abundance. The contribution from the decay of ^{234}U has was not included, for lack of published data. In this sense our determination is a lower limit to the contribution of actinides to lead production. We comment this result, and we note that if a NLTE analysis, not yet possible, doubles our observed abundance, the decay of the 3 actinides will still represent 50 per cent of the total lead, a proportion higher than the values considered so far in the literature.

Key words. stars: abundances – physical data and processes: nuclear reactions, nucleosynthesis, abundances – atomic data

1. Introduction

The detection of uranium in an old, very metal-poor star of the galactic halo, BPS CS 31082-001, was first reported in Cayrel et al. (2001). A greatly improved analysis, Hill et al. (2002), (quoted as Paper I) was made possible by a redetermination of crucial atomic data by Nilsson et al. (2002a,b). Hill et al. have determined the abundance of U ($\log(\mathrm{U/H})+12. = -1.92\pm0.11$) and of Th ($\log(\mathrm{Th/H}) + 12 = -0.98 \pm 0.05$), in the usual scale $\log(n_{\mathrm{H}}) = 12.0$, in CS 31082-001. These abundances have been used as cosmo-chronometers, comparing them to theoretical estimates of the initial production ratio. The time Δt in Gyr elapsed from the formation of the two actinides to now, is linked to the production ratio $(\mathrm{U/Th})_0$ and the ratio measured in the star $(\mathrm{U/Th})_{\mathrm{now}}$ by the simple relation: $\Delta t = 21.76[\log((\mathrm{U/Th})_0) - \log((\mathrm{U/Th})_{\mathrm{now}})]$ where the coefficient 21.76 is derived from the half-lives of ^{232}Th and ^{238}U. The superiority of the pair U/Th over the pair Th/Eu has been amply demonstrated, for example in Goriely & Clerbaux (1999), Goriely & Arnould (2001), or Wanajo et al. (2002, see their Fig. 7). As both U and Th decay to the stable element lead, it is of great interest to know the abundance of lead in the star. In Hill et al. (2002), only an upper limit to the lead abundance was given, and we report here the result of a new observation obtained at ESO Paranal to get this abundance. The time requested was 17 h, enough to detect the minimum amount of lead coming from the decay of the observed elements ^{238}U and ^{232}Th into ^{206}Pb, and ^{208}Pb, respectively. In addition, lead may come from other channels, in particular from the decay of ^{235}U into ^{207}Pb, and from more unstable nuclides decaying very quickly to lead, such as ^{234}U.

2. Observations and reduction procedure

The observations were carried out with the ESO VLT using the UVES spectrograph with image slicer #2, leading to a spectral resolution of ≃80 000. A total of 13 exposures were

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* Based on observations obtained with the Very Large Telescope of the European Southern Observatory at Paranal, Chile.

collected in service mode, reaching a total exposure time of 17 h. The signal-to-noise ratio of the combined spectrum is around 600 per pixel. The data were reduced using the standard UVES pipeline (Ballester et al. 2000).

The signal we were looking for is very weak: a depression of only ≃0.5 per cent expected at 4057.807 Å, in the red wing of a weak CH line located at 4057.718 Å. After correcting each spectrum for radial-velocity shifts, several methods for combining the 13 spectra were tested, including (i) a straight average of the best 10 spectra (those with no cosmic hits in that wavelength region); (ii) averaging the spectra after clipping points further away than 2.5σ from the median of the distribution for each pixel; and (iii) averaging the 9 spectra closest to the median of the distribution for each pixel. All methods yielded a very similar result in the Pb region, and we display only one of them (average of the nine spectra closest to the median) in Fig. 1, where the error bars represent the photon noise for each pixel.

3. Spectral synthesis and comparison with observations

We used the same model atmosphere and spectrum synthesis code (*turbospectrum*: Plez et al. 1993; Alvarez & Plez 1998) as in Paper I, achieving complete self-consistency between the model and the spectra computations. Our spectrum synthesis of the Pb 4057 Å region is displayed in Fig. 1, where it is compared to the observations. In addition to the photon noise itself (error bars in the observed points in Fig. 1), various sources of uncertainties on the Pb abundance determination were examined[1]:

(i) Continuum placement: there are two clean continuum windows close to the Pb line, in the 4057.90–4058.0 Å and 4058.4–4058.5 Å intervals, which are used to achieve the best normalization of the observations to the synthetic spectra. None of the two windows are perfectly clean, the first containing a very faint Mn I line at 4057.949 Å which seems slightly underestimated in the synthesis, while the second has a Co I line at 4058.599 Å, slightly overestimated in the synthesis. The two extreme normalizations differ by 0.17%, which leads to a maximum uncertainty on the Pb abundance of 0.15 dex.

(ii) The wavelengths precision of the Pb and the blending CH line at 4057.718 Å also affects the Pb abundance determination, but to a much smaller extent. We have tested that a reasonable maximum shift of 0.005 Å (0.35 km s^{-1}) affects the Pb abundance by at most 0.05 dex.

(iii) The isotopic ratio of ^{206}Pb, ^{207}Pb and ^{208}Pb can impact the Pb line shape, slightly changing its effective central wavelength and hence affecting the abundance determination. Following Van Eck et al. (2003), we considered five Pb components, one for each of the even isotopes 208 and 206 and the three hyperfine components for ^{207}Pb. All wavelengths and oscillator strengths were adopted from Van Eck et al. (2003). However, the two extreme cases of isotope ratios that we have considered (see next section) did not produce any noticeable difference in the spectrum synthesis and hence the derived Pb abundances.

Considering the best fit spectrum displayed in Fig. 1, and the various sources of uncertainty outlined above, the Pb abundance in CS 31082-001 is constrained to be $\log \epsilon(\mathrm{Pb}) = -0.55 \pm 0.15$ dex, 0.35 dex below our upper limit in Paper I.

In the next section we discuss this result with respect to former attempts to measure Pb abundance in other very old stars, and with respect to the amount of lead expected from the decay of the actinides Th and U. We do not attempt to explain our result by theoretical arguments, considering that it is the observational result that justify this letter. A more complete discussion of the impact of this new measurement on nuclear astrophysics will be included in a forthcoming paper also dealing with the analysis of our newly completed HST/STIS observations of CS 31082-001.

4. Discussion

4.1. Comparison with former observations of similar stars

Other *r*-process enhanced stars have been searched for Pb, leading only to upper limits or very uncertain detections, whether using the very weak λ4058 Å line or the intrinsically stronger (but observable only from space) UV line λ2833 Å. We report in Table 1 the log(Pb/Th) ratios for CS 31082-001 and the two other stars with secure upper limits: CS 22892-052 (Th from Sneden et al. 2003, Pb from Hill et al. 2002) and BD +17° 3248 (Cowan et al. 2002). For completeness, we note that Sneden et al. (1998) detected Pb from the UV line in HD 115444, but the line was affected by a spike and the authors themselves regarded the Pb abundance in this star as very uncertain. Th is taken as reference element for the Pb abundance, because of the direct connection between these elements. In the 3 stars, which are as old or older than globular clusters, about half of the initial Th content has decayed into ^{208}Pb, and half has survived. The Pb/Th ratio detected in CS 31082-001 clearly stands out as an *extremely low value* compared to any upper limit so far placed on an *r*-process enriched star.

4.2. Comparison with the amount expected from the decay of ^{232}Th, ^{235}U and ^{238}U

Clear channels of production of lead are the decay of ^{232}Th into ^{208}Pb , of ^{238}U into ^{206}Pb, and of ^{235}U into ^{207}Pb. The amount of ^{208}Pb is fixed by the observation of ^{232}Th now, and the knowledge of the decayed fraction after the matter has been isolated in the atmosphere of the star, at a known rate.

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[1] In addition, we noted a small, but clearly missing absorption component, in the synthesis around 4057.63 Å, bluewards of the CH line in Fig. 1. This feature is too far from the Pb line to affect its abundance, but to check the nature of this unidentified feature, we compared our CS 31082-001 spectrum with the spectra of C-rich stars of similar temperature, gravity, and metallicity, and found that these stars also exhibited absorption missing in the synthesis around 4057.63 Å, with an amplitude clearly linked to the C and N abundances. We therefore conclude that it is a CH or CN molecular line.

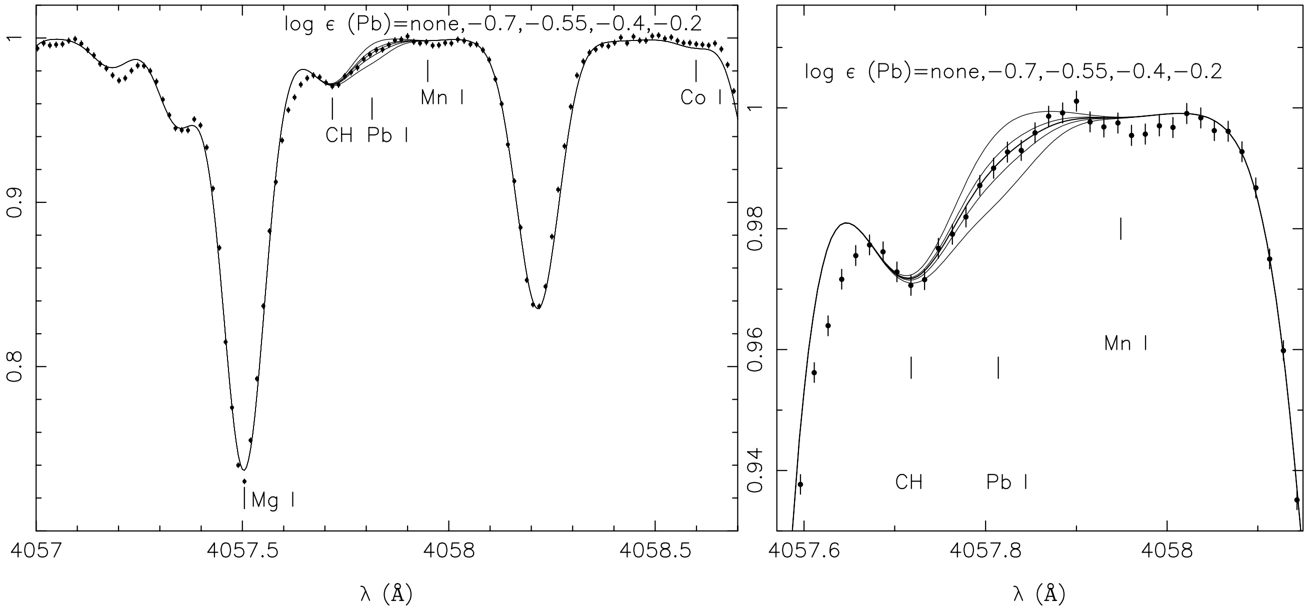

Fig. 1. The observed Pb I 4057.8 Å line in CS 31082-001. *Dots:* observed (combined) spectrum, with the photon noise plotted as error bars; *lines:* synthetic spectra computed for the abundances indicated in the figure. The *left panel* shows the surrounding wavelength region, including the two continuum windows that were used to normalize the observed spectrum, while on the *right panel*, a zoom on the Pb line is presented. The best fit is found for log ϵ(Pb) = −0.55 (thick line).

Table 1. Pb in CS 314082-001 and two other very metal-poor stars.

Star	CS 31082-001	CS 22892-052	BD +17° 3248
[Fe/H]	−2.9	−3.1	−2.0
log Pb/Th	0.43 ± 0.16	≤1.57	≤1.4

The epoch of the nucleosynthesis of the photospheric matter of CS 31082-001, cannot be more than 13.7 ± 0.2 Gyr ago (Big Bang epoch according to WMAP results, Spergel et al. 2003), and should be at least as much as the age of globular clusters (13.2 ± 1.5 Gyr according to Chaboyer 2001), taking into consideration the very low metallicity, [Fe/H] = −2.9 of the star. The median is 13.5, also the age of first stellar formation according to Kogut et al. (2003).

Adopting $t = 13.5 \pm 1.5$ Gyr for the age of the actinides in CS 31082-001, we easily derive both the original content in ^{232}Th and ^{238}U, and the fraction of them transformed into ^{208}Pb and ^{206}Pb. For example:

$$\epsilon(^{206}\mathrm{Pb}) = \epsilon(^{238}\mathrm{U})_{\mathrm{now}} \times (2^{(t/\tau)} - 1)$$

with $\tau = 4.47$ Gyr, the half-life of ^{238}U. A similar formula holds for ^{232}Th and ^{208}Pb with $\tau = 14.05$.

But ^{235}U cannot be treated the same way, as there is not enough ^{235}U left to have an observed value. We must then rely on theoretical works, usually done for reproducing the solar system isotopic abundances, but not necessarily adequate for CS 31082-001 which has a clear overabundance of the actinides with respect to the lighter *r*-elements, compared to the solar system. However we can hope that in the restricted mass range under consideration , ^{232}Th to ^{238}U, neutron exposures producing the right ratio ^{238}U/^{232}Th may also produce the right ratio ^{235}U/^{238}U. In Tables 1 and 2 of Goriely & Arnould (2001), several neutron exposures are considered with a wide set of mass models. Forgetting the solar system, we keep the exposures giving the right ^{238}U/^{232}Th production ratio for CS 31082-001, compatible with an age 13.5 ± 1.5 Gyr. With this constraint, the production ratio R of ^{235}U/^{238}U lies between 0.67 and 0.87. Taking the median 0.77 seems a reasonable estimate. The full amount of produced ^{235}U is converted into ^{207}Pb in CS31082-001, because of the fast decay of this isotope. Table 2 summarizes our findings. Interestingly, the case $R = 1.0$ gives an amount of total lead equal to the observed one, leaving no other channel for the production of *r*-lead. We have not included the ^{234}U decay to ^{206}Pb channel here, because of the lack of published estimates of the ^{234}U/^{238}U production ratio. This channel (which could be as high as the ^{235}U contribution) can only increase the contribution of the actinide-path to the total production of Pb, thereby reducing even further any other production channel.

A warning is appropriate here: our analysis is based on the LTE approximation, which must be questioned, especially in the blue and the UV in very metal-poor giants, where the continuum is in a large part due to Rayleigh scattering. We examine this in the next subsection.

4.3. NLTE versus LTE

It would be very useful to have a NLT analysis of Pb, as the lower level of the measured line is very deep, part of the ground-level term, and is of Pb I when most of lead is in the Pb II stage. In metal-poor stars these deep levels tend to be over-ionized, but not always. If the deep levels are indeed over-ionized, the LTE assumption predicts too large a population of the lower level, and an underestimated abundance. In an attempt to estimate the size of possible NLTE effects, we

Table 2. Three abundance patterns examined for the lead feature. The abundances of ^{207}Pb are computed for 3 assumed values of the production ratio $R =^{235}$ U/^{238}U, the first considered as the most probable, and the other two chosen 30 per cent below and above. All abundances are with respect to 10^{12} hydrogen atoms.

$^{238}\mathrm{U}_{\mathrm{now}}$	0.0120 ± 0.0035		
^{206}Pb	0.086 ± 0.036		
$^{232}\mathrm{Th}_{\mathrm{now}}$	0.105 ± .013		
^{208}Pb	0.099 ± 0.035		
R	0.77	0.59	1.00
^{207}Pb	0.075 ± .03	0.058 ± .02	0.098 ± .04
Tot. Pb	0.26 ± 0.10	0.243 ± 0.09	0.283 ± .11
log(ϵ(Pb))	−0.59 ± .2	−0.61 ± .2	−0.55 ± .2

checked the J_ν/B_ν ratio at the position of the Pb I line, as well as at 4076 Å and 2035 Å, corresponding to the ionization limit of the upper and lower levels of the transition, respectively. In these layers, the ratio J_ν/B_ν of the mean intensity to the local Planck function is larger than one, but remains on the order of two. It is unlikely that the NLTE correction is larger than this factor of two, so the production of Pb, outside the decay of ^{232}Th, ^{235}U, and ^{238}U is bound to be less or equal to the actinide production.

4.4. Digression about the rapid neutron capture lead in the solar system

Our result clearly concerns a particular class of objects: very metal-poor stars born in the early days of the Galaxy, and strongly enhanced in *r*-process elements. Is the observed low ratio Pb/Th particular to this class of objects, or is it a more general property of the *r*-process in the mass range 206–238? There is now a general agreement that the fraction of Pb produced by the *r*-process in the solar system it practically unknown, after the discovery that zero-metal stars can produce a lot of *s*-lead (Goriely & Siess 2001; Van Eck et al. 2003). This has modified the estimates of the amount of *s*-lead produced in the Galaxy before the birth of the Sun (Gallino et al 1998), and of the *r*-lead, obtained by subtracting the *s*-lead from the total lead. If the *r*-lead of the solar system were mainly produced by the decay of the actinides, as for CS 31082-001, it is easy to verify that the *r*-lead in the solar system would be of the order of only 1 to 3% of the total lead.

5. Conclusions

In one of the very metal-poor stars showing a large enhancement of *r*-process elements we have now a true determination of the lead abundance, instead of upper limits, only. This abundance is very low, −0.55 ± 0.15 dex in CS 31082-001, about one dex below the former upper limits in CS 22892-052 and BD +17° 3248. Also, our result shows that, in the purely *r*-process enriched photosphere of CS 31082-001, most of lead results from the decay of ^{232}Th , ^{235}U, and ^{238}U. This places a limit on the amount of ^{235}U which has contributed to the production of ^{207}Pb, as well as on that of ^{234}U. A non-LTE analysis of the spectrum is highly desirable, but hampered so far by the lack of photoionization cross-sections for Pb I.

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