THE ISOTOPE RATIO OF EUROPIUM IN THE SOLAR ATMOSPHERE

ÖIVIND HAUGE
Institute of Theoretical Astrophysics, University of Oslo, Norway

(Received 10 September, 1969)

Abstract. Europium has two stable isotopes, Eu 151 and Eu 153. The high isotope shift and the different hyperfine splitting of the energy levels of the two isotopes make it possible to study the isotope ratio by an analysis of the spectral line profiles. From five spectral lines the solar isotope ratio is found to be equal to the terrestrial ratio within an error limit of about 10 %.

1. Introduction

Europium is a 4f rare earth element with atomic number 63. The solar abundance of europium has been determined by Russell (1929), Righini and Rigutti (1966), Wallerstein (1966) and Grevesse and Blanquet (1969) and the values of $\log N(\mathrm{Eu})$ obtained are 1.9, 0.97, 0.96 and 0.49 ± 0.14 respectively on the $\log N(\mathrm{H}) = 12.00$ scale. Although the main purpose of the present investigation is to determine the isotope ratio, the calculations verify the low abundance given by Grevesse and Blanquet (1969) within the limits of error given.

Europium has two stable isotopes, Eu 151 and Eu 153 and the terrestrial isotope abundance ratio is $\log N(\mathrm{Eu}\ 153)/N(\mathrm{Eu}\ 151) = 0.03$. For a better understanding of the origin of the elements and of the processes active in building up the heavy elements a better knowledge of isotope abundances is of considerable interest. Eu 151 has a very large thermal neutron capture cross-section and can serve as an indicator of thermal neutron fluxes.

Both stable isotopes of europium can be created by neutron captures at low rates (the s-process). Eu 151 can be formed from Sm 150 after a neutron capture followed by a β-decay. Eu 153 can in the same way be formed from Sm 152 which again is formed from Eu 151 by a neutron capture followed by a β^+-decay or an electron capture.

The europium isotope ratio in meteorites has been investigated by Murthy and Schmitt (1963). They found the isotope composition in two chondrites, one achondrite and one carbonaceus chondrite to be identical with that of terrestrial material to within the experimental error of less than 1%.

Large neutron capture cross-section for Eu 151 exists only for neutron energies smaller than the thermal energy in the solar atmosphere. Any depletion of Eu 151 will most likely occur in bodies where the thermal energies of the neutrons are within the range of high neutron capture cross-section. On the earth, neutrons are produced by secondary emission from cosmic rays and by radioactive processes in the interior. Neutron production may also occur in planetesimals containing H_2O and oxides Mg,

Solar Physics **11** (1970) 17–21; © *D. Reidel Publishing Company, Dordrecht-Holland*

Si and Fe bombarded with charged particles, mainly protons (Fowler *et al.*, 1962). Marti *et al.* (1966) have shown that neutrons with approximately 100 eV energy are responsible for the isotope effects in krypton and xenon in chondrites.

The presence of lines from Eu I in the photospheric spectrum is doubtful (Grevesse and Blanquet, 1969) therefore the present investigation is limited to Eu II lines and is based on an analysis of the isotope shift and hyperfine structure given by Krebs and Winkler (1960). The high isotope shift together with the different hyperfine splitting of the energy levels of the two isotopes make it possible to investigate the isotope ratio by an analysis of the observed spectral line profiles. The fact that europium has only two stable isotopes which are of nearly equal terrestrial abundances also make this element favourable for such an investigation.

2. Observations and Results

High dispersion spectra of the eight wavelength regions investigated by Krebs and Winkler (1960) have been obtained at Oslo Solar Observatory. The spectra, taken in different orders and recorded on Kodak 103a-O emulsion, have linear dispersions between 7.5 and 13 mm/Å. Three spectral lines must be omitted owing to serious blends, the remaining five lines given in Table I are also more or less blended, but could be used in the present investigation.

TABLE I

Eu II transitions used for the determination of the isotope abundance ratio

Multiplet no.	Transition	Wavelength in Å
1	$[a6s)_4 - [a6p_{1/2}]_3$	4205.05
2	$[a6s]_4 - [a6p_{3/2}]_4$	3724.94
4	$[a6s]_3 - [a6p_{1/2}]_4$	4435.56
5	$[a6s]_3 - [a6p_{3/2}]_4$	3971.96
5	$[a6s]_3 - [a6p_{3/2}]_3$	3930.48

Each isotope has spectral lines consisting of six main hyperfine components. These main components have nearby satellite lines of considerably lower intensity. This complex hyperfine structure has also been investigated by Guthöhrlein (1968). Here we have added the intensities of the satellite components to the nearby main component. Thus in the present investigation the spectral line profile of each isotope is a superposition of six hyperfine components. The error introduced by this procedure is small and of no consequence in this context.

Expected spectral line profiles for different isotope abundance ratios are calculated with a computer program prepared by O. Engvold and O. Kjeldseth Moe. The Bilderberg Atmospheric Model (Gingerich and De Jager, 1968) were transformed to the actual wavelength regions by means of Bode's (1965) tables. The partition functions for europium are given by Corliss and Bozman (1962) and recently verified by Grevesse and Blanquet (1969). Examples of calculated profiles are shown in Figure 1.

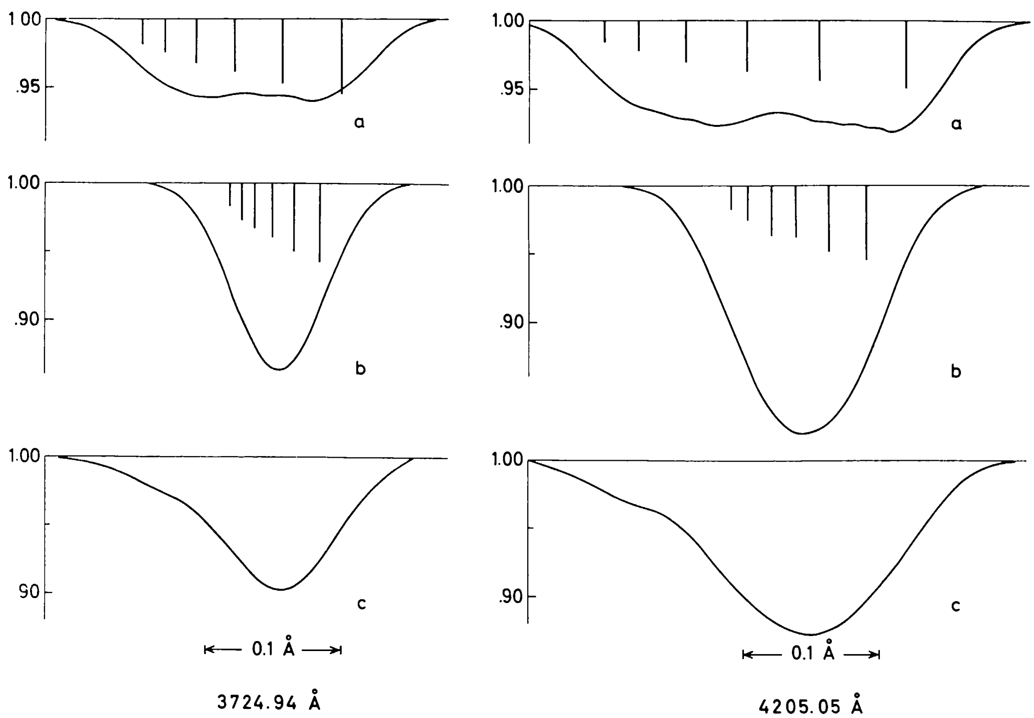

Fig. 1. The photospheric profiles of the Eu II lines at 3725 Å and 4205 Å computed in the following three cases of isotope composition: (a) pure Eu 151, (b) pure 153, and (c) the terrestrial isotope ratio. The intensity and position of the hyperfine components are indicated by vertical lines.

Accurate knowledge of the centre wavelengths of the spectral lines are of great importance, the wavelengths used are taken from Wybourne (1965).

The results of the present investigation are given in Table II. The estimated uncertainties listed are derived from the accuracy of the observed line profile and the sensitivity of the theoretical profile to changes in the abundance ratio.

TABLE II

The isotope ratio of europium in the solar atmosphere deduced from observed spectral line profiles

Wavelength in Å	$\log N(\text{Eu } 153)/N(\text{Eu } 151)$	Estimated uncertainty
3724.94	0.00	0.06
3930.48	0.18	0.20
3971.96	0.03	0.08
4205.05	0.02	0.09
4435.56	−0.09	0.20

A few comments are given in the following on each spectral line:

3724.94 Å. Although the line is blended on the violet side by a Ni I line, the characteristic profile is easy to recognize and the profile is rather sensitive to isotope abundance variations.

3930.48 Å. This line is situated in the violet wing of the Fraunhofer K line and in the red wing of a strong Fe I line. The Eu 151 spectral line component has nearly constant intensity within a wavelength interval of 0.15 Å and is difficult to distinguish from the local continuum level.

3971.96 Å. This line is in the red wing of the Fraunhofer H line between an Fe I line and an Ni I line. The central part of the Eu II line is very suitable for investigations and the uncertainty given in Table II is mainly due to the difficulty in fixing the continuum level.

4205.05 Å. The central part of this line is strongly blended. As shown in Figure 1, the profile may be reproduced by a superposition of two lines, a main line with a weaker line on the violet side. The weaker line is easily seen in the solar spectrum and is listed as unidentified by Moore *et al.* (1966) at the wavelength 4204.895 Å. The isotope ratio is determined by a comparison with another Eu II line from multiplet no. 1 at 3819 Å with an equivalent width recently given by Grevesse and Blanquet (1969). The equivalent width of the line at 4205.05 Å is calculated using Corliss and Bozman's (1962) $\log gf$ values. Only the relative values are then needed. The weak component is measured in the observed spectrum, while the total line is calculated. The weak line is mainly due to Eu 151 while the main component is a superposition of absorption from both isotopes. The estimated uncertainty given in Table II is derived on the assumption that the relative gf values of Corliss and Bozman (1962) for the two Eu II lines are correct.

Theoretical relative gf values for the two Eu II lines are also given by Wybourne (1965). Using these values in the same way as described above, the resulting isotope abundance ratio becomes, $\log N(\text{Eu } 153)/N(\text{Eu } 151) = -0.21 + 0.09$. When comparing other data given by Wybourne with observed spectra and computed profiles, the theoretical gf values seem to be less reliable than the values experimentally determined by Corliss and Bozman (1962).

4435.56 Å. The Eu II line is situated in the violet wing of a Ca I line. The calculated profile of this line shows also a double structure with a considerably higher component splitting than the 4205 Å line mentioned above. Both components are visible in the observed spectrum. The smaller component is mainly due to Eu 151 and is listed as an unidentified line at 4435.441 Å by Moore *et al.* (1966). Since the isotope ratio given in Table II is so low, the weaker line component may also be blended by another faint line. The estimated uncertainty is based on the assumption that the weak line is entirely due to Eu II.

3. Conclusion

From the values listed in Table II and the comments given above it is reasonable to conclude that the solar isotope ratio of europium is equal to the terrestrial ratio within an error limit of about 10%.

From the present result on the solar europium isotope abundance ratio and the isotope ratios in terrestrial material and meteorites referred to above, it is possible to set an upper limit to the thermal neutron flux during the history of the planetary system. A rather rough estimate to this upper limit would be 10^3–10^4 n/cm^{2}sec which is many orders of magnitude higher than the natural background neutron flux at the earth's surface.

Acknowledgements

The author is indebted to Dr. A. Storruste for discussions and to Dr. E. Jensen for reading the manuscript.

This research has been sponsored in part by the Norwegian Research Council for Science and the Humanities and by the Air Force Cambridge Research Laboratories through the European Office of Aerospace Research OAR, U.S. Air Force under Contract F61052 67 C 0070.

References

Bode, G.: 1965, *Die kontinuierliche Absorption von Sternatmosphären in Abhängigkeit von Druck, Temperatur und Elementhäufigkeiten*, Kiel.
Corliss, C. H. and Bozman, W. R.: 1962, *NBS Monograph No. 53.*
Fowler, W. A., Greenstein, J. L. and Hoyle, F.: 1962, *Geophys. J. Roy. Astron. Soc.* **6**, 148.
Gingerich, O. and De Jager, C.: 1968, *Solar Phys.* **3**, 5.
Grevesse, N. and Blanquet, G.: 1969, *Solar Phys.* **8**, 5.
Guthöhrlein, G.: 1968, *Z. Phys.* **214**, 332.
Krebs, K. and Winkler, R.: 1960, *Z. Phys.* **160**, 320.
Marti, K., Eberhardt, P. and Geiss, J.: 1966, *Z. Naturforsch.* **21a**, 398.
Moore, C. E., Minnaert, M. G. J. and Houtgast, J.: 1966, *NBS Monograph No. 61.*
Murthy, V. R. and Schmitt, R. A.: 1963, *J. Geophys. Res.* **68**, 911.
Righini, A. and Rigutti, M.: 1966, *Ann. Astrophys.* **28**, 379.
Russell, H. N.: 1929, *Astrophys. J.* **70**, 11.
Wallerstein, G.: 1966, *Icarus* **5**, 75.
Wybourne, B. G.: 1965, *Spectroscopic Properties of Rare Earths*, John Wiley & Sons, Inc., New York.