Proc. of Kofu Symposium, NRO Report No. 360, July, 1994

IONIZATION STATES OF SOLAR-FLARE PARTICLES

K. Sakurai

Institute of Physics, Kanagawa University, Rokkakubashi, Yokohama 221, Japan

Abstract

It is thought that observed properties for the chemical composition of solar-flare particles give some clue to understand the mechanism for these particles to be accelerated in the flare regions and the outer corona of the sun. In this paper, the most probable ionization states of these particles are estimated for them in these regions before acceleration. Then, it is shown that their ionization states play the key role to form the chemical composition of solar-flare particles which shows the enhancement of heavy nuclei up to the iron group ones.

1. Introduction

It has been known (e.g., Gloeckler and Geiss, 1988) that the most elements consisting of solar-flare particles are partially ionized and that their chemical composition is dependent on the ionization states of these elements, which may reflect upon the nature of their acceleration sites. According to the observed results on this chemical composition as currently available, heavy elements up to the iron group ones are relatively enhanced as compared with that of the solar atmosphere and their enhancement tends to increase with their atomic numbers up to the element Ar. Beyond this element, such elements as Fe, Ni and Co, being heavier than Ar, are enhanced in the same order of magnitude as compared with those found in the chemical composition of the solar atmosphere.

The observed results as described above have been known for many years, but it does not seem that they have ever been interpreted successfully despite that the theories of the particle acceleration in solar flares have been extensively developed up to the present (e.g., Sakai and Osawa,1987; Melrose, 1992). In the year 1975, a possible effect of the ionization states of particles on the acceleration processes taking place in the flare regions was proposed for the first time in order to explain the observed overabundances of heavy nuclei in solar-flare particles (Sakurai,1975).

Referring to the new observational data on the chemical composition of solar-flare particles, in this paper, a possible mechanism will be considered for the acceleration of nuclear particles in association with solar flares. The ionization states of particles in the pre-flare

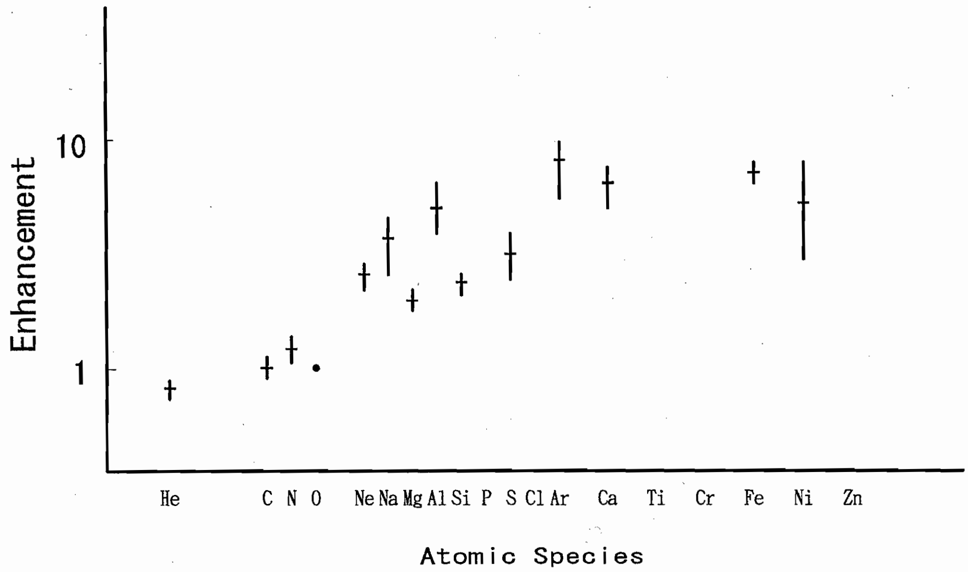

Fig. 1. The enhancement of the elements as observed in the chemical composition of solar-flare particles as compared with that of the solar atmosphere(Reames, 1993).

condition will be pointed out to be important on the basis of the acceleration mechanism whose efficiency depends on the effective charge to mass ratios of the elements under consideration.

2. The Chemical Composition of Solar-Flare Particles

The observed results as recently obtained are summarized by Reames and others (e.g., Reames, 1993; Garrard and Stone, 1993; Selesnick et al., 1993). The one of these results is shown in Fig.1 (Reames, 1993). The chemical composition of solar-flare particles is indicated here for each nuclear species as compared with that of the solar atmosphere. In doing so, both of these compositions are normalized of the element Oxygen. As is clearly seen in this figure, in comparison with those of the solar atmosphere, the elemental abundances of solar-flare particles have a tendency to become enhanced up to the element Ar with respect to the mass of the elements. The enhancement of the elements heavier than Ar remains almost constant as the excess of these elements as compared with the chemical composition of the solar atmosphere.

The result shown in Fig.1 is, of course, well coincident with many others obtained earlier. It follows, therefore, that the overabundances of heavy nuclei in the chemical composition of solar-flare particles as compared with that of the solar atmosphere necessarily reflect upon some physical processes which take place in the acceleration regions as developed in association with solar atmosphere. Such physical processes seem to be related to either the acceleration mechanism of particles in solar flares or the propagation mechanism in the solar corona after their acceleration. It is further noted that both of these mechanism may be highly related to the ionization states of particles in or near the flare sites before their acceleration.

3. Theoretical Interpretation to the Observed Results

In order to estimate the degrees of the ionization states for various elements in or near the solar flare sites before acceleration, it is necessary to infer how high the temperature is in these sites or their neighboring region. According to Reames (1993), this temperature is 3.2 million degrees in Kelvin, for example. Using his estimation, the main ionization states

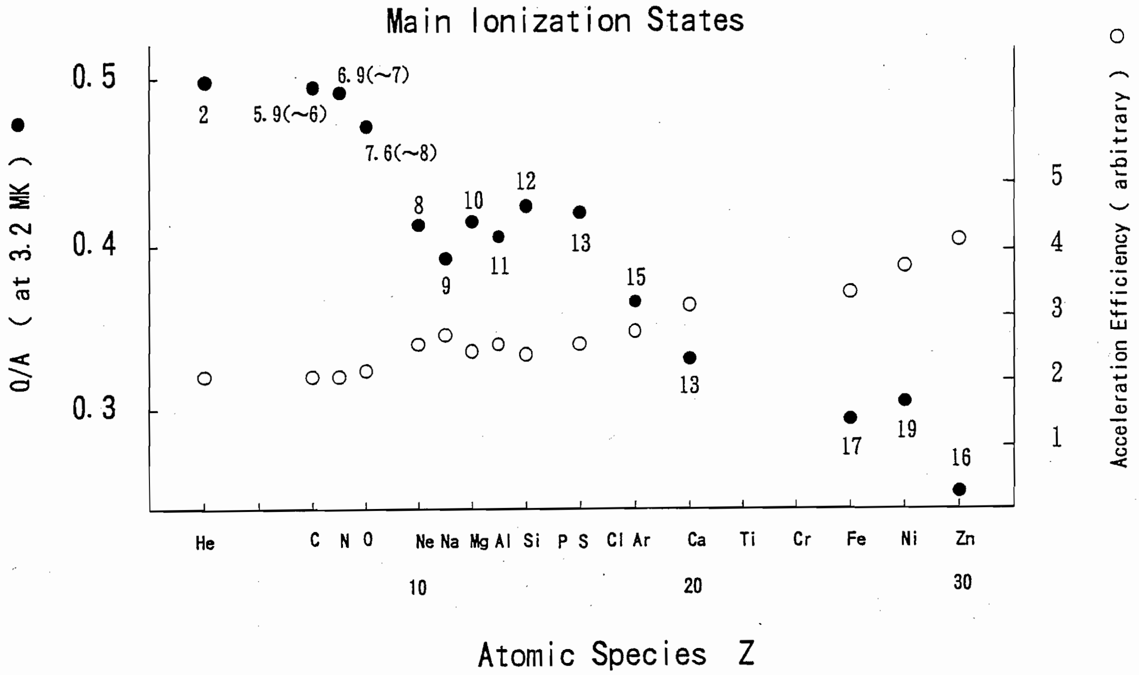

Fig. 2. The effective charge to mass ratios of the elements, being indicated by black circles, and their acceleration efficiency, being given by white circles. The numbers attached to black circles indicate the main ionization states of these elements.

have been calculated for various elements which mainly consist of solar-flare particles and are shown in Fig. 2 with digit numbers except for three elements, C, N and O. It is clear from this figure that, for the temperature cited above, the most elements up to Zn are partially ionized except for the elements, He and C. These results necessarily lead to the result that the effective charge to mass ratios (Q/A) for the elements tend to decrease with the increase of atomic numbers as indicated with black circles in the figure. Here, the quantities, Q and A, are respectively the effective charge and the mass numbers for the elements to be accelerated.

The general theory of particle acceleration has been extensively developed earlier by Hayakawa et al. (1964) and Sakurai (1974a,b). Here this theory has been applied to estimate the acceleration efficiency to those elements partially ionized as discussed earlier in this paper. According to this theory, this efficiency tends to become proportional to the ratios of the mass to the effective charge numbers for the elements before acceleration. This tendency is shown in Fig. 2 with white circles. As indicated more clearly in Fig. 3, the efficiency of particle acceleration thus becomes higher as the atomic numbers of the elements does larger. This figure is highly suggestive to reach an idea that the ionization states of the elements in their acceleration regions plays a crucial role to produce the observed results on the relative enhancement of the elements as shown in Fig.1 for the chemical composition of solar-flare particles as compared with that of the solar atmosphere. As seen in Fig. 3, for the elements up to Ar, the acceleration rate for the elements, being partially ionized, tend to increase exponentially as a function of their atomic numbers. Although the acceleration efficiency increases with the atomic numbers of the elements heavier than the element Ar, the enhancement for them remains almost constant as shown in Fig. 3, because their ratios, being given by A/Q, are almost equal among them. Since this result cannot be explained only by referring to the acceleration efficiency of particles as given in Fig. 2, it is urgently needed to search for some mechanism capable of interpreting the enhancement of these heavy elements.

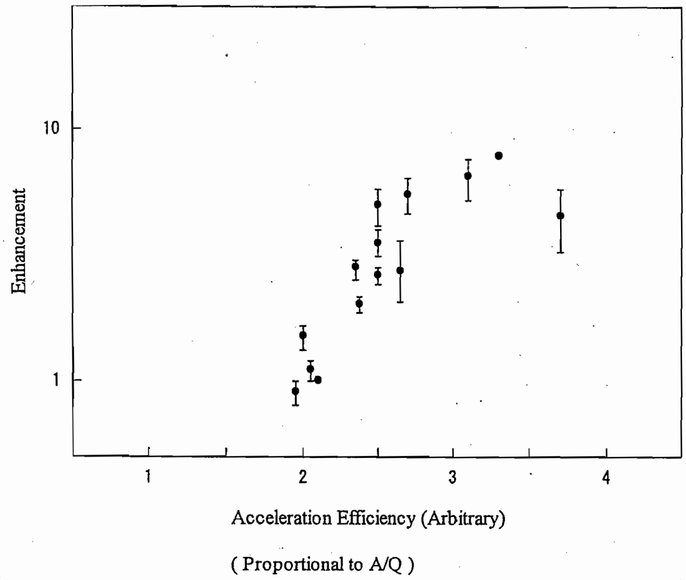

Fig. 3. Relation between the enhancement and the acceleration efficiency of the elements.

4. Concluding Remarks

It has been shown that the ionization states of the elements plays a crucial role in producing their relative enhancement as observed in the chemical composition of solar-flare particles as compared with that of the solar atmosphere. This means that these states essentially determine the acceleration efficiency of the nuclear particles in association with solar flares, since this efficiency is dependent on the ratios of the effective charge to mass numbers of these particles. As shown in Fig. 3, this efficiency tends to increase exponentially as a function of these ratios for the elements up to Ar with respect to their atomic numbers. It is, therefore, noted that the temperature ambient in the acceleration sites of solar-flare particles is substantially important in producing the observed chemical composition of solar-flare particles as clearly seen in Fig.1.

References

1. Garrard, T. L. and Stone, E. C., Proc. 23rd Int. *Cosmic Ray Conf., Calgary,* Vol. 3, SH, 384(1993)
2. Gloeckler, G. and Geiss, J., AIP Conf. Proc. 183, *Cosmic Abundances of Matter* (ed. C.J. Waddington), AIP, p.49(1988).
3. Hayakawa, S., Nisimura, J., Obayashi, H. and Sato, H., *Prog, Theor. Phys. Suppl.* No. 30, p.86(1964)
4. Melrose, D. B., *AIP Conf. Proc. 264, Particle Acceleration in Cosmic Plasmas* (eds. G. P. Zank and T.K.Gaisser), AIP, p.3(1992)
5. Reames, D. V., *Proc. 23rd Int. Cosmic Ray Conf., Calgary,* Vol. 3, SH, 388(1993).
6. Sakai, J. I. and Osawa, Y., *Space Sci. Rev.* **46**, 133(1987).
7. Sakurai, K., *Physics of Solar Cosmic Rays,* Univ. of Tokyo Press(1974a)
8. Sakurai, K., *Astrophys. Space Sci.,* **28**, 375(1974b).
9. Sakurai, K., *Proc. 14th Int. Cosmic Ray Conf.,* Munich 5, 1552(1975).
10. Selesnick, R. S., Cummings, A. C., Cummings, J. R., Leske, R. A., Mewaldt, R. A., Stone, E.C. and von Rosenvinge, T. T., *Proc. 23rd Int. Cosmic Ray Conf., Calgary,* Vol. 3, SH, 392(1993).