# Mössbauer study of shock-induced effects in the ordered alloy $Fe_{50}Ni_{50}$ in meteorites

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**Abstract.** By adopting the flying-plate technique we have used Mössbauer spectroscopy to investigate shock-induced effects in the ordered iron–nickel alloy in meteorites. The degree of long-range order in the ordered alloy is reduced by the shock event.

## 1. Introduction

We have investigated the effects of shock on the ordered Fe–Ni phase with superstructure L1o, in the nickel-rich iron meteorite Santa Catharina and in the metal particles of the LL-chondrite Saint-Séverin. The ordered $Fe_{50}Ni_{50}$ phase with L1o superstructure (see figure 1) can be identified by Mössbauer spectroscopy, due to its characteristic asymmetric spectrum. This asymmetry results from a quadrupole splitting arising from the non-cubic environment of the Fe atoms in this Fe–Ni alloy (Danon *et al* 1978).

Shock effects have an important role in the history of meteorites. It is estimated that 65% of iron meteorites have been submitted to shock pressures above 130 kbar in pre-terrestrial impacts (Jain and Lipschutz 1971). Recent studies suggest that most petrological aspects of meteorites originated in shock events. Investigations of pre-terrestrial impacts in iron meteorites are more common than in chondrites. The heterogeneity and complex mineralogy of chondrites make it difficult to interpret their shock history.

The structures of iron–nickel alloys submitted to shock pressures have been studied by x-ray diffraction and electron microscopic analyses (Donukis *et al* 1971). The results obtained with Fe–30% Ni and Fe–32% Ni showed almost complete alpha–gamma transformation. The new gamma phase exhibits particular mechanical and structural properties.

The changes introduced by shock effects in the ordered state of the Fe–Ni ordered alloy have not yet been studied. Interesting results have been reported with $Cu_3Au$, showing that the degree of long-range order in the ordered $Cu_3Au$ alloy, as revealed by resistivity and stored energy, is reduced only moderately at shock pressures up to 290 kbar (Beardmore *et al* 1964). High shock pressures cause appreciable destruction of long-range order.

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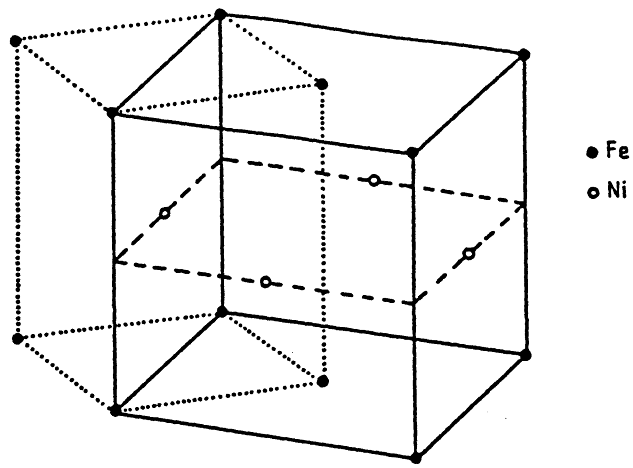


**Figure 1.** The unit cell of the superstructure FeNi (L1o). Cubic face-centred lattice (full lines, disordered alloy) and tetragonal body-centred lattice (dotted lines, ordered alloy).

## 2. Experiment

Using the flying-plate technique (Meyers 1974), we have investigated the effect of shock waves on the disordering processes of the Fe–Ni ordered phase in meteorites by Mössbauer spectroscopy, optical observations, scanning electron microscopy, microprobe and x-ray analyses.

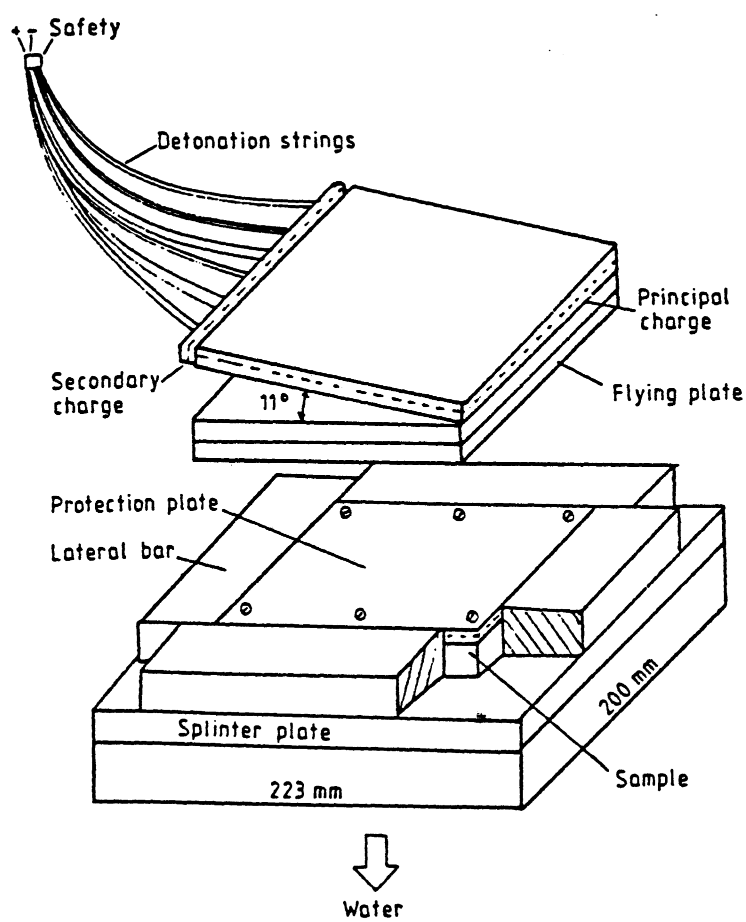


**Figure 2.** Flying-plate system.

To submit meteorite samples to a shock process, we used a special stainless steel system on which a flying plate submitted to an explosive charge permits the sample to be exposed to shock waves of hundreds of kbar (figure 2). In this technique the sample is cooled in water immediately after the shock in order to minimise simultaneous thermal effects.

The Mössbauer absorbers have been made with: (*a*) thin slices of the Santa Catharina meteorite, measured before and after exposure to shock pressures of 100 and 200 kbar, (*b*) a sample of the LL-chondrite Saint-Séverin submitted to shock pressures up to 530 kbar. The iron–nickel phases of the sample pulverised by shock have been studied using the magnetically separated fraction, which was purified from troilite (FeS) and the silicates with concentrated HF.

## 3. Results and discussion

The ordered $Fe_{50}Ni_{50}$ phase (superstructure L1o) is present as a major constituent of the nickel-rich ataxite Santa Catharina. We have investigated the effect of shock pressures up to 200 kbar on the order–disorder state of this meteorite.

The Mössbauer spectra before and after shock are shown in figure 3. The spectra were recorded at room temperature. The hyperfine parameters of the different Fe–Ni alloy phases obtained by Mössbauer spectroscopy are listed in table 1. The Mössbauêr spectrum of the unshocked meteorite can be fitted with a single paramagnetic gamma phase, the

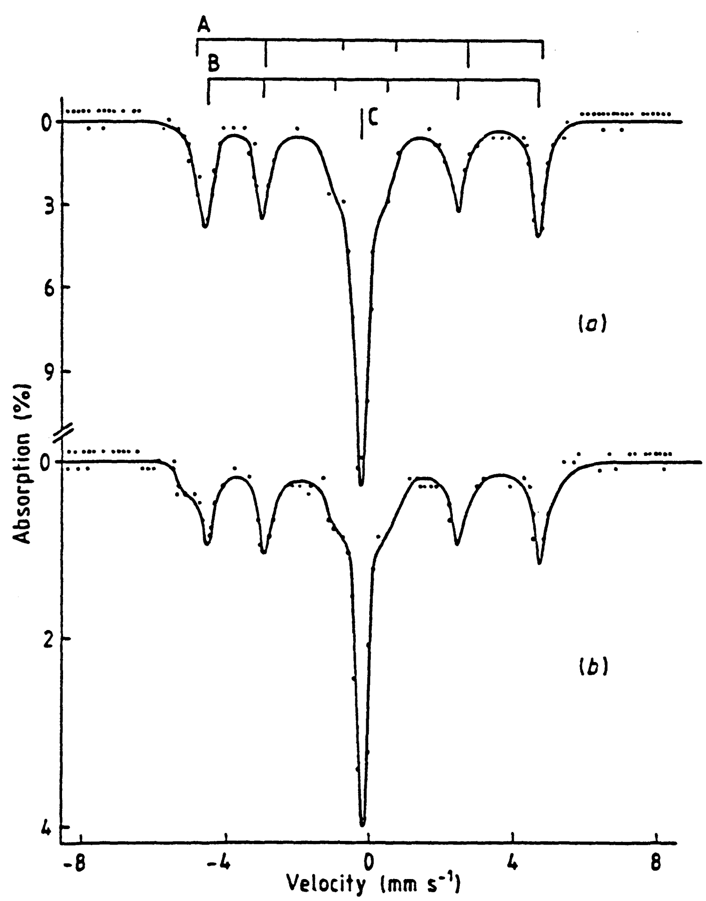


**Figure 3.** Mössbauer spectra and fitted curves of the Santa Catharina meteorite: (*a*) unshocked; (*b*) shocked at 200 kbar. Stick diagram index: A, disordered phase; B, ordered phase; C, paramagnetic phase.

Table 1. Hyperfine parameters of the Santa Catharina meteorite submitted to shock pressures. IS = isomer shift (referred to $^{57}$Co/Rh); QS = quadrupole splitting; $W$ = linewidth; $H$ = hyperfine field; $A$ = relative area.

| | Phase | IS (mm s$^{-1}$) ± 0.005 | QS (mm s$^{-1}$) ± 0.02 | $W$ (mm s$^{-1}$) ± 0.03 | $H$ (kOe) ± 2 | $A$ (%) ± 2 |
|---|---|---|---|---|---|---|
| Unshocked | Ordered | −0.06 | 0.18 | 0.43 | 290 | 50 |
| | Disordered | −0.03 | — | 0.71 | 305 | 12 |
| | Paramagnetic | −0.19 | — | 0.52 | — | 38 |
| Shocked 100 kbar | Ordered | −0.08 | 0.19 | 0.38 | 289 | 43 |
| | Disordered | −0.07 | — | 0.91 | 310 | 20 |
| | Paramagnetic | −0.19 | — | 0.42 | — | 38 |
| Shocked 200 kbar | Ordered | −0.07 | 0.20 | 0.33 | 289 | 24 |
| | Disordered | −0.05 | — | 1.00 | 301 | 42 |
| | Paramagnetic | −0.19 | — | 0.40 | — | 34 |

typical spectrum of the ordered phase Fe–Ni and a magnetic phase that can be attributed to the disordered Fe–Ni alloy (Danon *et al* 1979a).

As one goes from 100 to 200 kbar the proportion of the ordered phase decreases markedly from 50% to 24% and consequently the amount of disordered phase increases (from 12% to 42%). The linewidths of the disordered phase are broadened, as expected from the increase in the disordered state of the alloy. The paramagnetic gamma phase (taenite < 32% Ni) remains unalterable after shock, and no gamma–alpha transformation is observed (Danon *et al* 1981).

Shock-wave effects are visible from metallographic analyses as slip planes (figure 4). Scanning electron microscopy confirms the presence of the two different Fe–Ni phases (one richer in nickel than the other) and reveals morphological changes in the phase poorer in

Figure 4. Optical photomicrograph of the Santa Catharina meteorite after shock.

Ni. This can be a consequence of mechanical deformation. A similar morphology is produced by rolling effects.

Microprobe observations showed that the Ni content of the zone poorer in Ni remains unalterable after shock. The Ni-rich zone showed a larger dispersion of 40–50% Ni in relation to the unshocked meteorite.

The results of shock-induced pressures on the Santa Catharina ordered alloy can be explained by a reduction in the degree of long-range order of the ordered $Fe_{50}Ni_{50}$ phase by shock waves. This result is similar to that observed with the $Cu_3Au$ ordered alloy, in which the degree of long-range order decreases sharply in the pressure range 290–370 kbar (Beardmore *et al* 1964).

The metal particles of the LL-chondrite Saint-Séverin contain a large proportion of the Fe–Ni superstructure. The relatively large Ni/Fe ratio found in the metallic phase of the LL-chondrites favours the formation of the L1o superstructure.

The metal fraction extracted from the Saint-Séverin meteorite exhibits a complex Mössbauer spectrum, which arises from the superposition of (i) a magnetic spectrum due to the alpha phase (kamacite) with low Ni content, (ii) the typical pattern of the Fe–Ni ordered phase and (iii) a smaller proportion of a paramagnetic phase corresponding to the disordered gamma phase with less than 32% Ni (Danon *et al* 1979b).

After shock we observe only a slight decrease of about 10% in the ordered phase, and some alterations in the values of the hyperfine parameters. The quadrupole splitting decreases slightly and the hyperfine field increases from 289 to 292 kOe, showing a tendency to decrease in the degree of long-range order of the Fe–Ni ordered alloy (Albertsen *et al* 1980). An increase of 16% in the proportion of the paramagnetic gamma phase is also observed.

The alteration in the ordered state of the Fe–Ni alloy in Saint-Séverin by shock is less remarkable than that observed in the Santa Catharina meteorite. This is probably because the degree of ordering in Saint-Séverin is higher than that in Santa Catharina (Larsen *et al* 1982), and as a consequence a much higher shock would be required in order to observe disordering effects in the metal phases of Saint-Séverin.

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