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EQUILIBRIUM CHARGE-STATE FRACTIONS FOR 3.3-39 keV DEUTERIUM ATOMS AND IONS IN MAGNESIUM VAPOR*

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Equilibrium charge-state fractions of 3.3-39 keV deuterium atoms and ions in magnesium vapor are reported. The maximum D^- yield is 6.2% at low energies.

A high-intensity source of D^- ions is desirable for the Magnetic Fusion Energy (MFE) neutral-injection program, for certain particle accelerators, and for research in atomic physics. Cesium is often used as the charge-exchange medium for the formation of D^- beams because it has the highest conversion efficiency of any target studied to date[1]). However, this conversion efficiency is largest at energies below 1 keV; at such low energies beam transport and source intensity may be unsatisfactory for some applications. Other alkalis are less efficient for formation of D^-, but their maximum negative ion yield is at a higher, more convenient energy[2]), and their smaller nuclear charge may help reduce high-Z contamination in certain MFE applications.

Extrapolation of known cross sections and trends in cross-section

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data[3]) provide some *a priori* expectations that alkaline earths might be useful as charge-exchange media for D^- production. Equilibrium charge-state fractions in magnesium have been reported previously[4-10]); these measurements are summarized in table I. The poor agreement among the various results at D energies below 10 keV, as well as the interest for MFE applications, prompted the present measurements.

Positive deuterium ions produced in a radio-frequency ion source were extracted, electrostatically focused, and accelerated. The beam was chopped at a frequency of 2.6 Hz by square-wave modulation of a transverse electric field. Momentum analysis separated the D^+ component which was then collimated before it entered the section of the apparatus shown in fig. 1. The oven, machined from a massive block of steel, was heated by deeply impedded electrical-resistance heaters and was surrounded by heat shields. Temperature was measured by 2 chromel-alumel thermocouples imbedded at two locations in the steel. The entrance aperture (0.96-mm diam) and the exit aperture (2.6-mm diam) were kept hotter than the oven by radiant heating of a tube (0.48-cm diam, 2.5-cm long), external to the oven, of which each aperture was an integral part. The effective beam path length through the oven was 5.3 ± 0.7 cm, including a correction for the tube to which the exit aperture was attached. The center of the beam leaving the oven was sampled by limiting the beam with a 0.61-cm diam aperture 23.7 cm from the exit of the oven. This ensured that the beam at the position of the detectors was smaller than the detectors. The half-angle from the center of the oven to the detectors, through the limiting aperture, was ± 0.67°. The beam was then analyzed in a transverse electric field.

The D^+ and D^- beams were detected using two 2.5-cm-diam magnetically suppressed Faraday cups located 54 cm from the exit of the oven. The D^0 beam was measured using a 2.5-cm-diam lead zirconate titanate pyroelectric disk and a lock-in amplifier[11]). Beam power as low as 0.5 μW could be readily measured, enabling us to carry the beam-fraction measurement to very thick Mg targets in spite of attenuation due to multiple scattering. All three signals were integrated simultaneously for 30 sec at each target thickness. Pressure down-beam from the target was $\sim 1 \times 10^{-4}$ Pa.

Charge-state fractions as a function of Mg target thickness are shown in fig. 2 for 11 keV D^+ incident on Mg vapor. The target density was inferred from the oven temperature using Hultgren's compilation of saturated vapor pressure as a function of temperature[12]). Uncertainty in the target thickness is estimated to be ±25%, taking into account the uncertainties in the path length through the target, the temperature measurement, and the vapor-pressure data.

The beam energy was determined by electrostatic beam analysis to an accuracy of ±5%.

Results for the equilibrium charge-state fractions as a function of energy are shown in figs. 3 and 4. The error bars shown in figs. 3 and 4 are based on estimates of uncertainty in calibration of the neutral-beam detector and on the scatter of data for different target-thickness values greater than that necessary for equilibrium. Our results are in excellent agreement with those of Baragiola *et al.*[10]), for all three charge-state fractions, over the entire energy range where there is overlap. Agreement is also good with the higher-energy results of Futch and Moses[8]. The results of D'yachkov et al.[5,6] are in serious disagreement with our results over most of the energy range. This discrepancy may arise because, in their experiment, the neutral beam was not measured; thus correction for beam loss due to scattering was not possible.

If D ions in Mg were a 3-component system (D^+, D^0, D^-), it would be possible to check measured equilibrium charge-state fractions with reported cross-section values[8,13] for consistency. We have done so at 20-keV deuterium energy (10-keV H energy), where 5 of the 6 necessary cross sections have been measured; σ_{-+} ($D^- + Mg \rightarrow D^+$) is not known, but most likely is so small as to be negligible. The calculated value of F_-^∞ is 0.026 ± 0.009, in agreement with the measured value of 0.036 ± 0.004. However, the calculated value of F_+^∞, 0.035 ± 0.009, agrees poorly with the experimental value of 0.056 ± 0.006. This discrepancy could be explained by taking into account the presence of excited D^0 atoms in the charge-equilibrated beam. The stripping cross section for D^0 atoms in excited states is much larger than for ground-state D^0 atoms[4]. The effective stripping cross section weighted over the distribution of excited states for 15-keV H atoms in a charge-equilibrated beam in Mg is larger than the ground-state stripping cross section[13] by a factor of 1.7. If this same ratio holds for 10-keV H energy, the calculated value of F_+^∞ is increased to 0.059, which is in excellent agreement with the experimental value.

Our conclusion is that the present results, together with those of Baragiola et al., give a good description of the equilibrium charge-state fractions of D ions and atoms in Mg vapor over the deuterium energy range 3.3-80 keV. The D^- yield of greater than 5% at deuterium energies up to 5.4 keV could make Mg an attractive choice as a charge-exchange medium for certain MFE and accelerator applications, such as:

1) where a moderate yield at higher energy is more useful than a higher yield at lower energy;

2) where the ease of handling Mg compared to the difficulties of handling alkali metals is a consideration; or

3) where light impurities are not as undesirable as heavy impurities (as in tokamaks).

Finally, we show, in fig. 4, D^- yields from beams transmitted through solid Mg[14]). The higher yield from solids is consistent with speculations by Hiskes[15]) that clusters of metal atoms might be more effective than vapors as charge-exchange media.

We would like to thank Dr. John R. Hiskes for many stimulating conversations, and we acknowledge the skillful technical assistance of L. A. Biagi, H. H. Hughes, and members of their groups.

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TABLE I. Summary of reported measurements of equilibrium charge-state fractions for hydrogen and deuterium ions in magnesium vapor. All energies shown are equivalent deuterium energies (i.e., for experiments run with hydrogen, the energy is shown multiplied by 2).

Reference	Fraction measured	(D) Energy range (kev)
Oparin *et al.*[4]	F_0^{∞}	20-240
D'yachkov *et al.*[5,6]	F_0^{∞}, F_-^{∞}	2-80
Butusov *et al.*[7]	F_0^{∞}	50
Futch and Moses[8]	F_+^{∞}, F_0^{∞}, F_-^{∞}	8-88
Panasenkov and Semashko[9]	F_0^{∞}	20-60
Baragiola *et al.*[10]	F_+^{∞}, F_0^{∞}, F_-^{∞}	8-80
Present experiment	F_+^{∞}, F_0^{∞}, F_-^{∞}	3.3-39

FIGURE CAPTIONS

Fig. 1. Schematic diagram of the apparatus. The incident D^+ beam is momentum-analyzed and chopped.

Fig. 2. Sample data: Charge-state fractions as a function of Mg target thickness, for 11-keV D^+ incident on Mg vapor.

Fig. 3. Equilibrium yields F_+^∞ and F_0^∞ for D in Mg vapor target. The symbol ●: present work; curve B (solid line): Baragiola *et al.*[10]; curve D (dashed line): D'yachkov *et al.*[5,6]; curve FM (dotted line: Futch and Moses[8]); ▽: Oparin *et al.*[4]; □: Panasenkov and Semashko[9]).

Fig. 4. Equilibrium yield F_-^∞ for D in Mg vapor target. The symbol ●: present work; curve B (solid line): Baragiola *et al.*[10]; curve D (dashed line): D'yachkov *et al.*[5,6]; curve FM (dotted line): Futch and Moses[8]; △ shows D^- fraction emerging from a *solid* Mg target[14]).

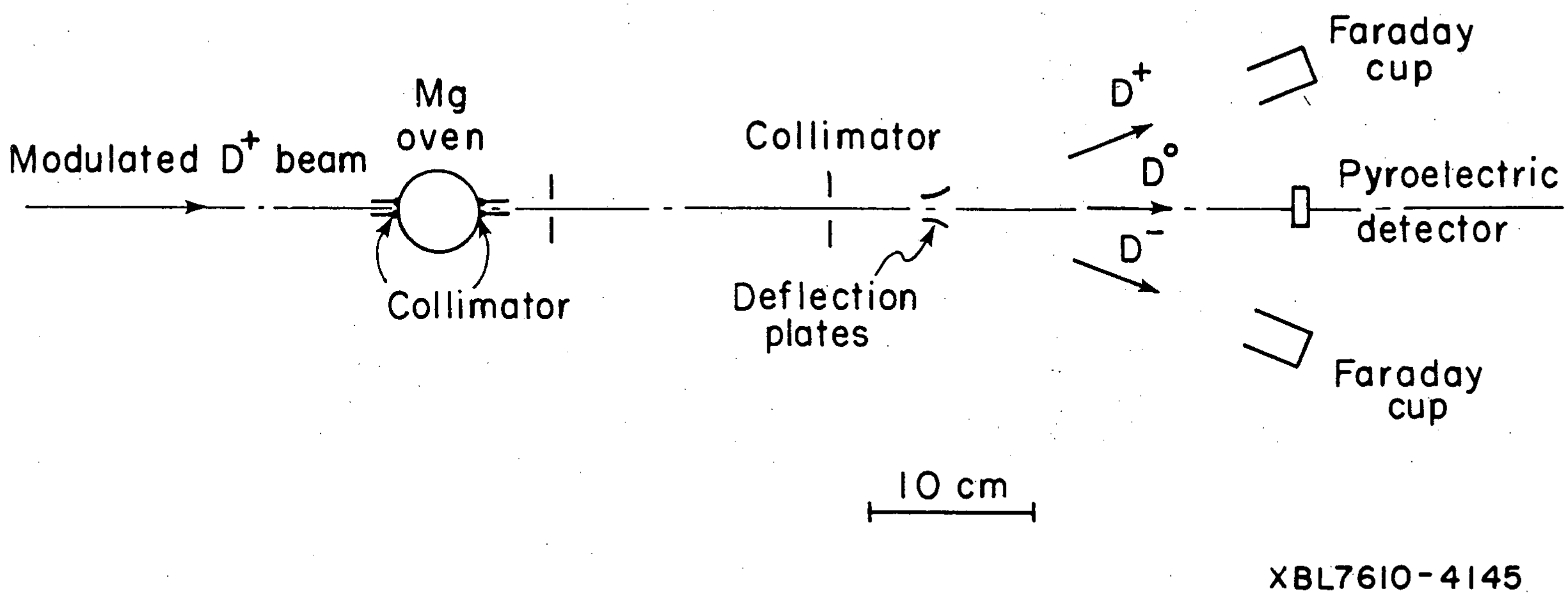
Modulated D+ beam
Mg oven
Collimator
Collimator
Deflection plates
D+
D°
D−
Faraday cup
Pyroelectric detector
Faraday cup
10 cm
XBL7610-4145

Fig. 1

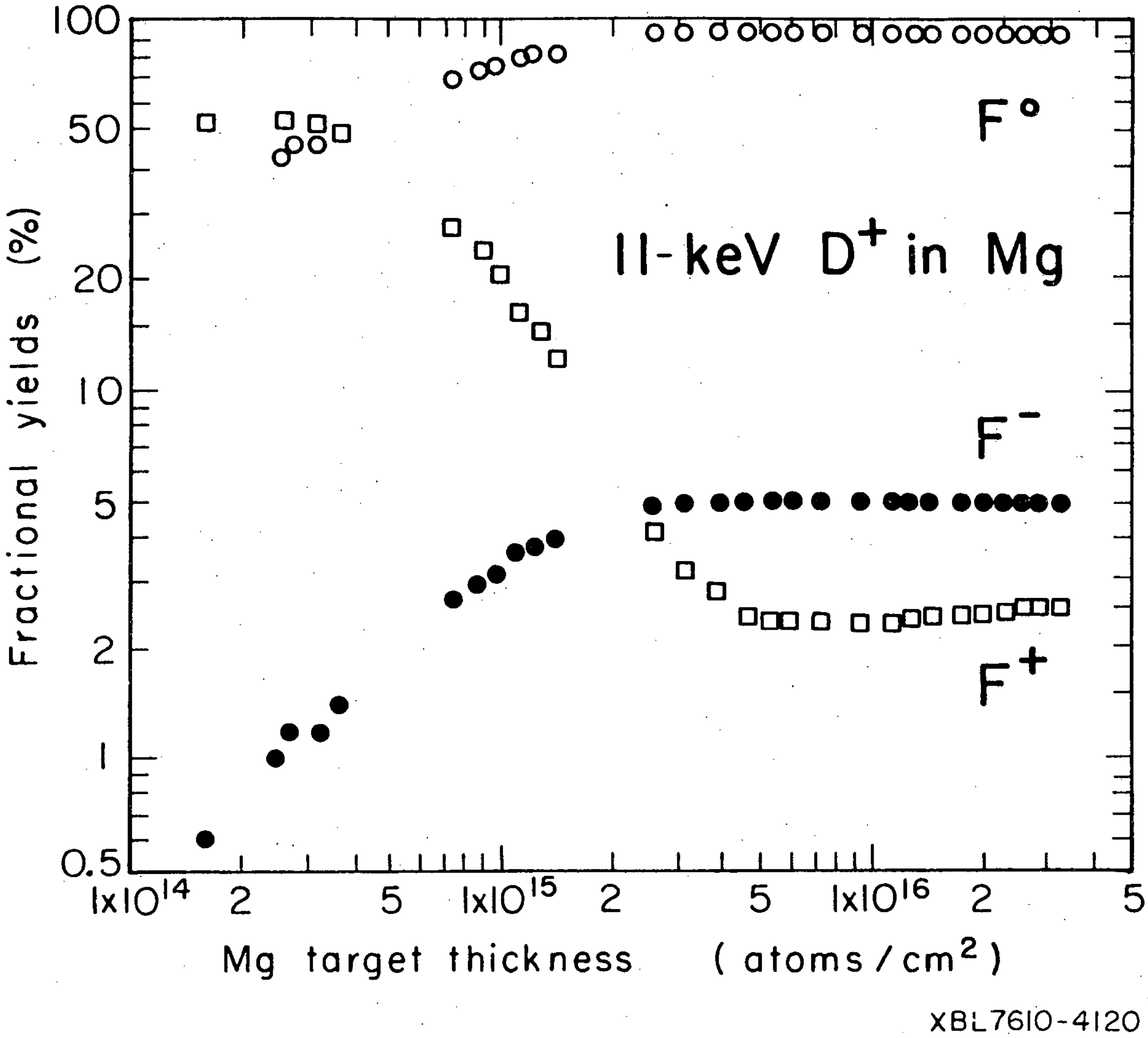
100
50
20
10
5
2
1
0.5
Fractional yields (%)
F°
11-keV D+ in Mg
F−
F+
1x10^14
2
5
1x10^15
2
5
1x10^16
2
5
Mg target thickness (atoms/cm2)
XBL7610-4120

Fig. 2

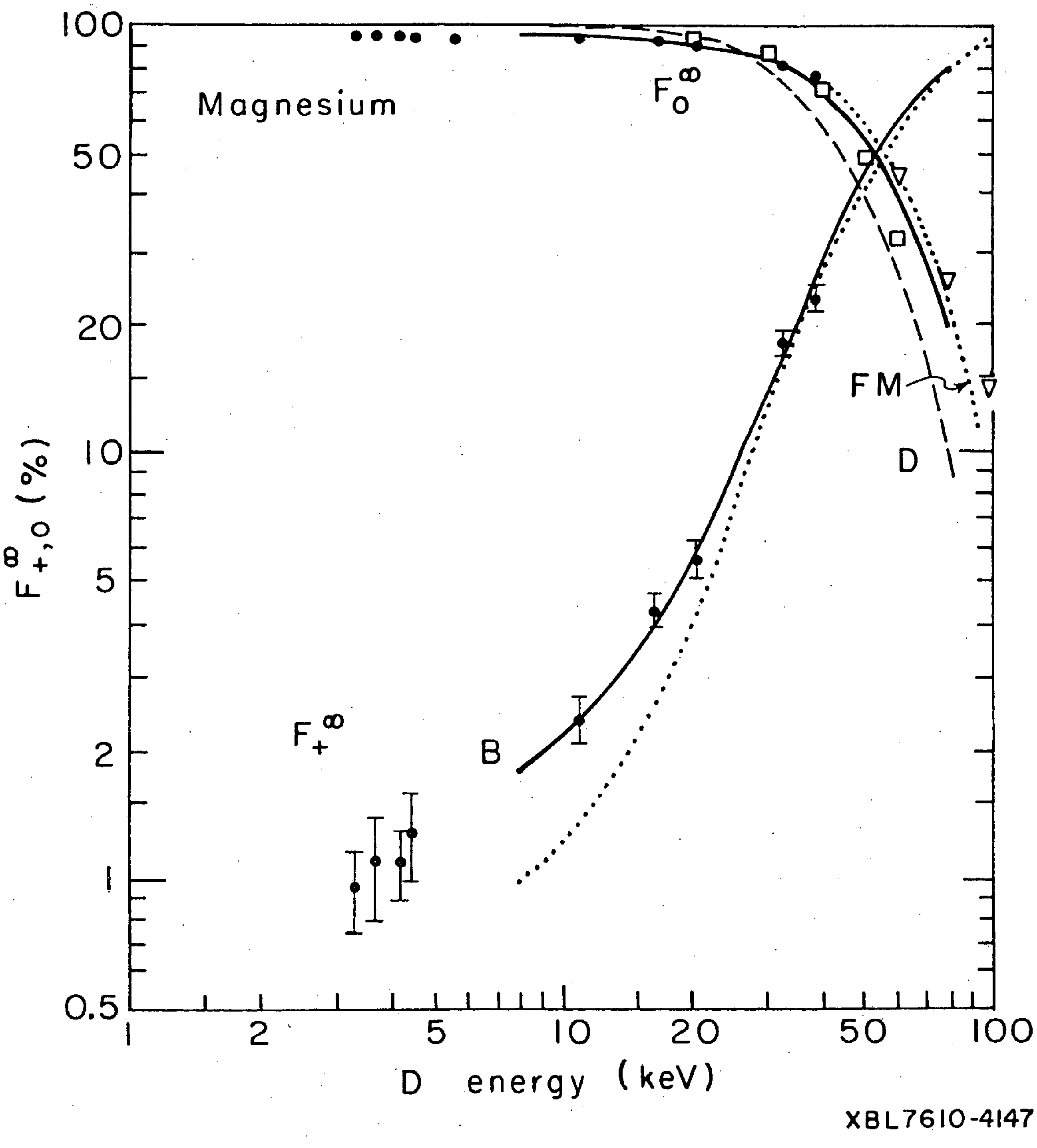
Magnesium
F_0^∞
F_+^∞
B
D
FM
$F^\infty_{+,0}$ (%)
D energy (keV)
100
50
20
10
5
2
1
0.5
1
2
5
10
20
50
100
XBL7610-4147

Fig. 3

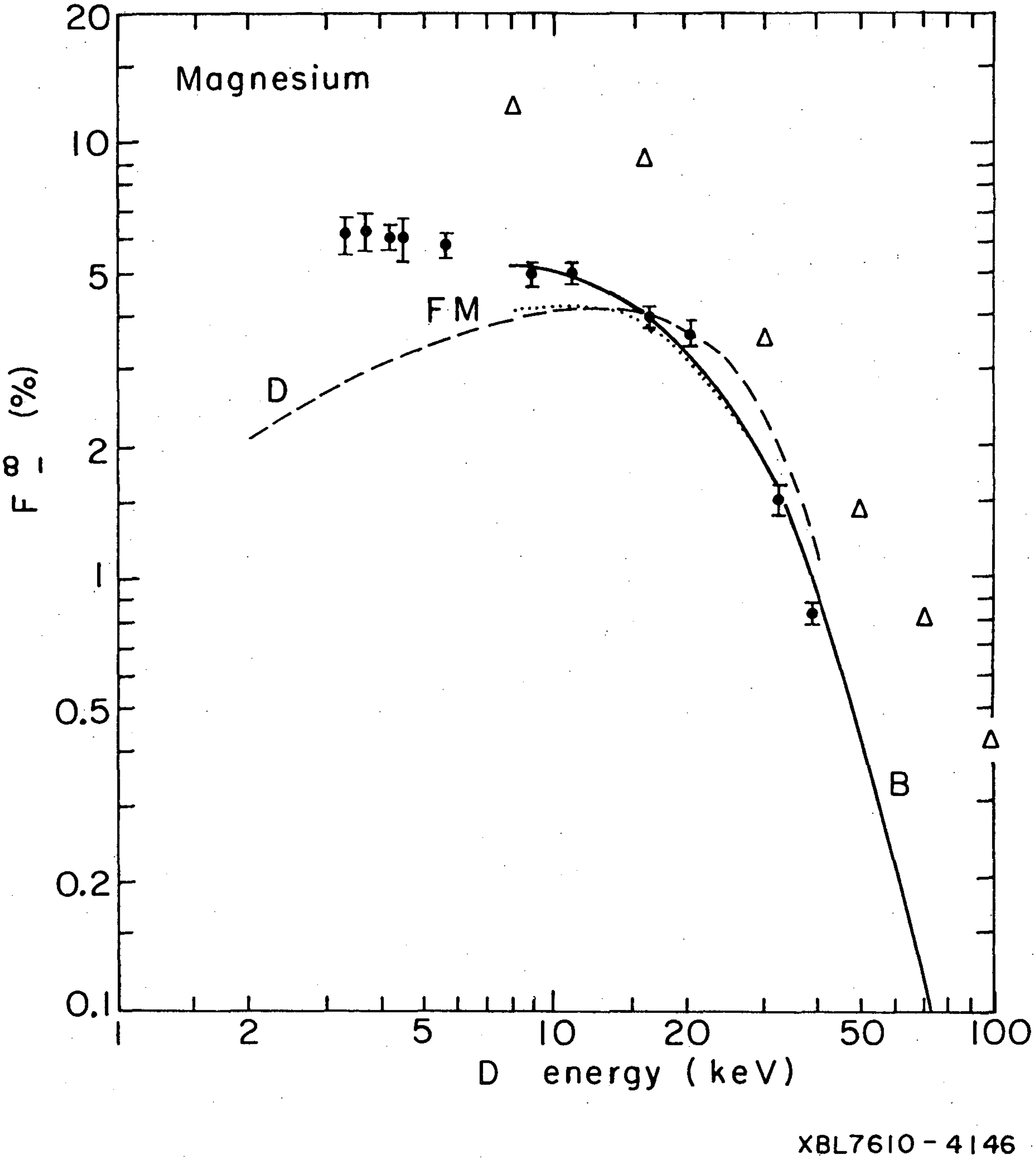
Magnesium
20
10
5
2
1
0.5
0.2
0.1
FM
D
B
F_-^8 (%)
1
2
5
10
20
50
100
D energy (keV)
XBL7610-4146

Fig. 4

0 0 0 4 5 0 6 5 7 4

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