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FINAL TECHNICAL REPORT

on

"New Aspects of Heavy Cosmic Rays from Calcium to Nickel (Z = 20 to 28)"

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Abstract

Over the two year course of this grant a study was conducted to explore the implications of composition measurements of heavy cosmic rays made by the Third High Energy Astronomy Observatory (HEAO-3). To interpret these and other measurements this study combined for the first time new laboratory measurements of the fragmentation cross sections of heavy nuclei, a new semi-empirical cross section formula, and the latest in cosmic ray propagation and solar modulation models. These models were used to interpret abundance measurements from six recent satellite experiments, including, in particular, two from HEAO-3. The principal results of the study were: 1) an improved interpretation of the ^{54}Mn clock in cosmic rays, including predictions of the isotopic abundances of Mn for comparison with future isotope measurements; 2) the first realization of the effect of ^{54}Mn decay on studies of the source abundances of Fe isotopes; 3) Improved source abundances of the elements Ar, Ca, Cr, Mn, Fe, and Ni in the cosmic ray source material; 4) an improved fit to the abundances of Fe secondaries in cosmic rays, and 5) additional evidence that supports the validity of the leaky-box" model of cosmic ray propagation in the Galaxy.

This final report summarizes these new results, the new tools that were developed to obtain them, and presents a bibliography of talks and publications that resulted from this work.

1. Approach

This study brought together for the first time several recent developments in cosmic ray physics.

1.1 Cosmic Ray Measurements

The principal data that were studied were measurements made by two of the cosmic ray instruments on HEAO-3, the HEAO-C3 experiment, including data published by Jones (1985), Binns et al. (1988), and Vylet et al. (1990), and The HEAO-C2 experiment, including data published by Koch et al. (1981), and Engelmann et al. (1983, 1990). These data covered the energy range from ~0.6 to >100 GeV/nuc. To supplement these measurements and extend their energy range we also included data from additional satellite experiments, including IMP-8 (Simpson, 1983), ISEE-3 (Leske et al. 1990, 1992), and Voyager 1 & 2 (Ferrando et al. 1990a, 1990b).

1.2 The Interstellar Propagation Model

This study used the standard energy dependent propagation model described by Soutoul et al. (1985) and Engelmann et al (1990), including the effects of ionization energy loss, energy-dependent leakage from the Galaxy, radioactive decay, and nuclear fragmentation. The source spectra were chosen to be compatible with recent shock acceleration models. The model included a network of all stable isotopes from ^{7}Be to ^{64}Ni.

1.3 Solar Modulation

The effects of solar modulation were computed with both the force-field approximation, and the more complete approach of Fisk (1971) that includes the effects of diffusion, convection, and adiabatic deceleration. Small, but noticeable differences were found between the two approaches.

1.4 Fragmentation Cross Sections

A principal goal of this study was to explore for the first time the effects of new cross sections measured at the LBL Bevalac by the University of New Hampshire Group (Webber et al. 1990a and references therein). To supplement these we also used the predictions of a new semi-empirical cross section formula (Webber et al. 1990b). These new cross sections are believed to be several times more accurate than previous semi-empirical estimates that were in standard use.

1.5 Electron Capture Reactions

Also included were the effects of electron capture and subsequent decay for nuclei such as ^{54}Mn and ^{55}Fe, using the work of Crawford (1979).

2. The Propagation of Heavy Cosmic Rays in the Galaxy

It is conventional to use the secondaries from the breakup of Fe as a measure of the mean pathlength of heavy cosmic ray nuclei in the Galaxy. Previous studies have often used the abundance ratio (Sc+Ti+V+Cr)/Fe [Z = (21-24)/Z=26] as a "secondary to primary" ratio to study the pathlength distribution and its dependence on energy. In this study we used the ratio (Sc+Ti+V)/Fe, because it is likely that Cr has a significant source abundance (Cr/Fe = 0.014 in the solar system). Figure 1 shows this ratio along with a fit to a rigidity dependent leaky box model in which $X_e = 24.9\beta R^{-0.6}$ g/cm^2 for rigidity $R > 4$ GV, and $X_e = 10.8\beta$ g/cm2 for $R < 4$ GV. The excellent fit ensures that the effects of Fe fragmentation have been accurately accounted for.

The HEAO data allow us to extend the use of this approach to much higher energy than before. Note the "break" in this ratio at ~15-20 GeV/nuc above which both the model and the data indicate a steeper dependence on energy (rigidity). This break occurs at the energy where the interaction mean free path (X_i) for Fe in interstellar H equals the mean free path for escape from the Galaxy (X_e, from above). Here $X_i = X_e = 3$ g/cm^2. Below this energy the losses of Fe-group cosmic rays are dominated by fragmentation interactions, while above this rigidity the losses are dominated by escape from the Galaxy. The corresponding rigidity where this steepening occurs is ~35 GV. The observed steepening of this ratio (observed for the first time in this work, Mewaldt and Webber 1990a) can therefore be taken as a confirmation of the basic assumptions of the leaky box model.

3. Improved source abundances of Fe-group Cosmic Rays

At the highest energy covered by these data (~100 GeV/nuc) the escape pathlength has decreased to ~1 g/cm^2, only ~10% of its value at 1 GeV/nuc. As a result of this decreased pathlength cosmic ray sources become almost "bare" at higher energies and an improved determination of the source composition can be obtained by modeling composition observations over a broad energy interval. As an example, Figure 2 shows the Cr/Fe ratio extended to high energy by the HEAO-C2 data, while Figure 3 shows the Cr/(Sc+Ti+V) ratio, which corresponds to a "secondary to secondary" ratio at low energies where fragmentation losses dominate, and a "primary to secondary" ratio at high energies. With this modeling approach, aided with the improved cross sections from Webber (1990a,b), it has been possible to obtain improved source abundances for Fe-group cosmic rays, as summarized in Table 1. The Cr source abundance is particularly interesting because it indicates an excess of Cr in cosmic ray sources compared to the solar system, consistent with the predictions of the so-called "supermetallicity" model for cosmic ray origin.

4. ^{54}Mn as a Cosmic Ray Clock

The radioactive nucleus ^{54}Mn decays by electron capture in the laboratory, but at cosmic ray energies where it is fully stripped can only decay by β^+-decay to ^{54}Fe with a poorly known halflife of >4 x 10^4 years. Some years ago Koch et al. (1981) had claimed from HEAO measurements of the Mn/Fe elemental abundance ratio that a significant fraction of ^{54}Mn produced by Fe fragmentation had decayed. We have re-examined this question using improved fragmentation cross sections, and conclude that present cosmic ray data cannot establish the degree of ^{54}Mn decay on the basis of elemental abundance observations alone, since an enhanced source abundance of ^{55}Mn can easily masquerade as energy dependent decay of ^{54}Mn. Figures 4 and 5 illustrate some of these possibilities, as reported in Grove et al. (1990, 1991). This study also pointed out for the first time that the possible decay of ^{54}Mn in cosmic rays has important implications for determinations of the ^{54}Fe source abundance, which is of interest for nucleosynthesis studies.

The only unambiguous approach to exploiting ^{54}Mn as a cosmic ray clock is with isotopic studies of Mn. Figur 6 shows how the ^{54}Mn/^{53}Mn ratio depends on the ^{54}Mn half-life, while Figure 7 shows

Table - 1: Fe-Group Composition

Element	GCR Source (This Work)	Solar Photosphere[2]	Meteorites[2]	Solar Energetic Particle-Derived Corona[3]
Ar	0.019 ± .006	0.078 ± .019	0.078 ± .019	0.019 ± .004
Ca	0.055 ± .010	0.049 ± .004	0.068 ± .005	0.065 ± .013
Cr	0.024 ± .006	0.0100 ± .0010	0.0148 ± .0011	0.014 ± .003
Mn	0.018 ± .018	0.0052 ± .0005	0.0106 ± .0010	0.005 ± .003
Fe	≡1.00	≡1.00	≡1.00	≡1.00
Ni	0.055 ± .005	0.038 ± .004	0.055 ± .003	0.037 ± .006

1) Note that the three solar system compositions are in some cases interdependent.

2) Anders and Grevesse (1989).

3) Breneman and Stone (1985).

how the $^{55}Mn/^{53}Mn$ ratio can be used to determine the Mn source abundance. Shortly after these results were reported in Ap. J., Leske et al. (to be published) reported the first clean isotopic measurements of Mn; which indicate that a substantial portion of ^{54}Mn in cosmic rays has indeed decayed at low energies. Their results, when compared to the calculations in Figures 6 and 7, indicate that the ^{54}Mn halflife is apparently $<10^6$ years, while the Mn/Fe ratio at the source is ~0.01. Measurements from the coming generation of experiments on CRRES, Ulysses, SAMPEX, and WIND should further exploit the use of this clock.

6. Education and Awards

During the course of this study, Brian Hayes, a Caltech undergraduate, was awarded a Caltech Summer Undergraduate Study Fellowship (SURF) to work on this project. His work was reported in the SURF Annual Report for 1987 and in a talk deliver on SURF Seminar Day at Caltech during the fall of 1988. This work serves as the partial basis for two papers by Grove et al. (1990, 1991). Brian also worked on this project during the summer of 1988.

Eric Grove, a Caltech graduate student also contributed to this work during 1989.

7. Bibliography

A bibliography of the talks and papers that resulted from this grant is attached.

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Webber, W. R., Kish, J. C., and Schrier, D. A. 1990b, *Phys. Rev. C*, **41**, 566.

FIGURE CAPTIONS

Figure 1: Spacecraft observations of the "secondary/primary" abundance ratio (Sc+Ti+V)/Fe are fit by the leaky-box propagation model with a rigidity-dependent pathlength distribution (from Mewaldt and Webber 1990). References to the measurements: upward triangles (HEAO-3; Jones 1985; Vylet et al. 1990); circles (HEAO-3; Engelmann et al. 1990); square (IMP-8; Simpson 1983); downward triangle (ISEE-3; Leske and Wiedenbeck 1990); cross (Voyager-2; Ferrando et al. 1990a). The dotted extensions on the HEAO-3 points represent possible systematic uncertainties (see Mewaldt and Webber 1990).

Figure 2: Comparison of measured and calculated Cr/Fe ratios for various assumed Mn source abundances. For references to the data see Figure 1.

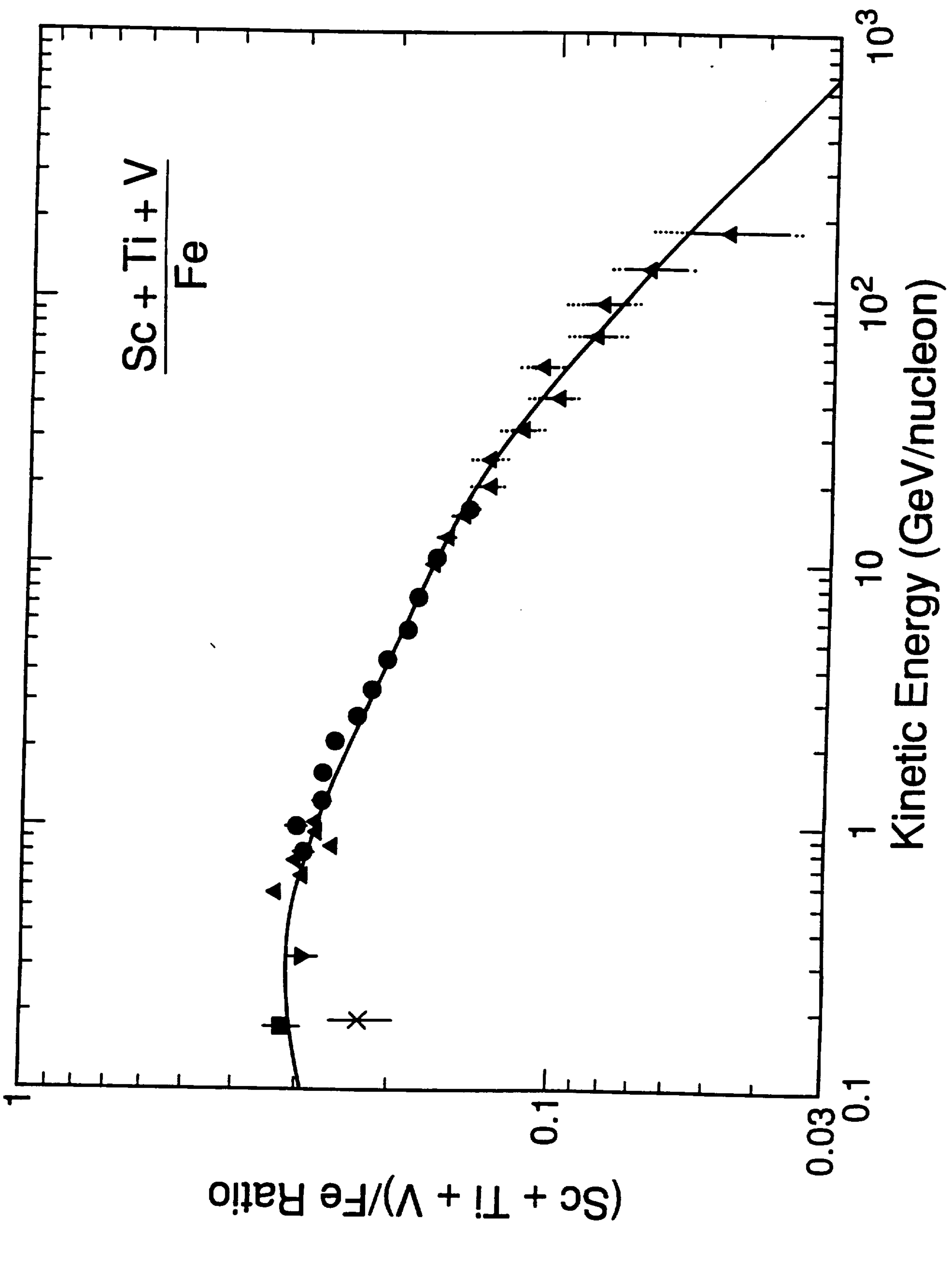
Figure 3: Comparison of measured and calculated Cr/(Sc+Ti+V) ratios for various assumed Mn source abundances. For references to the data see Figure 1.

Figure 4: A comparison of measured and calculated Mn/Fe ratios for various assumed ^{54}Mn β^--decay halflives. The calculations assume an interstellar H density of $n_H = 0.3$ cm^{-3}, but also apply to arbitrary interstellar densities with the same $n_H t_{1/2}$ product. For references to the measurements see Figure 1.

Figure 5: Measured and calculated Mn/Fe ratios as in Figure 2, except that the source abundances of Mn (in the form of ^{55}Mn) have been adjusted as indicated to fit the observations.

Figure 6: ^{54}Mn/^{53}Mn ratio vs. kinetic energy/nucleon for various possible values of the ^{54}Mn halflife. In each case the ^{55}Mn source abundance has been adjusted to fit the observed Mn elemental abundance (see Figures 4 and 5), although these curves are relatively independent of the ^{55}Mn source abundance. The calculations assume an interstellar H density of 0.3 cm^{-3}.

Figure 7: ^{55}Mn/^{53}Mn ratio vs. kinetic energy/nucleon, labeled with the assumed ^{55}Mn source abundance relative to Fe. In the solar system, Mn/Fe = 0.011. The increase in the ratio below 500 Mev/nucleon is due to the decay of ^{55}Fe following electron pickup, while the increase at high energies results from the reduced production of secondary Mn as the rigidity dependent pathlength decreases. These curves depend only weakly on the degree of ^{54}Mn decay.



$\frac{Sc + Ti + V}{Fe}$
(Sc + Ti + V)/Fe Ratio
Kinetic Energy (GeV/nucleon)
1
0.1
0.03
0.1
1
10
10^2
10^3

Figure 1

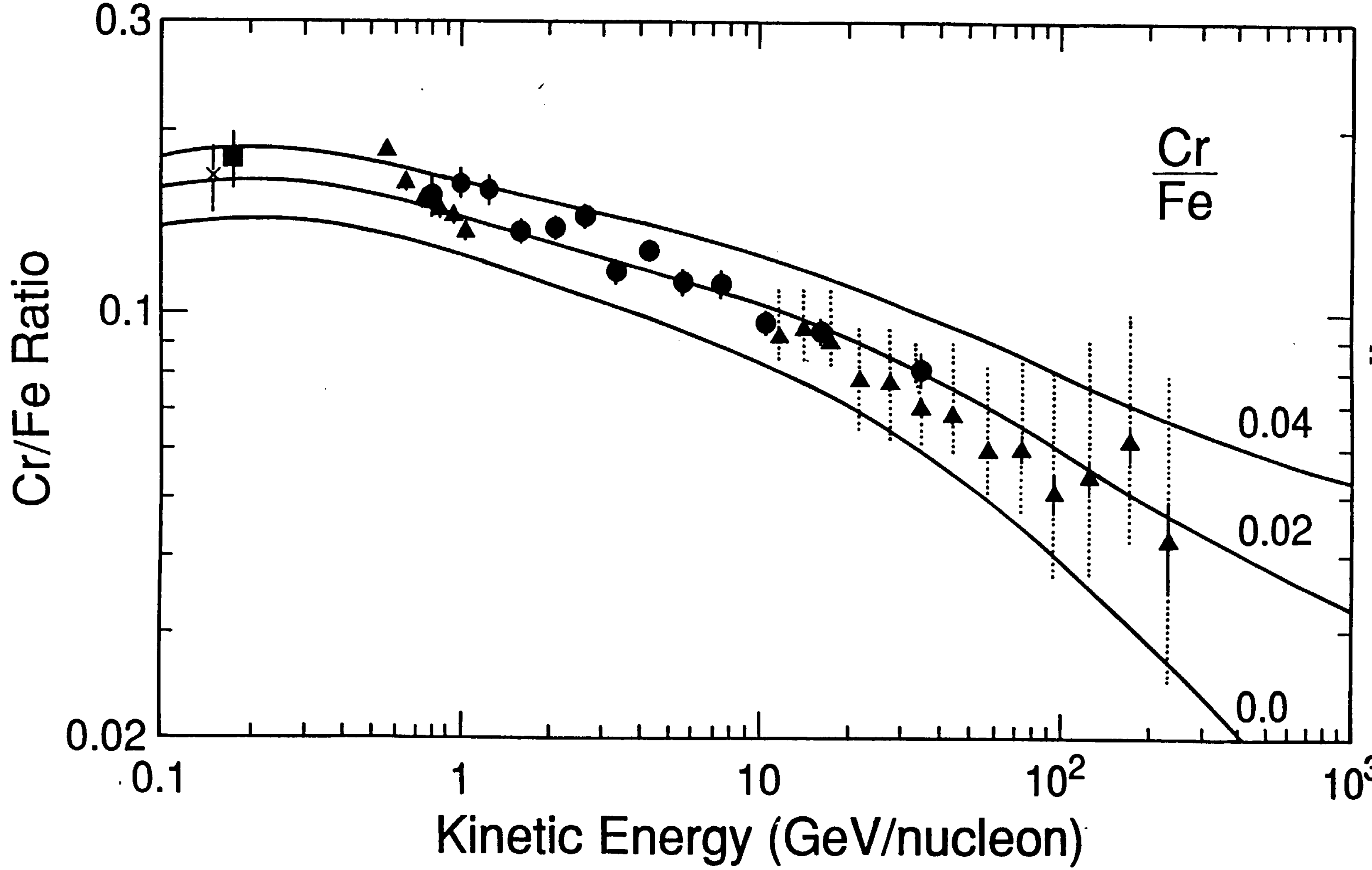

Cr/Fe
0.04
0.02
0.0
0.3
0.1
0.02
Cr/Fe Ratio
0.1
1
10
10^2
10^3
Kinetic Energy (GeV/nucleon)

Figure 2

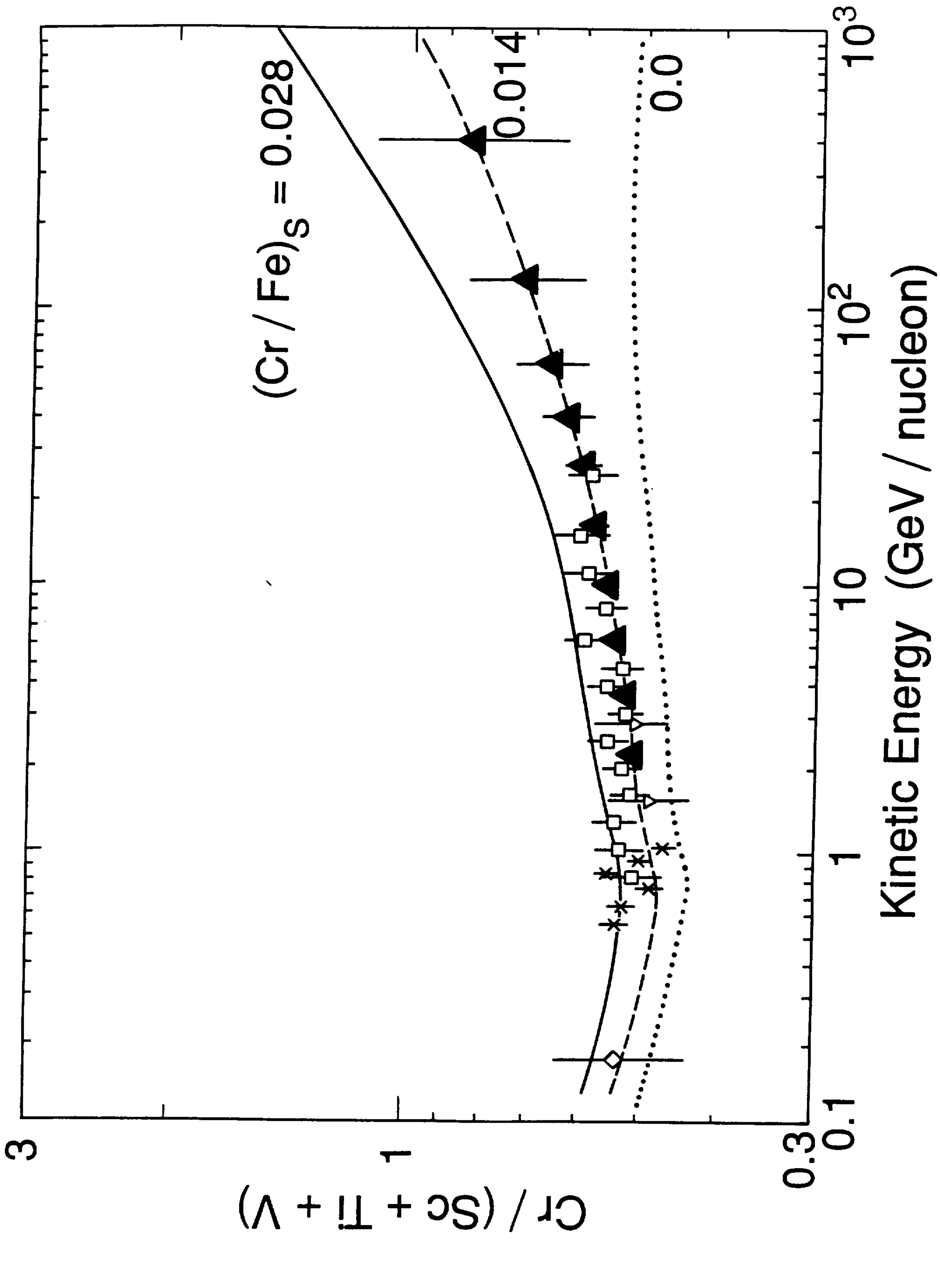
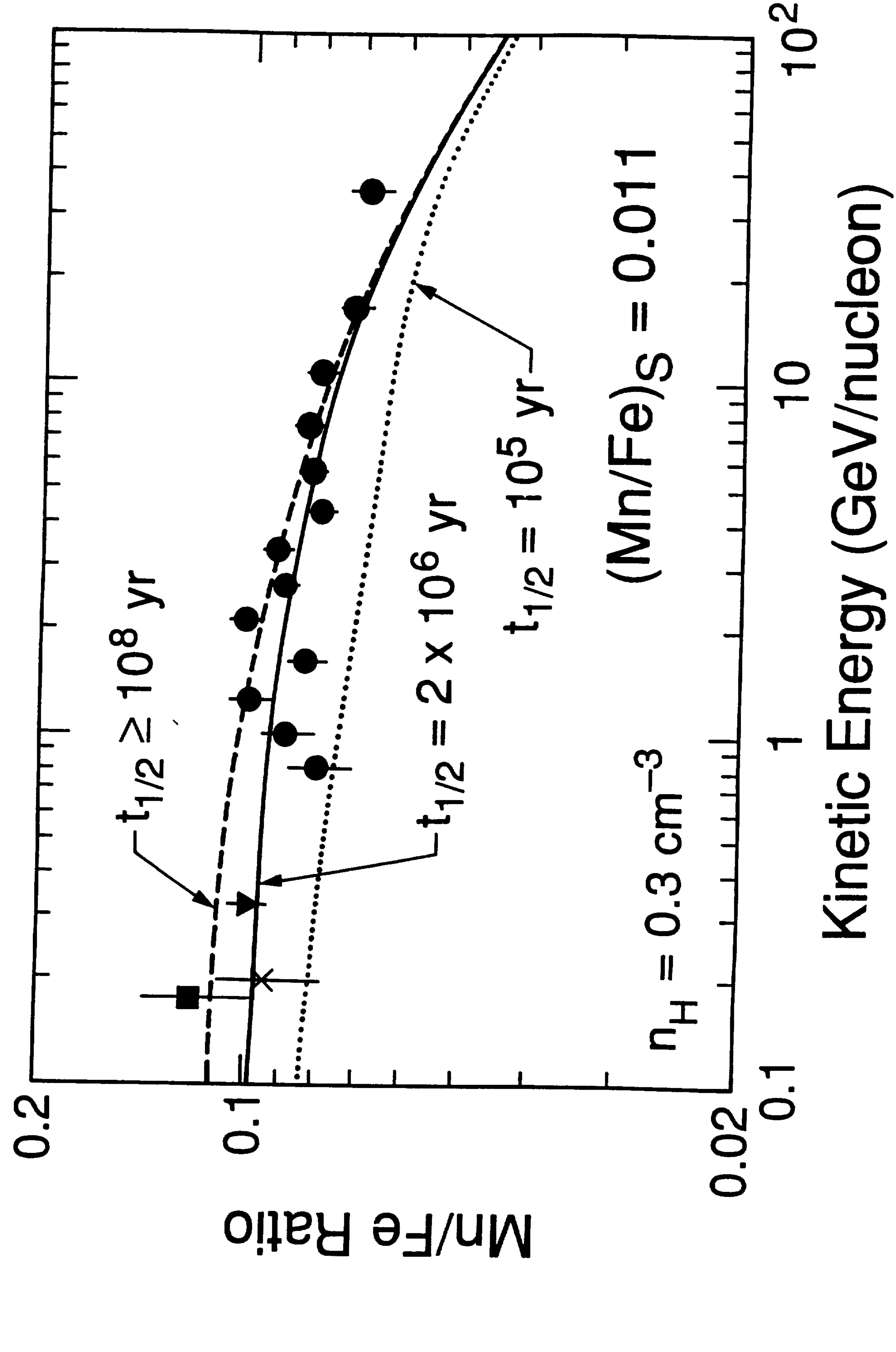

(Cr / Fe)S = 0.028
0.014
0.0
Kinetic Energy (GeV / nucleon)
Cr / (Sc + Ti + V)
0.1
1
10
10^2
10^3
0.3
1
3

Figure 3



$t_{1/2} \geq 10^8$ yr
$t_{1/2} = 2 \times 10^6$ yr
$t_{1/2} = 10^5$ yr
$(Mn/Fe)_S = 0.011$
$n_H = 0.3\ cm^{-3}$
Kinetic Energy (GeV/nucleon)
Mn/Fe Ratio
0.02
0.1
0.2
0.1
1
10
10^2

Figure 4

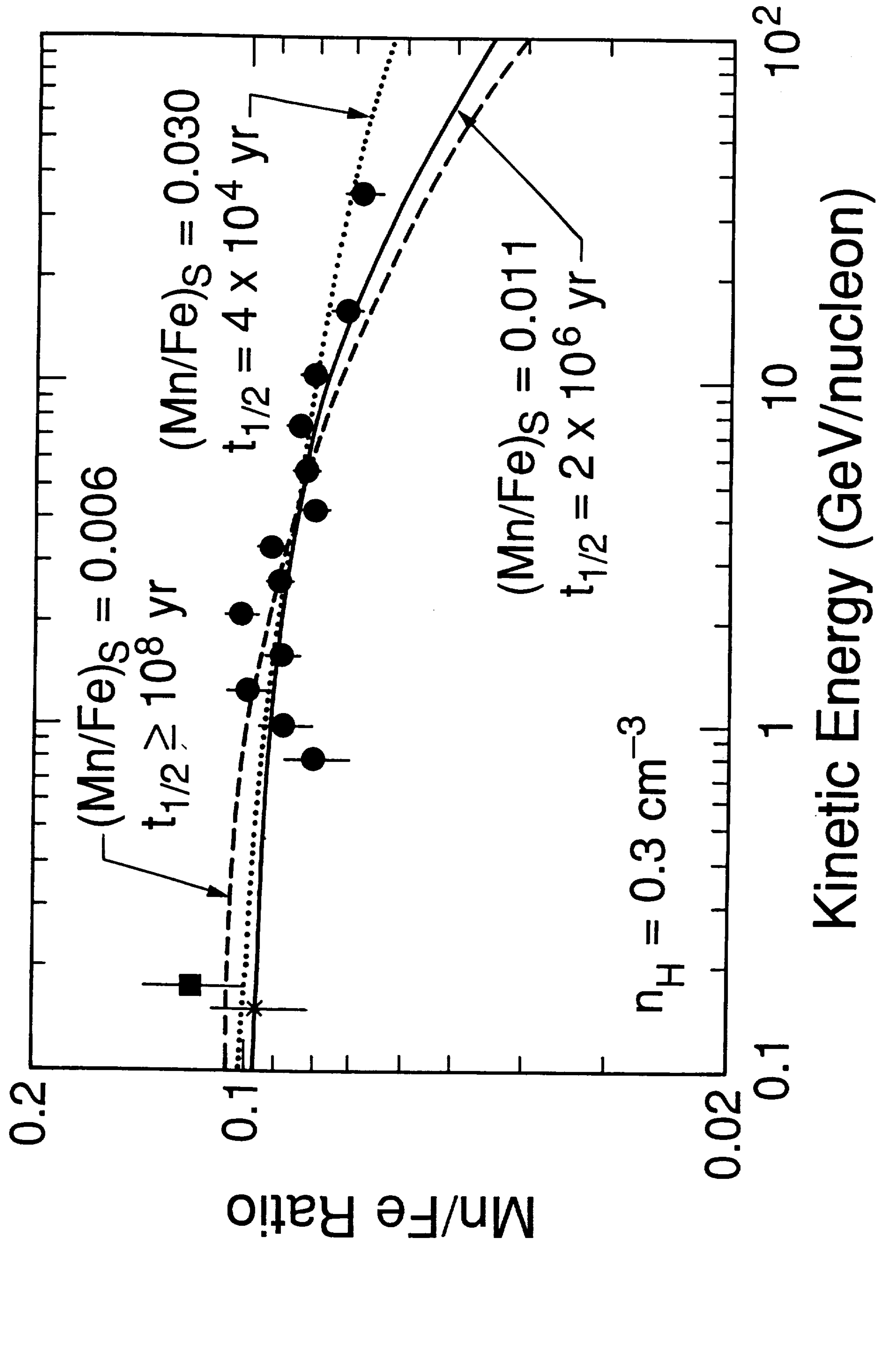

Mn/Fe Ratio
0.2
0.1
0.02
0.1
1
10
10^2
Kinetic Energy (GeV/nucleon)
$(Mn/Fe)_S = 0.006$
$t_{1/2} \geq 10^8$ yr
$(Mn/Fe)_S = 0.030$
$t_{1/2} = 4 \times 10^4$ yr
$(Mn/Fe)_S = 0.011$
$t_{1/2} = 2 \times 10^6$ yr
$n_H = 0.3\ cm^{-3}$

Figure 5

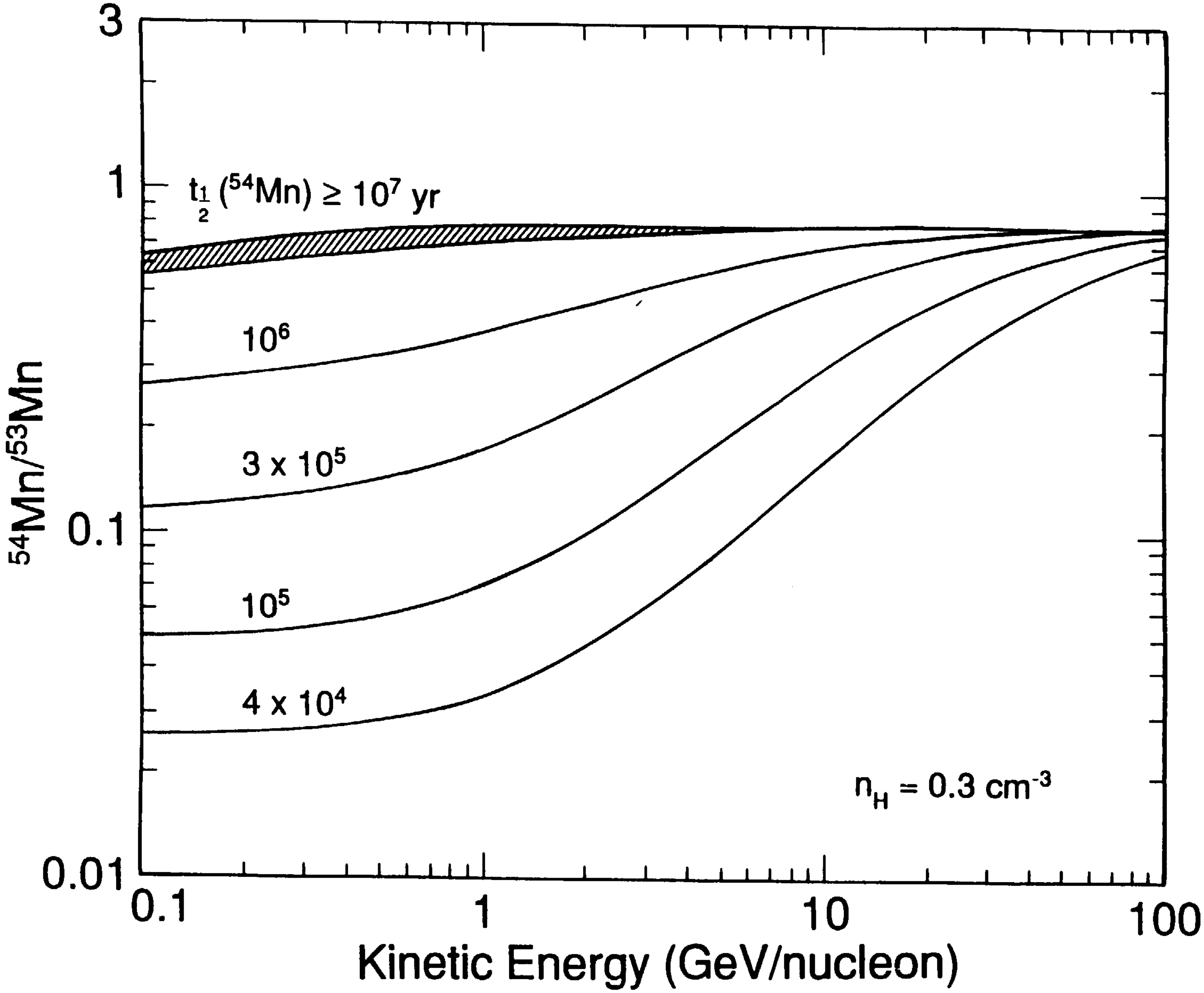

3
1
0.1
0.01
0.1
1
10
100
$^{54}Mn/^{53}Mn$
Kinetic Energy (GeV/nucleon)
$t_{\frac{1}{2}}(^{54}Mn) \geq 10^7$ yr
10^6
3×10^5
10^5
4×10^4
$n_H = 0.3\ cm^{-3}$

Figure 6

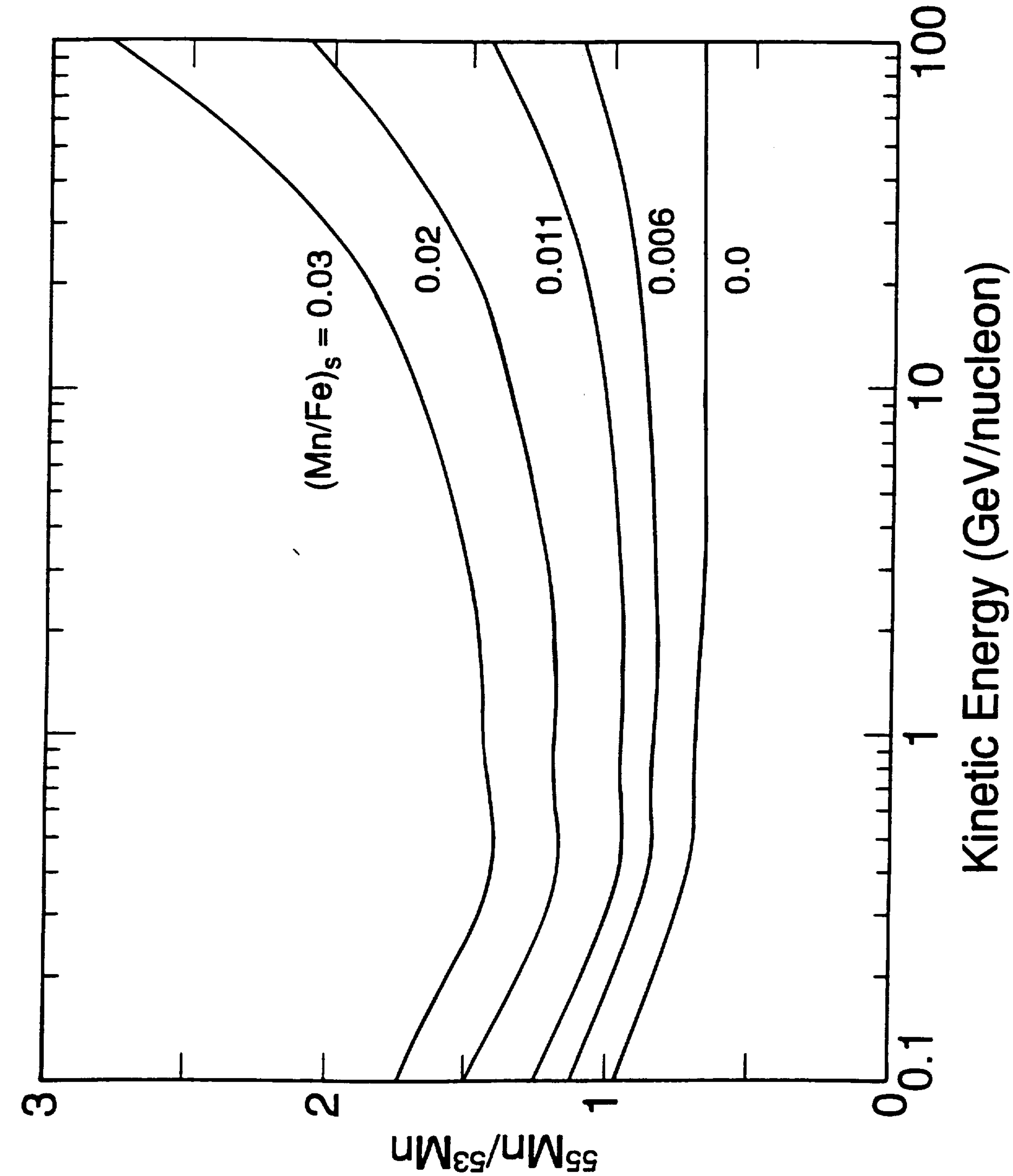

$^{55}Mn/^{53}Mn$
Kinetic Energy (GeV/nucleon)
$(Mn/Fe)_s = 0.03$
0.02
0.011
0.006
0.0
0
1
2
3
0.1
1
10
100

Figure 7