Precise measurements of the energy losses of heavy ions.

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1. Introduction

Accurate measurements of the energy loss of all charged particles are needed to determine the reliability of the Bethe theory of stopping power. Few measurements have been made for particles with energies greater than 20 MeV/u. A first step to accurate measurements is to establish the precision of an experimental method. We report here about our recent energy loss measurements for 290 MeV/u carbon ions from the HIMAC. They have been made with the method used for 70 MeV protons [1]. The ion beam traverses an absorber of thickness t and the residual range of the ions is measured with a water container of adjustable thickness ("range gauge") Figs. 1,2.

2. Energy of the ion beam

The beam of carbon ions emerging from the beam line of the synchrotron has an energy of 290 MeV/u with an uncertainty estimated to be less than 0.3 %. It traverses mylar vacuum windows and several meters of air with a total thickness of 1.53 g/cm^2 before it enters the water container through a 4 mm quartz window. It traverses the variable water column, another 4 mm quartz window and finally passes through a flat thin ionization chamber with a measurement volume 1 cm in diameter and 4 mm thick. A Bragg curve is measured by changing the thickness of the water column. Measurements have been made on 8 days between 31 January and 6 July 1995. For each measurement series of one day, Bragg curves

for water only were measured about three times: first and last run and one in the middle of the series. The stability and reproducibility of the beam energy at the range gauge can be assessed from the thickness of the water column. Such measurements are shown as a function of time schematically in Fig. 3. Since the beam travels through about 12 m of air before reaching the device, changes in air pressure will influence this energy. During the period shown, the largest observed difference in air pressure was 17 mbar, equivalent to 0.245 mm of water. This is shown in the figure. No full study of this effect has been made so far. It appears that a change in primary beam energy occurred between day 3 (11. May) and day 4 (25. May). A change in x of 1 mm corresponds to a change in energy of 1 MeV/u. We have not yet tried to correlate this change with parameters from synchrotron operation.

3. Measurements with absorbers

Absorbers of thickness t with a diameter of 5 cm are placed in front of the quartz window of the water container. Then the Bragg curve is measured again, and the water thickness defines the residual range of the ions. So far, measurements have been made for elemental absorbers, each for two thicknesses (one being about 38% thicker than the other one), with residual ranges of 60 and 30 mm, such as to reduce the energy of the ions to about 160 MeV/u and to 100 MeV/u.

4. Calculation of range-energy tables

A modified version of the Bethe theory [2] has been used to calculate stopping power and ranges for carbon ions. For small energies, a charge state correction has been applied [3]. It may be noted that this correction is very small for energies exceeding 10 MeV/u. Since the range on 10 MeV/u carbon ions in water is only about 0.4 mm or 0.25 mm in quartz, any

error in this correction will influence total ranges very little, and will be completely negligible for the calculation of relative energy loss. Mean excitation energies I used in the calculations are those measured for protons [1].

A computer program has been written to perform the calculations used in section 5. The residual mean energy of the beam is derived from the residual range in water and quartz windows. Absorber ranges are calculated for the initial T_0 and the residual mean energy T_1 for the absorber, and the difference $t_c = R(T_0) - R(T_1)$ is compared to the measured absorber thickness.

5. Preliminary evaluation of the measurements

We do not yet have an algorithm to simulate the beam transport completely, and do not yet have a reliable estimate of the uncertainty of the ion energy. Therefore we cannot determine absolute energy-range relations. Instead, we determine the energy loss in an absorber relative to that in water, and compare this ratio to a ratio calculated from range-energy tables. We assume that *the total csda range of the beam is represented by the water thickness x_7 for which the ionization is 70% of that at the peak of the Bragg ionization function.* The procedure is the following: from the measurements without an absorber we determine the initial beam energy T_0 (approximately 275 MeV/u at the surface of the range gauge). From the measurements with the absorber we get the mean value of the energy reduced by the absorber, T_1. Both T_0 and T_1 are interpolated from range tables for quartz and water. Then the range difference R_a

$$R_a = \int_{T_1}^{T_0} \frac{dT}{S(T)} \tag{1}$$

for the absorber is obtained from an interpolation in the calculated range table for the absorber, and the ratio $r = t/R_a$ is the preliminary result of our measurement.

Repeated determinations of r permit an estimate of the precision of the method. Results are given for $\delta = r - 1$ in Table 1, in percent. For all elements except Al and Cu the results of the measurements on 8 days from January to July 1995 are given. Results for thin and thick absorbers are combined in one number. For each element, the number of measurements is given, followed by the average values of δ and its standard deviation σ. For Al and Cu, the measurements on three days in January and February are listed separately from those made on five days in May-July ("second series"). The precision of the measurements is expressed by the standard deviation. If we exclude the values for Sn and W, the average value of *sigma* is ± 0.05 %. We shall examine the Sn absorber for surface defects which may cause the large *sigma*. Since the W absorbers were made from powder, they may not be homogeneous, and further thought must be given to these data.

The values of δ represent in effect systematic differences from measurements with 70 MeV protons [1]. No systematic trends with atomic number can be seen, and the only conclusion we can draw at present is that any systematic error in the Bethe theory for protons and carbon ions of widely different speeds is at most of the order of 1%. An estimate of the influence of the choice of the value representing the csda range (x_7) of the Bragg function (the 70% point) can be made by repeating the calculations with the 80% value for water, keeping the 70% value for the elements. The values of δ change by about 0.12%. This effect is much smaller than the values of δ.

Corrections are needed for the current method of evaluation since the paths travelled by the ions differ for different absorbers because of the following effects:

a) multiple scattering

b) energy loss straggling

c) fragmentation of the ions.

The Bragg curves also include ionization by fragments from the absorbers. All of these effects will influence δ. We believe though that they will amount to no more than the current values of δ.

6. Considerations about Bragg functions

Interesting observations are obtained from a comparison of Bragg curves for different absorbers. They are shown in Figs. 4-6. In Fig. 4, the ionization functions are given for equal ion fluences and are plotted so that the values x_7 (shown by the vertical line at 133.3 mm) coincide. It is seen that the ionization beyond $x = 134.5$ mm does not depend strongly on the absorber, suggesting that these particles are produced from the C-ions. On the other hand, the contributions in the peak depend strongly on the absorber.

In Fig. 5, the functions of Fig. 4 are scaled to agree at the peak. For water and Al they are almost the same, but for Pb the curve is wider. This probably is caused by multiple scattering. The differences in widths are much smaller than they were for protons. Thus we expect that the correction for multiple scattering and straggling of the C-ions will be much less than 1%. On the other hand, we do not have any estimate of the influence of fragment ions.

In Fig. 6, the function for W is considerably wider than that for water (and Pb). In analogy to the observations for grainy absorbers [4] we assume that this is an excess straggling effect due to the internal structure of the W disk (which is made by compressing tungsten powder).

7. Statistics and precision of measurements

An estimate of the ultimate limit in the precision of the measurements can be ob-

tained from the reproducibility of repeated measurements seen in Table 1. It is probably better than the average standard deviation of $\pm 0.05\%$ because the fluctuations of the beam energy within each day have not yet been incorporated in the data analysis [1]. The differences of 0.01% between the average δ for the two series for Al and Cu promise an ultimate precision of close to 0.01%.

8. Conclusions

1. Fluctuations of the energy of the beam exceeded the ultimate precision of the range gauge. Thus T_0 must be measured frequently.

2. The reproducibility of the relative energy loss (expressed by *sigma* of Table 1) is very good. This is independent of the assumptions about beam fragmentation (as long as it is constant for a given absorber).

3. The difference between measured and calculated relative energy losses is of order of 1%, much larger than the precision of the data. A variety of corrections must be made in order to explore the reasons for these differences.

4. The error of the stopping power algorithm described in Sect. 4 appears to be small enough for practical applications such as cancer therapy

5. Measurements with organic absorbers are planned.

References

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Table 1. Deviation δ, with standard deviation σ of the ratio of measured thicknesses t to thicknesses calculated from residual range in water and range-energy tables.

element	Z	*No.*	$\delta(\%)$	σ	*second*	*series*
Al	13	8	0.37	± 0.02	9	0.37 ± 0.05
Si	14	4	-0.04	± 0.06		
Ti	22	4	1.04	± 0.06		
Fe	26	3	1.16	± 0.07		
Ni	28	3	0.84	± 0.04		
Cu	29	4	0.88	± 0.05	3	0.87 ± 0.03
Zn	30	3	1.05	± 0.04		
Mo	42	3	1.12	± 0.04		
Ag	47	4	1.33	± 0.08		
Sn	50	3	0.5	± 0.19		
W	74	4	1.7	± 0.20		
Pb	82	4	0.74	± 0.04		

Fig. 1. Schematic representation of apparatus ("range gauge") used to measure Bragg curves in water.

Fig. 2. Photograph of the apparatus

Fig. 3. Water thickness x (no absorber) as a function ot time. The abscissa is schematic (day 1= 31.Jan. 1995, day 8=6. July 1995), within days, successive measurements are not at equal time intervals. The range of change in x expected from a change of 17 mbar is shown by the vertical bar labelled p.

Fig. 4. Ionization functions $J(x)$ for a constant fluence of 290 MeV/c carbon ions in water (continuous line, peak at 3.5), Al(5.66cm)+water (dashed line, peak at 4.1), and Pb(2.2 cm)+water (dashed-dotted line, peak at 4.8). The functions have been plotted so that the x_7 points coincide.

Fig. 5. Same as Fig. 4 but the functions are reduced to the same peak heights.

Fig. 6. Bragg functions for 290 MeV/c carbon ions in water (continuous line, peak at 3.5), and W(1.25 cm)+water (dashed-dotted line, peak at 4.37). The functions have been plotted so that the x_7 points and the peak heights coincide.

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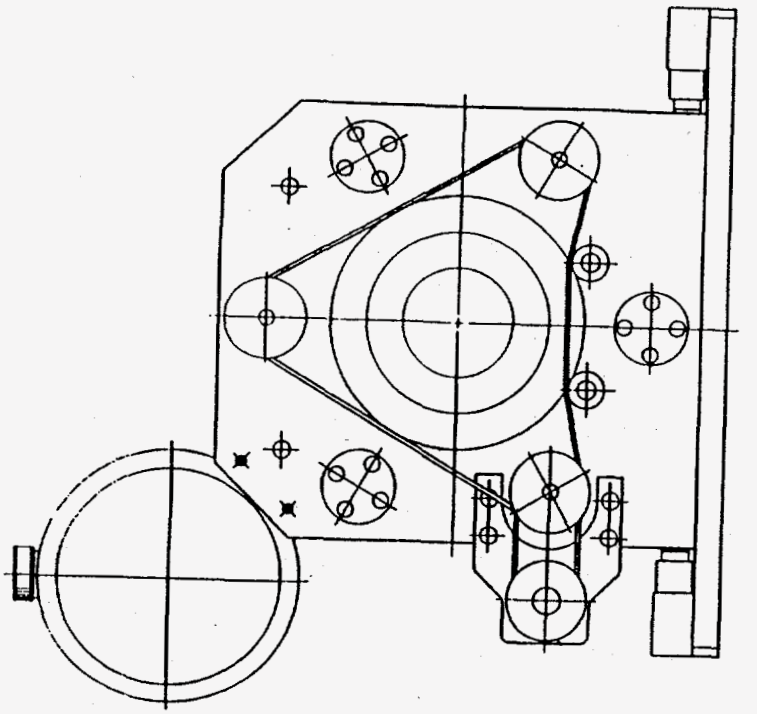

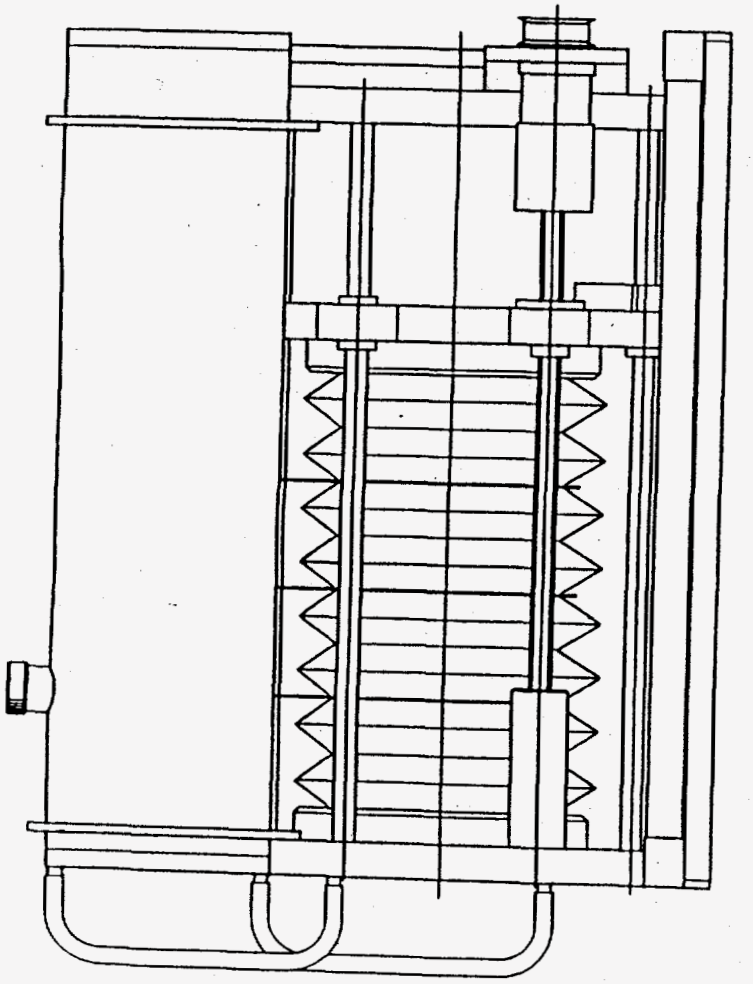

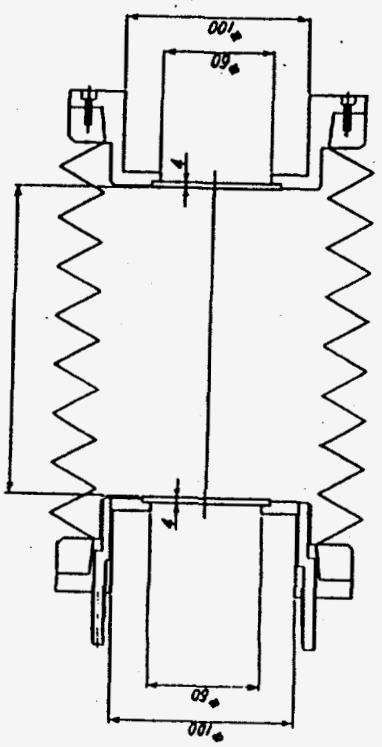
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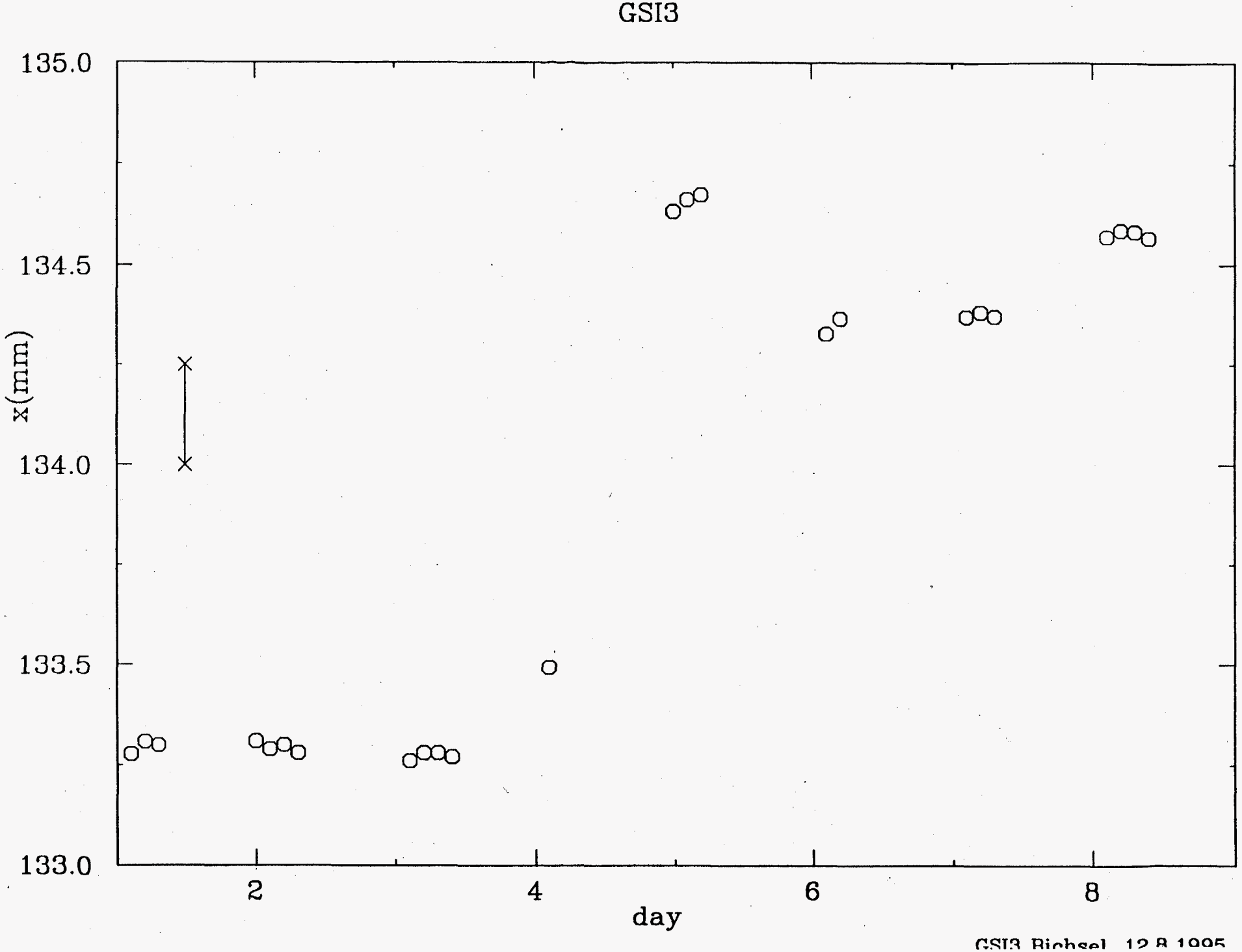
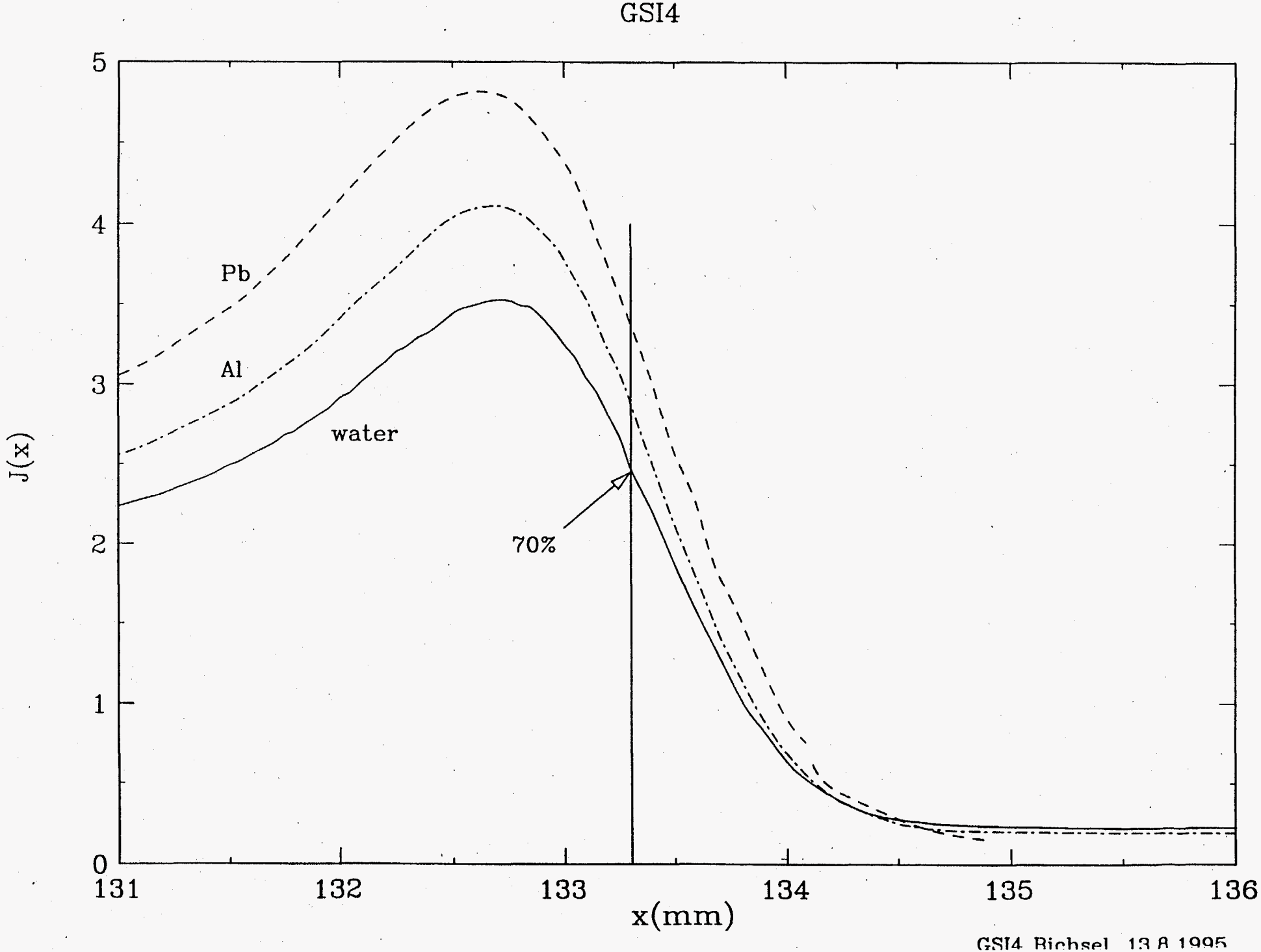
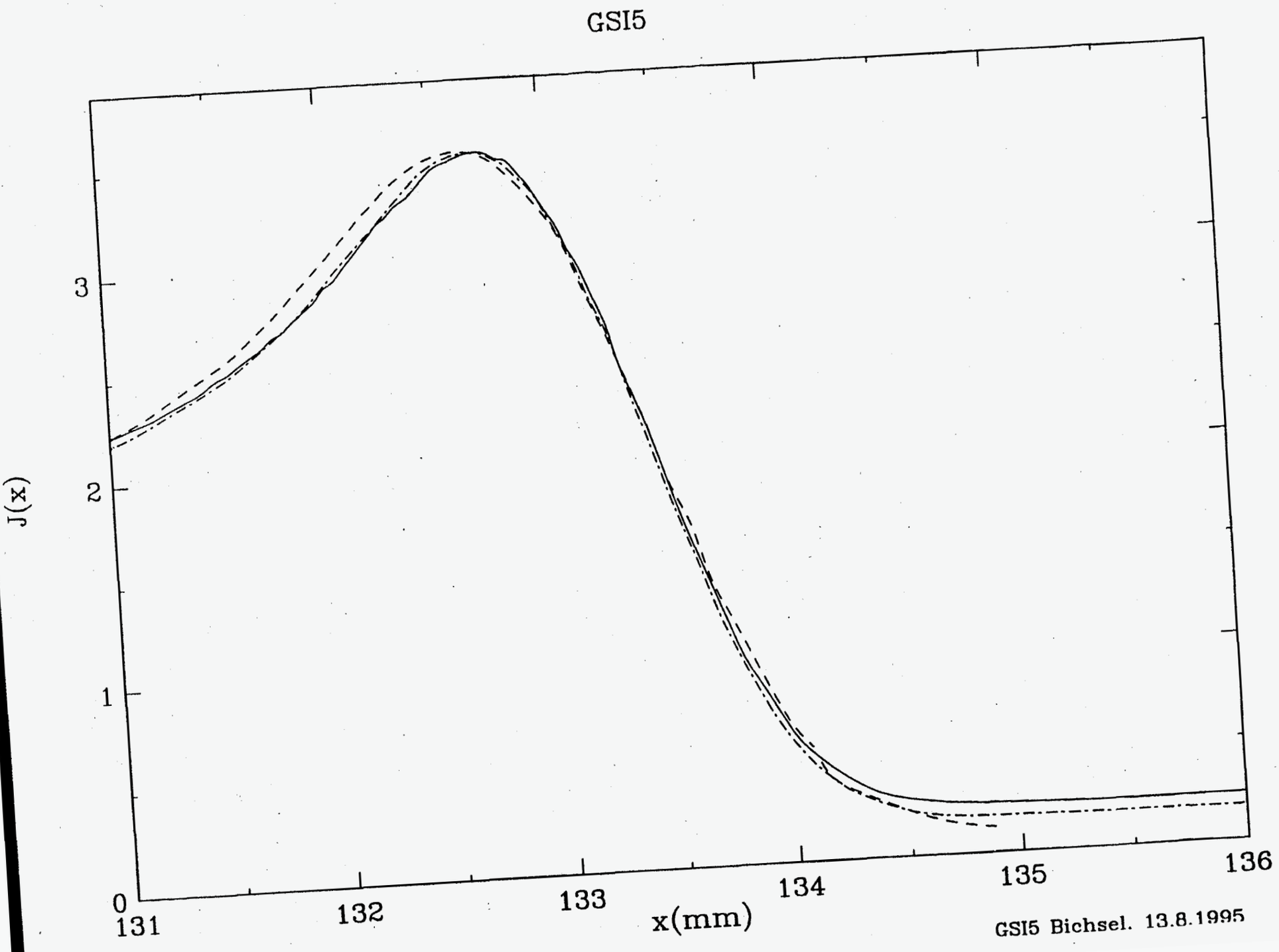

GSI3
135.0
134.5
134.0
133.5
133.0
x(mm)
2
4
6
8
day
GSI3 Bichsel 12.8.1995


GSI4
5
4
3
2
1
0
J(x)
Pb
Al
water
70%
131
132
133
134
135
136
x(mm)
GSI4 Bichsel 13.8.1995


GSI5
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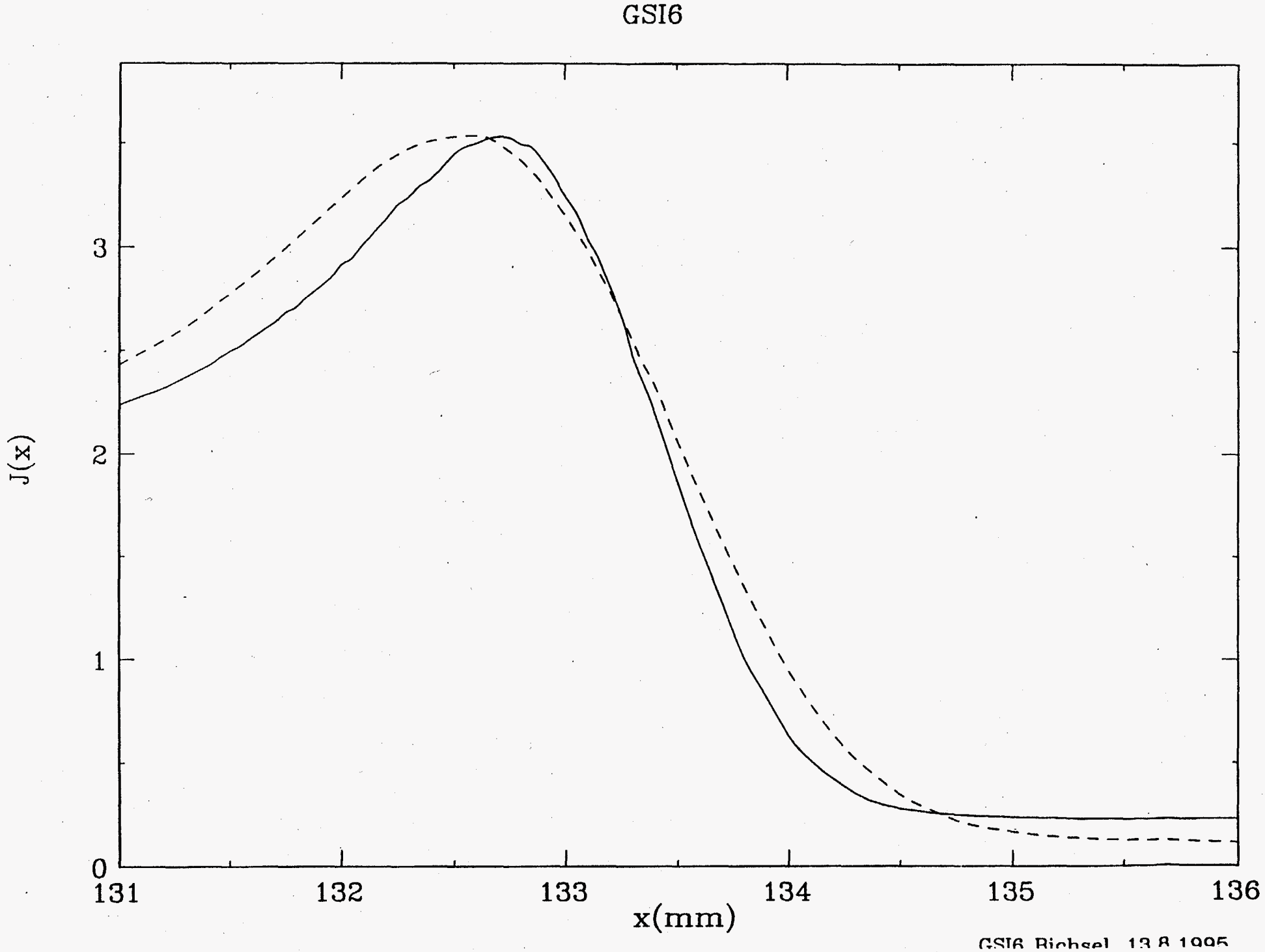
1
2
3
131
132
133
134
135
136
x(mm)
GSI5 Bichsel. 13.8.1995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2
3
131
132
133
134
135
136
x(mm)
GSI6 Bichsel 13.8.1995