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ABSTRACT

The slope b(s) of the forward diffraction peak of p-p elastic scattering has been measured in the momentum-transfer-squared range $0.005 \lesssim |t| \lesssim 0.09$ $(\mathrm{GeV}/c)^2$ and at incident proton energies from 8 to 400 GeV. We find that b(s) increases with s, and in the interval $100 \lesssim s \lesssim 750$ $(\mathrm{GeV})^2$ it can be fitted to the form $b(s) = b_0 + 2\alpha' \ell n\, s$ with $b_0 = 8.23 \pm 0.27$, $\alpha' = 0.278 \pm 0.024$ $(\mathrm{GeV}/c)^{-2}$.

In the course of the recent operation of the 400-GeV accelerator at the National Accelerator Laboratory, we have studied the distribution of large angle recoil protons from an internal hydrogen gas jet target for incident proton energies varying from 8 to 400 GeV in order to determine (i) the slope, b(s), of the diffraction peak of the elastic p-p scattering in the momentum transfer region $|t| < 0.1\ (\mathrm{GeV}/c)^2$, (ii) the ratio of the real to the imaginary part of the forward p-p nuclear scattering amplitude, and (iii) the differential cross section for the diffraction excitation of the proton to the low mass isobars at small t and large s. In this paper, we report on the slope parameter b(s). Results on parts (ii) and (iii) of the experiment will be presented in future publications.

Small angle p-p elastic scattering has been investigated at every existing high-energy proton accelerator. Most recently, extensive measurements were performed at Serpukhov[1] and at the ISR.[2,3] The results for $|t| \lesssim 0.12\ (\mathrm{GeV}/c)^2$ can be fitted by the form

$$\frac{d\sigma}{dt} = A(s)\, e^{-b(s)|t|} \tag{1}$$

and show that b increases with s. In an optical model with constant opacity, b is related to the radius R of the interaction, $b = R^2/4$, and the results indicate that R increases with energy. The exact form of the variation of b with s is of particular significance in models of high-energy interactions of elementary particles. For example, the frequently used parametrization

$$b(s) = b_0 + 2\alpha' \ell n(s/s_0) \tag{2}$$

is based on a simple Regge-pole model where α' corresponds to the slope of the vacuum trajectory (Pomeron). Although the ISR experiments extended the measurement of b(s) from the Serpukhov interval of $26.2 < s < 133\ \mathrm{GeV}^2$ to the much higher s values of $460 < s < 2800\ \mathrm{GeV}^2$, no clear conclusion about the validity of Eq. (2) over the entire range covered by these experiments can be drawn from the combined results. The present experiment tests Eq. (2)

over a large range of s[$17 < s < 745$ (GeV)^2], which partially overlaps both the Serpukhov and the ISR data. In an earlier experiment[4] at NAL, we obtained results on b(s) in the interval $47 < s < 375$ GeV^2. The present experiment is more accurate primarily due to theuse of a gas jet target.

The experimental method of studying small angle p-p scattering by measuring the energy T and the angle θ of the recoil protons[5] can be appreciated by examining the recoil kinematics. For the reaction

$$p + p \rightarrow p + X \tag{3}$$

the relationship $|t| = 2M_p T$ holds exactly and, for incident proton momentum $p_0 >> M_x$, the recoil angle near 90° in the laboratory is given approximately by

$$\cos\,\theta \simeq \frac{1}{\beta}\frac{\sqrt{|t|}}{2M_p} + \frac{M_x^{\;2} - M_p^{\;2}}{2p_0\sqrt{|t|}}\,, \tag{4}$$

where $\beta = p_0/(E_0 + M_p)$ is the c.m. velocity. For elastic scattering, θ is a function of t and only a weak function of p_0. For example, at a fixed angle the recoil energy changes by at most 2% for incident energies between 50 and 400 GeV, an ideal condition for measuring the variation of b(s) with s.

The experimental setup consisted basically of a hydrogen gas jet target which was pulsed to intercept the beam at predetermined times during the acceleration cycle, thus selecting the desired incident beam momenta, and a set of 10 Si(Li) solid-state detectors spanning the angular range from 80.8° to 87.8° at a distance 2.5 m from the target. These detectors were used to measure the kinetic energy of the recoil proton.

The jet target had the following characteristics[6]: pulse duration, ~200 msec; density, $\sim 5 \times 10^{-7}$ g/cm^3; and FWHM diameter at the beam axis, ~12 mm. The beam, accelerated at the rate of 100 GeV/sec was ~5 mm in diameter at the target and, circulating with a period of 20μsec, traversed the target $\sim 10^4$ times during the jet pulse. Thus, with 10^{12} protons per machine pulse and a 5-sec repetition period, the effective luminosity was $\sim 6 \times 10^{32}$ cm^{-2}sec^{-1}.

The detectors, collimated down to circular areas of 1-cm diameter, were mounted on a movable carriage so that their angular position could be changed. Since the energy of the recoil protons of interest was in the range $0.25 < T < 50$ MeV, and our thickest detectors (5 mm) were capable of stopping protons up to only 30 MeV, copper degraders were placed in front of the 5 detectors on the high $|t|$ side of the apparatus so that the elastic protons would stop in the detectors. In this way, inelastic protons from Eq.(3) always appeared on the low energy side of the elastic peak in the pulse-height spectra of all detectors. One such spectrum is shown in Fig. 1. The elastic peak is superposed on a background which, mainly, was not produced in the immediate vicinity of the target. This "room" background was measured by running for 5 out of every 15 pulses with the detector carriage moved to a position 56 mrad closer to 90°, where the elastic peaks were either completely eliminated or considerably shifted towards lower energies. Two extra detectors were mounted at fixed positions and served as normalization monitors together with two 3-fold scintillation counter telescopes. Figure 1(b) shows the same spectrum appearing in Fig. 1(a), but with the "room" background subtracted by this procedure. The width of the peak is consistent with the kinematic spread over the angular acceptance determined by the sizes of target and detector. The small remaining background of 1% in the spectra for $p_0 \lesssim 50$ GeV/c, such as the one in Fig. 1(b), is attributed to tails of the hydrogen gas jet. In one method of analysis, this background was removed by interpolation under the peak. In another approach, limits were placed on the pulse-height spectra to correspond to a definite interaction region in the gas jet, thus insuring that the events in all detectors came from the same amount of hydrogen gas. As p_0 is increased, the energy of recoil protons from diffractively produced low mass isobars increases. For $p_0 \lesssim 50$ GeV/c, the energy of the recoil from N(1470) production is much lower than the elastic peak energy. Above $p_0 \sim 100$ GeV/c, some inelastic recoil protons could contribute background events within our resolution for the elastic peak. Anticipating this inelastic contribution, we pulsed the jet twice during the acceleration ramp, once at ~50 GeV and the second time at the higher energy. For each detector, the 50-GeV spectrum was subtracted from that of the higher incident energy, after normalizing the spectra with the elastic peaks, yielding the inelastic events in the vicinity of the elastic peak. These data were transformed to $d^2\sigma/dt\,dM_x^2$, fitted by resonance formulae, and the results[7] were used to make a correction for the inelastic contribution. This correction amounts to at most 4%. The obtained elastic yields were then corrected for nuclear interactions in the detector,[8] at most a 3% correction.

About 8 million elastic events were collected in ~100 runs distributed over 16 different incident proton energies. The differential cross sections calculated from the data in the interval $0.005 \lesssim |t| \lesssim 0.09$ were corrected for the Coulomb contribution[9] and fitted by Eq.(1). The fits were generally good, not requiring higher order terms in the exponent. The errors for b(s) reflect both the statistical and background subtraction uncertainty. However, we estimate that s-independent errors, such as collimator sizes and angle calibration, lead to an overall systematic uncertainty of ±0.2 $(\mathrm{GeV}/c)^{-2}$ in the absolute normalization of b(s).

The results for b(s) are shown in Table I and plotted in Fig. 2 along with data from other experiments.[1-3,10,11] In examining this figure, one must keep in mind the s-independent systematic normalization uncertainty of ±0.2 $(\mathrm{GeV}/c)^{-2}$ for all b values of this experiment, and of ±0.3 $(\mathrm{GeV}/c)^{-2}$ for the values of Beznogikh[1] et al. We observe that b(s) increases with energy, while $db(s)/d(\ell n\, s)$ decreases continuously up to $s \simeq 100\ \mathrm{GeV}^2$, approaching thereafter what appears to be a nearly constant value. A fit of our data with Eq.(3) above $s \simeq 100\ \mathrm{GeV}^2$ yields $b_0 = 8.23 \pm 0.27$ and $\alpha' = 0.278 \pm 0.024\ (\mathrm{GeV}/c)^{-2}$ with $\chi^2 = 0.44$ per degree of freedom, where we have taken $s_0 = 1\ \mathrm{GeV}^2$. This fit is compatible with the existing data both at higher and lower energies, considering the mentioned systematic uncertainties.

We are very grateful to many individuals at the National Accelerator Laboratory who, with their generous assistance at the various stages of this experiment, contributed to its success. In particular, we wish to thank the members of the Internal Target Laboratory for their help in installing and operating the target. We are also grateful to D. Nitz for his help during part of the running of the experiment.

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[7] V. Bartenev et al., to be published.

[8] The correction for nuclear interactions was taken from D. F. Measday and C. Richard-Serre, CERN Report No. CERN 69-17, 1969 (unpublished).

[9] The ratio of the real to imaginary part of the p-p scattering amplitude, ρ, was parametrized as $\rho = -0.654 + [0.384 - 0.047 \log_{10}(P_0)] \cdot \log_{10}(P_0)$ consistent with dispersion relation calculations based on the recent ISR data; see, for instance, C. Bourrely and J. Fischer, CERN Preprint

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Table I. Energy Dependence of b(s).

p_{lab} (GeV/c)	b(s) $(GeV/c)^{-2}$	p_{lab} (GeV)	b(s) $(GeV/c)^{-2}$
8.5	8.72±0.38	175	11.52±0.11
11	9.03±0.30	199	11.56±0.12
50	10.70±0.18	239	11.61±0.19
58	10.83±0.07	270	11.69±0.10
78	10.84±0.20	312	11.90±0.28
102	11.24±0.13	348	11.96±0.15
128	11.30±0.20	371	11.87±0.15
150	11.57±0.23	396	11.77±0.10

The momentum bins are ~20 GeV/c wide centered at the given p_{lab} except for the 8.5 and 11 GeV/c points which have widths of ~1 and 4 GeV/c respectively.
Δb (syst) = ±0.2, independent of s. The errors in b(s) reflect both the statistical and background subtraction uncertainty.

FIGURE CAPTIONS

Fig. 1. Typical pulse-height spectrum from a 2-mm thick solid-state detector at 50 GeV incident energy; the proton energy is approximately 10 MeV. (a) Original spectrum, (b) Spectrum after correction for "room" background.

Fig. 2. The slope of the diffraction peak, $b(s)$ for $|t| \leq 0.12 (\mathrm{GeV/c})^2$, as a function of the square of the c.m. energy. The solid line is a fit of $b(s) = b_0 + 2\alpha' \ln(s/s_0)$ only to our data points for $s \gtrsim 100\ \mathrm{GeV}^2$.

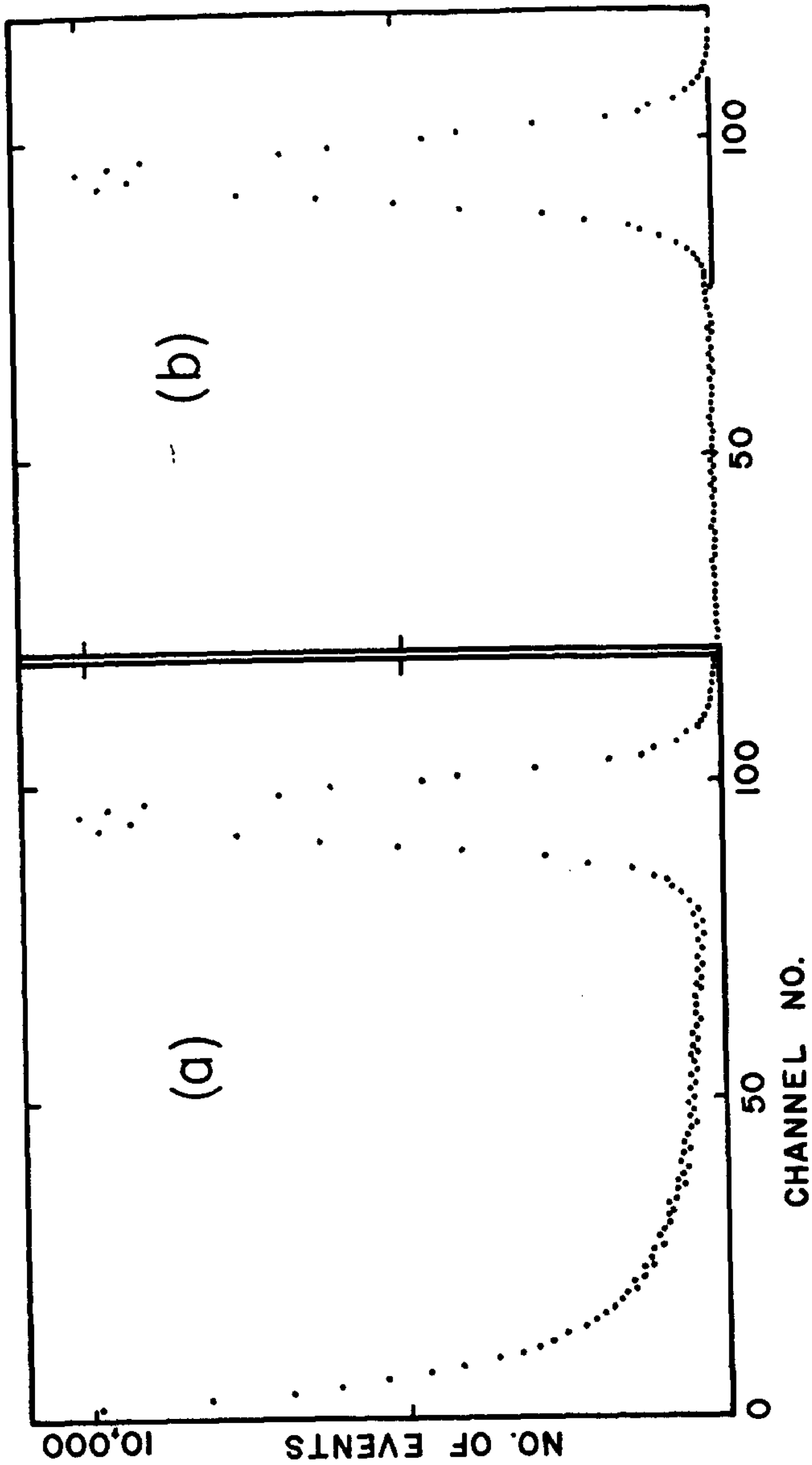
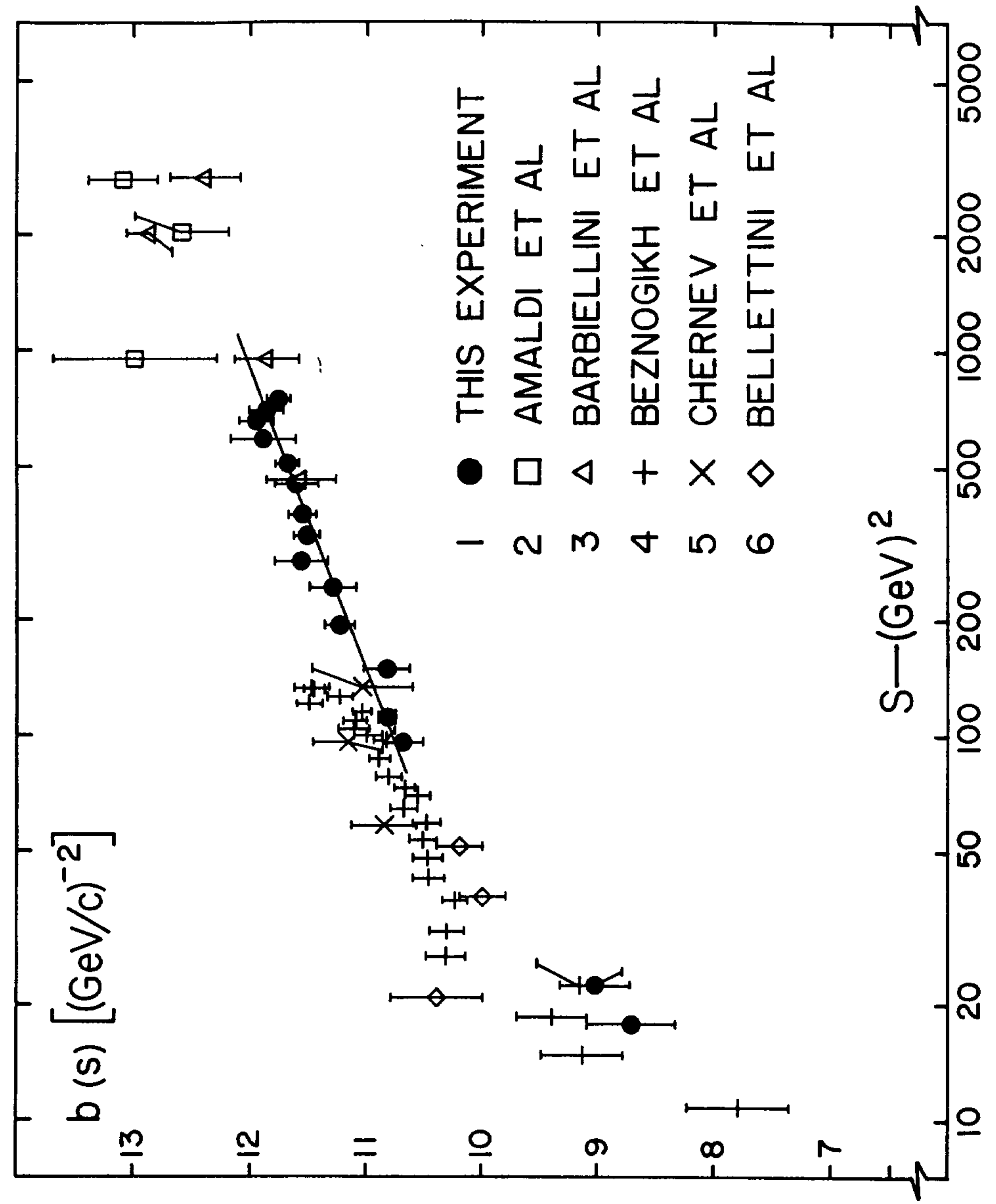


Fig. 1


b (s) [(GeV/c)$^{-2}$]
S—(GeV)^2
1 ● THIS EXPERIMENT
2 □ AMALDI ET AL
3 △ BARBIELLINI ET AL
4 + BEZNOGIKH ET AL
5 × CHERNEV ET AL
6 ◇ BELLETTINI ET AL
13
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100
200
500
1000
2000
5000

Fig. 2