manuscripta math. 82, 407 - 415 (1994)

manuscripta mathematica

Regularity of p-harmonic maps from the p-dimensional ball into a sphere

Paweł Strzelecki[1]

We prove that, for $p \geq 2$, all weakly p-harmonic maps $u = (u_1, \dots, u_n)$ from the p-dimensional ball into a sphere, i.e. weak solutions of class $W^{1,p}$ of the constrained elliptic system

$$-\mathrm{div}\,(|\nabla u|^{p-2}\nabla u_i) = u_i|\nabla u|^p$$
$$\sum (u_i)^2 = 1,$$

are Hölder continuous. This result is an analogue of an earlier theorem of F. Hélein for the case $p = 2$.

1. Introduction

Let $B^p = \{x \in \mathbb{R}^p : \sum (x_i)^2 < 1\}$ denote the unit p-dimensional ball, and write S^{n-1} to denote the unit sphere in $\mathbb{R}^n$. Define the functional

$$I_p(u) = \int_{B^p} |\nabla u(x)|^p \, dx \qquad \text{for } u \in W^{1,p}(B^p, S^{n-1}).$$

We wish to investigate those mappings which are critical points of I_p.

Definition. By a weakly p-harmonic map (or simply p-harmonic map) we mean here any u belonging to the Sobolev space

$$W^{1,p}(B^p, S^{n-1}) \equiv \{f = (f_1, \dots, f_n) \mid f_i \in W^{1,p}(B^p) \text{ and } \sum_{i=1}^{n} (f_i(x))^2 = 1 \text{ a.e.}\},$$

and being a critical point of the functional I_p in the class of functions having fixed trace (equal to that of u) on ∂B^p, with respect to variations on S^{n-1}, i.e.

$$\left.\frac{d}{dt}\right|_{t=0} I_p\left(\frac{u + t\psi}{|u + t\psi|}\right) = 0 \qquad \text{for all } \psi \in C_0^\infty(B^p, \mathbb{R}^n). \tag{1}$$

[1] This work is partially supported by KBN grant no. 2 1057 91 01

Condition (1) is easily checked to be equivalent to the fact that $u \in W^{1,p}(B^p, S^{n-1})$ is a weak solution to the Euler-Lagrange elliptic system

$$-\mathrm{div}\,(|\nabla u|^{p-2}\nabla u_i) = u_i|\nabla u|^p, \qquad i = 1, 2, \dots, n. \tag{2}$$

More precisely, the integral identity

$$\int_B |\nabla u|^{p-2}\nabla u_i \cdot \nabla \psi_i \, dx = \int_B \psi_i u_i |\nabla u|^p \, dx, \tag{3}$$

holds true for all $i = 1, \dots, n$, and for every $\psi = (\psi_1, \dots, \psi_n) \in C_0^\infty(B, \mathbb{R}^n)$. Here and everywhere below,

$$|\nabla u|^2 = \sum_{i=1}^{n}\sum_{j=1}^{p}\left(\frac{\partial u_i}{\partial x_j}\right)^2.$$

One can find solutions of (2) which are minimizers of I_p in the class of mappings with fixed boundary values. However, weakly p-harmonic maps do not have to be minimizers of I_p. It is also possible to define and consider p-harmonic maps $u : M^m \to N^n$ between Riemannian manifolds.

In general, weakly p-harmonic maps do not have to be continuous: the familiar map $x \mapsto x/|x|$ from the unit ball B^n to its boundary $\partial B^n \equiv S^{n-1}$ is singular at 0 and weakly p-harmonic for all $p \in [1, n)$. However, there are lots of results about regularity and partial regularity of weakly p-harmonic maps under various additional assumptions. Let us mention below just a few; the list is obviously far from being complete.

M. Fuchs [7], R. Hardt and F.H. Lin [11], and S. Luckhaus [16] proved indepedently a theorem stating that *minimizing* p-harmonic maps $u : M^m \to N^n$ are of class $C^{1,\alpha}$, $0 < \alpha < 1$, outside a set of Hausdorff dimension $m - [p] - 1$ (that was a generalization af an earlier result of R. Schoen and K. Uhlenbeck [19] concerning the case $p = 2$ of minimizing harmonic maps). In the series of his recent papers [12], [13], [14] F. Hélein proved that any weakly harmonic map $f : M \to N$ defined on a two-dimensional Riemannian manifold M is continuous; [12] contains the proof for $N = S^{n-1}$, [13] concerns the case when N is a compact manifold with a Lie group of isometries acting transitively, and [14] deals with the case of arbitrary compact Riemannian N. By standard elliptic regularity methods, continuity of a weakly harmonic map implies its C^∞-smoothness. L.C. Evans [3] and F. Bethuel [1] generalized Hélein's result to the case of the so-called *stationary* harmonic maps on n-dimensional manifolds, $n \geq 2$, proving their regularity outside a singular set of $(n-2)$-dimensional Hausdorff measure zero. The interested reader is referred to the papers mentioned above for brief lists of other results in the field.

In this paper we give a short proof of an analogue of the main result of [12], namely of the following

Theorem 1. *Let u be a weakly p-harmonic map from the p-dimensional ball unit ball $B^p \equiv \{x \in \mathbb{R}^p : |x| < 1\}$ into the sphere S^{n-1} of arbitrary dimension $(p \geq 2)$. Then, u is necessarily Hölder continuous on B^p.*

Remark. M. Fuchs in his recent paper [8] has proved (among other things) the same result independently and with different methods.

In the case $p = 2$ this is precisely Hélein's theorem. Note that for *minimizing* p-harmonic maps u our Theorem 1 follows immediately e.g. from [11, Theorem 1]. However, this restrictive assumption about the map u is not needed here.

Our proof heavily relies on the results of Coifman, Lions, Meyer, and Semmes [2] and the fact that the right-hand side of (2) turns out to be an element of the local Hardy space $\mathcal{H}^1_{\text{loc}}$, a proper subspace of L^1 (for $p = 2$ this was noticed and exploited by Hélein [12], [13], [14]). This is a starting point of our proof. In Section 2, for the reader's convenience, we recall an important theorem from [2] and state explicitly some of its consequences (well known in the folklore).

The idea of the remaining part of the proof resembles slightly that of Evans [3]. Here is a brief sketch of our reasoning. First, note that $u \in W^{1,p}(B^p)$ implies $u \in BMO$. Then, exploit the duality between $\mathcal{H}^1(\mathbb{R}^p)$ and $BMO(\mathbb{R}^p)$ to obtain, by appropriate choice of test functions in (3), the inequality

$$\int_{B(x,r)} |\nabla u(y)|^p \, dy \leq \lambda \int_{B(x,2r)} |\nabla u(y)|^p \, dy, \qquad 0 < \lambda < 1,$$

valid for all sufficiently small radii r, and finally apply Dirichlet growth theorem [10], [17]. Section 3 contains all necessary details of that proof.

Notation. For a measurable function w and a measurable set A of positive Lebesgue measure, we write

$$[w]_A \equiv \fint_A w(x)\, dx := \frac{1}{\operatorname{meas} A} \int_A w(x)\, dx$$

to denote the average of w over A.

The standard Sobolev space of functions of class $L^p(\Omega)$ having their first order distributional partial derivatives in $L^p(\Omega)$ is denoted by $W^{1,p}(\Omega)$. If V is a normed vector space of finite dimesion m with a fixed basis, then $W^{1,p}(\Omega, V)$ is the space of mappings

$$u = (u_1, \dots, u_m) : \Omega \to V$$

with all coordinates u_i of class $W^{1,p}(\Omega)$.

$\Lambda^\ell(\mathbb{R}^n)$ denotes the $\binom{n}{\ell}$-dimensional space of all ℓ-covectors in $\mathbb{R}^n$ (with the standard norm and basis).

In all the calculations, C denotes a general constant (depending only on the dimension and integrability exponents) which may change its value from one line to another.

Throughout Section 2, by a slight abuse of notation, p stands for an arbitrary real from $(1, \infty)$, not necessarily an integer.

Acknowledgement. The author is very grateful to Piotr Hajlasz for numerous stimulating conversations about the Hardy spaces and for his helpful comments about the first draft of this paper.

2. Prerequisites for the proof

Definition. A measurable function $f \in L^1(\mathbb{R}^n)$ belongs to the *Hardy space* $\mathcal{H}^1(\mathbb{R}^n)$ if and only if

$$f_* := \sup_{\varepsilon>0} |\varphi_\varepsilon * f| \in L^1(\mathbb{R}^n).$$

Here, $\varphi_\varepsilon(x) := \varepsilon^{-n}\varphi(x/\varepsilon)$, and φ is a fixed function of class $C_0^\infty(B(0,1))$ with $\int \varphi(y)\,dy = 1$. The definition does not depend on the choice of φ (see [5]).

Equivalently, one can define $\mathcal{H}^1(\mathbb{R}^n)$ as the space of those elements of $L^1(\mathbb{R}^n)$, for which all the Riesz transforms $R_j f$, $j = 1, 2, \ldots, n$, are also of class $L^1(\mathbb{R}^n)$. The reader is referred to [9] or [20] for more details. Let us just mention here that $\mathcal{H}^1(\mathbb{R}^n)$ is a Banach space with the norm

$$\|f\|_{\mathcal{H}^1} = \|f\|_{L^1} + \|f_*\|_{L^1}.$$

Moreover, the condition $f \in \mathcal{H}^1(\mathbb{R}^n)$ implies $\int f(y)\,dy = 0$.

C. Fefferman [4], [5] proved that the dual of $\mathcal{H}^1(\mathbb{R}^n)$ is equal to the space of functions of bounded mean oscillation, $BMO(\mathbb{R}^n)$. More precisely, there exists a constant C such that

$$\int_{R^n} h(y)\psi(y)\,dy \leq C\|h\|_{\mathcal{H}^1}\|\psi\|_{BMO}, \tag{4}$$

for all functions $h \in \mathcal{H}^1(\mathbb{R}^n)$ and $\psi \in BMO(\mathbb{R}^n)$.

The interesting paper of S. Müller [18] inspired some of the research reported in [2], in particular the following remarkable theorem.

Theorem 2 (Coifman, Lions, Meyer, Semmes). *Let $u \in W^{1,p}(\mathbb{R}^n)$, $1 < p < \infty$, and assume that $H \in L^{p/(p-1)}(\mathbb{R}^n, \mathbb{R}^n)$ satisfies the condition $\operatorname{div} H = 0$ in $\mathcal{D}'(\mathbb{R}^n)$. Then, $\nabla u \cdot H \in \mathcal{H}^1(\mathbb{R}^n)$, and*

$$\|\nabla u \cdot H\|_{\mathcal{H}^1} \leq C \cdot \|\nabla u\|_{L^p} \cdot \|H\|_{L^{p/(p-1)}} \tag{5}$$

for some constant C depending only on n and p.

The estimate (5) was not explicitly stated in [2], but follows from the proof presented there (cf. also [3, Section 2]).

Let us now make explicit a corollary of the above theorem (more or less well known to specialists).

Corollary 3. *Let Ω be a ball in $\mathbb{R}^n$. Assume that $u \in W^{1,p}(\Omega)$, $1 < p < \infty$, and that $H \in L^{p/(p-1)}(\Omega, \mathbb{R}^n)$ satisfies the condition $\operatorname{div} H = 0$ in $\mathcal{D}'(\Omega)$. Then, one can find a function $h \in \mathcal{H}^1(\mathbb{R}^n)$ such that*

$$h(x) = \nabla u(x) \cdot H(x), \qquad x \in \Omega,$$

and

$$\|h\|_{\mathcal{H}^1} \leq C \cdot \|\nabla u\|_{L^p(\Omega)} \cdot \|H\|_{L^{p/(p-1)}(\Omega)}.$$

The constant C does not depend on the size of Ω.

Proof. This is a simple consequence of Theorem 2 and the results of [15, Section 4]. The idea is to extend ∇u to a gradient field on $\mathbb{R}^n$ and H to a divergence free vector field on $\mathbb{R}^n$ without increasing too much the appropriate L^s-norms, and then to apply Theorem 2.

Denote $q = p/(p-1)$. Take the bounded, linear operator

$$T : L^q(\Omega, \Lambda^\ell(\mathbb{R}^n)) \to W^{1,q}(\Omega, \Lambda^{\ell-1}(\mathbb{R}^n)), \qquad \ell = 1, 2, \ldots, n$$

satisfying

$$\omega = T(d\omega) + d(T\omega), \qquad \|T\| \leq C(n, q)$$

for all forms $\omega \in L^q(\Omega, \Lambda^\ell(\mathbb{R}^n))$ such that $d\omega \in L^q(\Omega, \Lambda^{\ell+1}(\mathbb{R}^n))$. (See [15, Section 4] for the precise definition of T.)

Let, for $1 \leq s < \infty$, E_s be the extension operator,

$$E_s : W^{1,s}(\Omega, \Lambda^\ell(\mathbb{R}^n)) \to W^{1,s}_{\text{loc}}(\mathbb{R}^n, \Lambda^\ell(\mathbb{R}^n)),$$

such that $\|\nabla E_s(u)\|_{L^s(R^n)} \leq C(n,s)\|\nabla u\|_{L^s(\Omega)}$. Identify the vector field H with the $(n-1)$-form ω,

$$\omega = \sum_{j=1}^{n} (-1)^{j-1} H_j \underbrace{dx_1 \wedge \ldots \wedge dx_n}_{dx_j \text{ omitted}}, \qquad d\omega \equiv \operatorname{div} H \cdot dx_1 \wedge \ldots \wedge dx_n.$$

It is easy to see that $h = \nabla E_p(u) \cdot d(E_q T(\omega))$ has all the desired properties. Here, as before, we identify the $(n-1)$-form $d(E_q T(\omega))$ with a (divergence free) vector field of class $L^q(\mathbb{R}^n)$. □

3. Proof of Theorem 1

Let us begin with a straightforward calculation proving that the right-hand side of each equation of system (2) can be extended to a function $h_i \in \mathcal{H}^1(\mathbb{R}^p)$. In the case $p = 2$ this crucial observation is due to F. Hélein.

Write $V_i = |\nabla u|^{p-2} \nabla u_i$. The condition $\sum (u_k)^2 = 1$ implies that $\sum u_k \nabla u_k = 0$, hence

$$V_i = \sum_{k=1}^{n} u_k (u_k V_i - u_i V_k) \qquad \text{for } i = 1, 2, \ldots, n.$$

Now, note that (2) implies

$$\operatorname{div}(u_k V_i - u_i V_k) = \nabla u_k \cdot V_i - \nabla u_i \cdot V_k + u_k \operatorname{div} V_i - u_i \operatorname{div} V_k = 0,$$

and therefore

$$\operatorname{div} V_i = \sum_{k=1}^{n} \nabla u_k \cdot (u_k V_i - u_i V_k). \tag{6}$$

This is a starting point for the following energy decay estimate.

Lemma 1. *Let $u \in W^{1,p}(B^p, S^{n-1})$ be a weak solution of (2). Then, there exist $\lambda \in (0,1)$ and $r_0 > 0$ such that*

$$\int_{B^p(x,r)} |\nabla u(y)|^p \, dy \le \lambda \int_{B^p(x,2r)} |\nabla u(y)|^p \, dy \tag{7}$$

for all $x \in B^p(0,1)$ and all $r < \frac{1}{2}\min(r_0, \operatorname{dist}(x, \partial B^p))$.

Proof. Fix $x \in B^p$ and $r < \frac{1}{2}\operatorname{dist}(x, \partial B^p)$. Use Corrolary 3 to construct, for each $i = 1, 2, \ldots, n$, a function $h_i \in \mathcal{H}^1(\mathbb{R}^p)$ satisfying

$$-\operatorname{div}(|\nabla u|^{p-2}\nabla u_i) = h_i \qquad \text{on } B^p(x, 2r),$$

and such that

$$\|h_i\|_{\mathcal{H}^1} \le C \int_{B^p(x,2r)} |\nabla u(y)|^p \, dy. \tag{8}$$

Therefore, for all test functions ψ_i with support contained in $B^p(x, 2r)$,

$$\int_{B^p} |\nabla u(y)|^{p-2} \nabla u_i(y) \cdot \nabla \psi_i(y) \, dy = \int_{B^p} h_i(y) \psi_i(y) \, dy. \tag{9}$$

Write A_r to denote the annulus $B^p(x,2r) \setminus B^p(x,r)$. Choose $\psi_i = \eta^p(u_i - [u_i]_{A_r})$, where $\eta \in C_0^\infty(B^p(x,2r))$ satisfies

$$0 \le \eta(y) \le 1, \qquad |\nabla \eta(y)| \le \frac{C}{r}, \qquad \eta(y) \equiv 1 \text{ for } y \in B^p(x,r).$$

Then, identity (9) leads after a routine calculation to

$$\int_{B^p(x,r)} |\nabla u(y)|^p \, dy \le J_1 + J_2,$$

where

$$J_1 = \sum_{i=1}^{n} \left| \int_{\mathbb{R}^p} h_i(y) \psi_i(y) \, dy \right|,$$

$$J_2 = p \sum_{i=1}^{n} \int_{A_r} |\nabla u(y)|^{p-1} \cdot |\nabla \eta(y)| \cdot |u_i(y) - [u_i]_{A_r}| \, dy.$$

In the second sum, all the integrations are performed over the annulus A_r since $\nabla \eta$ vanishes on $B^p(x,r)$. We apply Hölder inequality and then Poincaré inequality to estimate J_2 in the following way

$$J_2 \le \frac{C}{r}\Big(\int_{A_r} |\nabla u(y)|^p\, dy\Big)^{1-1/p} \sum_{i=1}^{n}\Big(\int_{A_r} |u_i(y) - [u_i]_{A_r}|^p\, dy\Big)^{1/p} \\ \le C \int_{A_r} |\nabla u(y)|^p\, dy. \tag{10}$$

To deal with J_1, we shall prove that $\psi_i \in BMO(\mathbb{R}^p)$ and

$$\|\psi_i\|_{BMO(\mathbb{R}^p)} \le C\Big(\int_{B^p(x,2r)} |\nabla u(y)|^p\, dy\Big)^{1/p}. \tag{11}$$

Indeed, take a cube $Q \subset \mathbb{R}^p$. We apply Poincaré inequality two times: first, to estimate the integral over cube, and then to estimate the one over $Q \cap \{\nabla\eta \neq 0\}$, a subset of A_r. This calculation gives:

$$\begin{aligned} &⨍_Q |\psi_i(y) - [\psi_i]_Q|\, dy \le \Big(⨍_Q |\psi_i(y) - [\psi_i]_Q|^p\, dy\Big)^{1/p} \\ &\le C\,(\operatorname{diam} Q)\Big(⨍_Q |\nabla\psi_i(y)|^p\, dy\Big)^{1/p} \\ &\le \frac{C}{r}\Big(\int_{Q\cap\{\nabla\eta\neq 0\}} |u_i(y) - [u_i]_{A_r}|^p\, dy\Big)^{1/p} + C\Big(\int_{Q\cap\{\eta\neq 0\}} |\nabla u_i(y)|^p\, dy\Big)^{1/p} \\ &\le C\Big(\int_{B^p(x,2r)} |\nabla u(y)|^p\, dy\Big)^{1/p}, \end{aligned}$$

and (11) is proved.

To conclude the proof, note that (4), (8), and (11) imply that

$$J_1 \le C\sum_{i=1}^{n} \|h_i\|_{\mathcal{H}^1(\mathbb{R}^p)} \|\psi_i\|_{BMO(\mathbb{R}^p)} \le C\Big(\int_{B^p(x,2r)} |\nabla u(y)|^p\, dy\Big)^{1+1/p}. \tag{12}$$

Hence, denoting $I(x,r) = \int_{B^p(x,r)} |\nabla u(y)|^p\, dy$, we obtain from (10) and (12) the inequality

$$I(x,r) \le C_0 \cdot (I(x,2r))^{1+1/p} + C_0 \cdot (I(x,2r) - I(x,r)),$$

or, equivalently,

$$I(x,r) \le \frac{C_0}{C_0+1} I(x,2r)\left(1 + (I(x,2r))^{1/p}\right). \tag{13}$$

Now, use absolute continuity of the integral to find r_0 such that for all $z \in B^p$ and all $r < \frac{1}{2}\min(r_0, \operatorname{dist}(z, \partial B^p))$ the integral $I(z,2r)$ does not exceed $(2C_0)^{-p}$. Then, (13) implies that

$$I(x,r) \le \lambda I(x,2r), \qquad \lambda := \frac{2C_0+1}{2C_0+2} \in (0,1).$$

This completes the proof of Lemma 1. □

Proof of Theorem 1. By iterations of inequality (7), Lemma 1 implies that for some positive constants C and β we have

$$\int_{B^p(x,r)} |\nabla u(y)|^p \, dy \leq C \cdot r^\beta \tag{14}$$

for all $x \in B^p(0,1)$ and all sufficiently small r. Inequality (14) allows us to apply Morrey's Dirichlet growth theorem (see [17, Theorem 3.5.2] or [10, Chapter 3, pages 64–65]) and conclude that u is uniformly Hölder continuous with exponent $\alpha = \beta/p$ on compact subsets of B^p.

Remark. Theorem 1 is of course not a final result; we expect that it is possible to generalize the results of Bethuel [1] and prove that stationary p-harmonic maps $u : M^m \to N^n$ between arbitrary compact Riemannian manifolds are of class $C^{1,\alpha}(V)$ for some open $V \subset M^m$ with $H^{m-p}(M \setminus V) = 0$ (or maybe even with $\dim(M \setminus V) < m - p$).

References

1. Bethuel, F.: On the singular set of stationary harmonic maps. Manuscripta Math. **78**, 417-443 (1992)
2. Coifman, R; P. L. Lions, Y. Meyer, S. Semmes: Compacité par compensation et espaces de Hardy. C. R. Acad. Sci. Paris **309**, 945-949 (1989); *and* Compensated compactness and Hardy spaces, Cahiers Mathematiques de la Decision, preprint no. 9123, CEREMADE
3. Evans, L.C.: Partial Regularity for Stationary Harmonic Maps into Spheres. Arch. Rat. Mech. Anal. **116**, 101-113 (1991)
4. Fefferman, C.: Characterizations of bounded mean oscillation. Bull. AMS **77**, 585-587 (1971)
5. Fefferman,C; E. Stein: H^p spaces of several variables. Acta Math. **129**, 137-193 (1972)
6. Fuchs, M.: p-harmonic obstacle problems. Part II: Extensions of maps and applications. Manuscripta Math. **63**, 381-419 (1989)
7. Fuchs, M.: p-harmonic obstacle problems. Part I: Partial regularity theory; Part III: Boundary regularity. Annali Mat. Pura Appl. **156**, 127-180 (1990)
8. Fuchs, M.: The blow-up of p-harmonic maps. Preprint no. 1511, Technische Hochshule Darmstadt 1992; to appear in Manuscripta Math.
9. Garcia-Cuerva, J.; J.L. Rubio de Francia: Weighted Norm Inequalities and Related Topics. Mathematics Studies 116, Elsevier Science Publishers B.V., 1985
10. Giaquinta, M.: Multiple integrals in the Calculus of Variations and Nonlinear Elliptic systems. Annals of Math. Study no. 105, Princeton University Press, Princeton 1983
11. Hardt, R.; F. H. Lin: Mappings minimizing the L^p norm of the gradient. Comm. Pure Appl. Math. **40**, 555-588 (1987)
12. Hélein, F.: Regularité des applications faiblement harmoniques entre une surface et une sphère. C. R. Acad. Sci. Paris **311**, 519-524 (1990)
13. Hélein, F.: Regularity of weakly harmonic maps from a surface into a manifold with symmetries. Manuscripta Math. **70**, 203-218 (1991)

14. Hélein, F.: Regularité des applications faiblement harmoniques entre une surface et une variètè riemannienne. C. R. Acad. Sci. Paris **312**, 591-596 (1991)
15. Iwaniec, T.; A. Lutoborski: Integral estimates for null Lagrangians. Preprint, Syracuse University 1992 (to appear in Arch. Rat. Mech. Anal.)
16. Luckhaus, S.: Partial Hölder continuity for minima of certain energies among maps into a Riemannian manifold. Indiana Univ. Math. J. **37**, no. 2, 346-367 (1988)
17. Morrey, C.B.: Multiple integrals in the calculus of variations. Springer Verlag 1968.
18. Müller, S.: Higher integrability of determinants and weak convergence in L^1. J. Reine Angew. Math. **412**, 20-34 (1990)
19. Schoen, R.; K. Uhlenbeck: A regularity theory for harmonic maps. J. Diff. Geom. **17**, 307-335 (1982)
20. Torchinsky, A.: Real-Variable Methods in Harmonic Analysis. Acad. Press 1986

Paweł Strzelecki
Instytut Matematyki
Uniwersytet Warszawski
ul. Banacha 2
02–097 Warszawa
Poland
email: pawelst@mimuw.edu.pl

This article was processed by the author
using the Springer-Verlag TEX mamath macro package 1990.

(Received August 11, 1993;
in revised form November 9, 1993)