Nucleophilic Substitution onto Poly(methyl methacrylate). 2. The Reaction of Organolithium Compounds as a General Route to Ketonic Model Copolymers

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ABSTRACT: The reaction of organolithium reagents RCH_2Li (R = SC_6H_5 (THF), SO_2CH_3 (DMSO), $SO_2N(CH_3)_2$ (THF + HMPA)) with poly(methyl methacrylate) (PMMA) has been investigated as a general route to ketonic copolymers. Using monomeric and dimeric model compounds as references, modified PMMA were characterized by IR, UV, and NMR spectroscopy, carbon acidity ($COCH_2R$), and molecular weight measurements. At room temperature nucleophilic substitution occurs quantitatively and selectively on the ester function without any degradation, cross-linking, or side reaction, and it leads to the clean introduction of the $COCH_2R$ function in the PMMA chain up to a molar fraction of 0.6 (stoichiometric ratio two RCH_2Li for one ester function). In the poly(alkyl methacrylate) series, this simple reaction affords a versatile preparation of model copolymers of the same $\overline{DP}_n$ and tacticity as the precursor polymer. Oxidation reactions at the sulfur group on copolymers may be selectively and quantitatively performed (S → SO → SO_2), allowing interconversion between homologous copolymers.

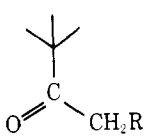
(I) Introduction

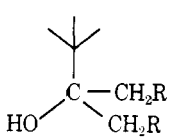
We have focused our attention on the reaction of primary organolithium compounds with poly(methyl methacrylate) (PMMA) with two different aims: (a) the evaluation of the reactivity of the ester function belonging to a well-defined polymeric chain; (b) the study of a general method of synthesis of ketonic functionalized MMA model copolymers. Because of their high versatility in organic chemistry, we have investigated a series of homologous primary organolithium compounds, stabilized by sulfur groups at different oxidation levels: phenylthiomethyllithium[1] ($C_6H_5SCH_2Li$); methylsulfinylmethyllithium[2,3] (CH_3SOCH_2Li); methylsulfonylmethyllithium[2c,4,5] ($CH_3SO_2CH_2Li$); dimethylaminosulfonylmethyllithium[2c] ($(CH_3)_2NSO_2CH_2Li$); methoxysulfonylmethyllithium[6] ($CH_3OSO_2CH_2Li$).

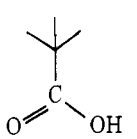
Some preliminary results have already been published;[7,8] the present article is devoted to a survey of these nucleophilic substitutions onto PMMA as a general method of preparing well-defined MMA copolymers.

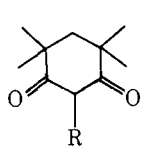
(II) Results

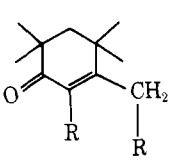
According to literature data[1-6,9-11] and to our previous results on the PMMA/$CH_3SOCH_2^-Na^+$/DMSO system,[7] no less than five types of new structural units may be expected from the reaction of a primary organolithium compound RCH_2Li with PMMA (A units):


ketone B[12]

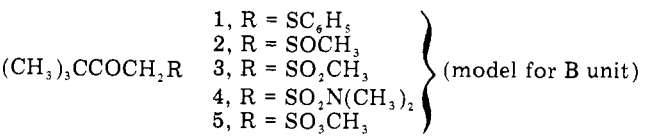

tertiary alcohol C

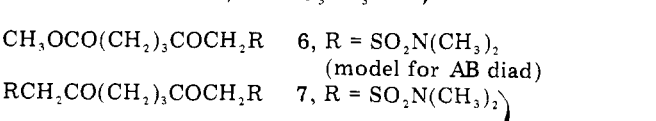

carboxylic acid D

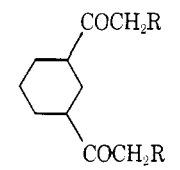

cyclic β-diketone E

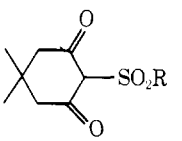

cyclic α-β ethylenic ketone F

We have studied the chemical structure of the derived MMA copolymers ($\overline{DS}_m$ and $\overline{DS}_w$, molar and weight average fraction of substituted units) by elemental analysis and spectrometric (^1H NMR, IR, and UV) and acidity (potentiometry) measurements, using the following model compounds as references:

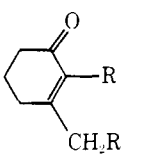








9, R = SO_2CH_3 (model for E unit)



10, R = SO_2CH_3 (model for F unit)

(1) Nuclear Magnetic Resonance Spectroscopy. ^1H-NMR spectra of the copolymers obtained at 100 MHz in $CDCl_3$ at 30 °C (or pyridin-d_5 at 90 °C for the highest $\overline{DS}_m$) allow the determination of copolymer composition, using both the OCH_3 ester singlet at 3.6 ppm and the peak resonance of the substituted group R: multiplet between 7.0 and 7.7 ppm for R = SC_6H_5; singlet at 2.7, 3.1, 2.9 ppm for R = $SOCH_3$, SO_2CH_3, and $SO_2N(CH_3)_2$, respectively. In general, there is a partial overlap of the resonance area of the acidic methylene group $COCH_2R$ (4.0–4.3 ppm) with that of the residual ester group. The accuracy is about 5%. A good agreement between the substitution degrees deduced from the OCH_3 and from R resonance patterns is a strong argument in favor of a simple binary structure: residual ester and new $COCH_2R$ groups. On the other hand, ^1H-NMR spectroscopy is not sensitive enough

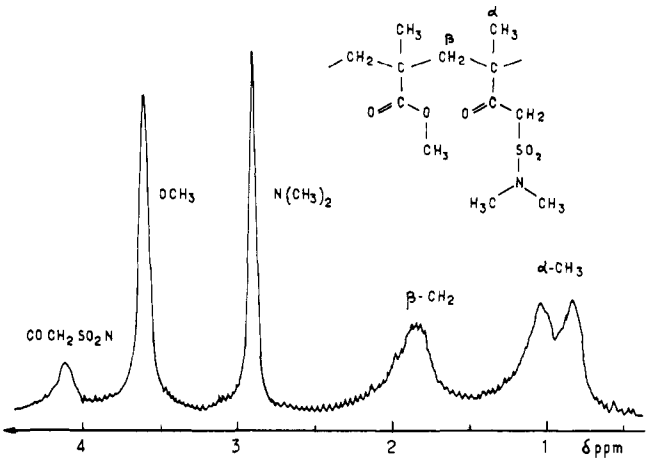


Figure 1. ^{1}H-NMR spectrum ($CDCl_3$, 30 °C) of modified radical PMMA (R = $SO_2N(CH_3)_2$, $\overline{DS}_m$ = 0.28).

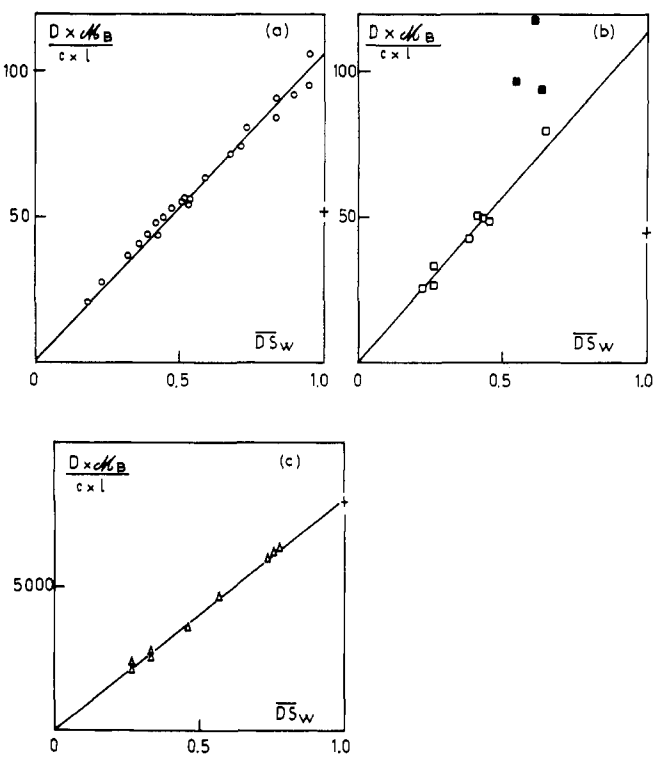


Figure 2. Correlation between UV absorbances and composition of modified PMMA. (a) and (b): n → π* transition of the $COCH_2R$ chromophore for R = $SO_2N(CH_3)_2$ (λ_{max} 296 nm in ACN) and R = SO_2CH_3 (λ_{max} 286 nm in TFE). (c): π → π* transition of the $COCH_2SC_6H_5$ chromophore (λ_{max} 254 nm in dioxane). The plus symbols are related to the monomeric models $(CH_3)_3CCOCH_2R$.

to afford an accurate identification and determination of small amounts of cyclic units, in spite of their quite specific resonance patterns (see models **9** and **10** in the Experimental Section). Moreover at 30 °C, neither the OCH_3 nor the R radical resonance peaks show a clear splitting with respect to compositional or configurational effects, and the poorly resolved α-CH_3 pattern does not allow direct measurements of the unit distribution in the copolymers.

(2) Infrared Spectroscopy. IR spectroscopy was used for qualitative analysis of the copolymers which show both the ν(C=O) ester carbonyl absorption at 1730 cm^{-1} [13] and the specific absorptions of the substituted groups $COCH_2R$ (models **1–8**): ν(C=O) keto carbonyl around 1720 cm^{-1},[14,15a] ν(SO_2) at 1340–1355 and 1135–1175 cm^{-1},[14] ν(C_6H_5) at 1580, 1475, 730 cm^{-1},[14] for instance (see Experimental Section). IR is most useful for the identification of cyclic structures owing to their characteristic absorptions: ν(conjugated C=O) at 1695 cm^{-1} and ν(C=C) at 1610 cm^{-1} for cyclic α–β ethylenic ketone[14,15a] (model **10**); ν(conjugated C=O) at 1720 cm^{-1} and ν(C=O + C=C) at 1675 and 1590 cm^{-1} for the cyclic β-diketone[15a] (model **9**).

Table I
Characteristic UV Transitions of the Various Model Compounds

Model compd	UV transition	Solvent	λ_{max}, nm	ε, L mol^{-1} cm^{-1}
1	C=O, n → π*	Dioxane	310	168
	"$COCH_2SC_6H_5$", π → π* [12d]		254	7900
2–8	C=O, n → π*	Acetonitrile	291 ± 2	36–88
		Trifluoroethanol	288 ± 2	36–88
9	Conjugated C=O, π → π* [15b]	Trifluoroethanol	272	14000
10			238	11000

(3) Ultraviolet Spectrometry. The UV transitions of the $COCH_2R$ chromophore have been studied first on model compounds, Table I.

The UV spectra of the copolymers (dioxane, ACN, or TFE solution according to their solubility) exhibit the same features as the model compounds, with no significant shifts of the λ_{max} and with no deviation from Beer's law. If the UV absorption of copolymers depends only on the total concentration of the chromophores, the optical densities D and composition $\overline{DS}_w$ (determined independently as discussed below) may be related through the simple relationship:

$$DM_B/cl = \epsilon_{cop.}\overline{DS}_w$$

where M_B is the molecular weight of the substituted unit B, c is the weight concentration of the solution, and $\epsilon_{cop.}$ is the molar absorptivity per chromophore in the copolymer chain.

Our experimental results plotted in Figures 2a–c lead us to the following conclusions: The n → π* transition of the $COCH_2R$ chromophore (when R = SO_2CH_3 and $SO_2N(CH_3)_2$) in the copolymers is not sensitive to unit distribution as shown by the independence of $\epsilon_{cop.}$ on composition, but it is characterized by a significant hyperchromicity with respect to the model compounds; for R = $SO_2N(CH_3)_2$ for instance, at λ 296 nm in ACN solution, $\epsilon_{cop.}$ = 106 as compared to ε = 52 for monofunctional models **4** and **6**, and ε = 86 ± 2 for difunctional models **7** and **8**. The deviation observed for $\overline{DS}_w > 0.55$ in the case of R = SO_2CH_3 (Figure 2b) arises from the presence of small amounts of cyclic conjugated units of very strong specific absorption producing band overlaps. The π → π* transition of the $COCH_2SC_6H_5$ chromophore in dioxane does not show any "polymer effect": $\epsilon_{cop.} = \epsilon_{model\ 1}$ = 8000 (Figure 2c).

(4) Acidity Measurements by Potentiometry in DMF Solution. Potentiometric titrations in DMF solution using tetrabutylammonium hydroxide or, better, sodium methoxide as base allow quantitative determinations of the total acidity of the modified PMMA with an accuracy of about 2%; carboxylic acid D and carbon acid units B, E, and F afford each one acidity equivalent, as checked on models **2** to **10.**

In spite of their differences in pK_A values,[16] we never could detect the presence of acidic groups of different strength on the potentiometric curves of the copolymers, but this feature is not to be taken as a final argument in favor of a single kind of acidic group like B units for instance. A total acidity higher than that expected from the amount of linear ketonic B units

Table II
Structural Characterization of Modified PMMA

Run	R	Molar fraction based on: Elemental anal. + potentiometry — Ketone	Elemental anal. + potentiometry — Carbox. acid	NMR spectroscopy[a] — Ketone	NMR spectroscopy[a] — Ester	NMR spectroscopy[a] — Carbox. acid[b]
R-32	SO_2CH_3	0.622 ± 0.012	0	0.61 ± 0.03	0.36 ± 0.02	0
R-36	SC_6H_5	0.442 ± 0.009	0	0.45 ± 0.02	0.56 ± 0.03	0
R-17	$SO_2N(CH_3)_2$	0.282 ± 0.006	0	0.30 ± 0.02	0.72 ± 0.04	0
R-4	$SO_2N(CH_3)_2$[c]	0.526 ± 0.010	0.109 ± 0.003	0.51 ± 0.05	0.42 ± 0.05	0.07 ± 0.05
	$SO_2N(CH_3)_2$[d]	0.517 ± 0.0010	0	0.50 ± 0.05	0.52 ± 0.05	0

[a] The five backbone hydrogen atoms are used for normalization of the different resonance areas. [b] Calculated as 1 − [ketone] − [ester]. [c] Before methylation of the sample. [d] After methylation of the sample.

Table III
Reaction of $(CH_3)_2NSO_2CH_2Li$ with PMMA in Homogeneous THF–HMPA Solution

Run[c]	[RCH_2Li]/[ester]	T, °C	Time, h	Molar fraction of: Keto units	Molar fraction of: Carbox. acids	Yield,[a] %	dn/dc,[b] dL/g	$\bar{M}_w \times 10^{-5}$: Calcd	$\bar{M}_w \times 10^{-5}$: Found
R-1	1.00	25	9.0	0.407	1.4×10^{-2}	81.4	0.0827		
R-2	1.20	25	4.0	0.434	4.0×10^{-2}	72.4			
R-3	1.20	60	10.0	0.400	9.9×10^{-2}	66.6		1.31	1.12
R-4	1.20	60	18.0	0.526	10.9×10^{-2}	87.6	0.0872		
R-5	1.50	25	66.0	0.573	4.6×10^{-2}	76.4	0.0870	1.46	1.04
R-6	1.60	25	4.0	0.455	4.8×10^{-2}	56.3		1.36	1.39
R-7	2.00	25	4.0	0.453	5.1×10^{-2}	45.3	0.0838	1.35	1.42
R-8	2.50	25	21.0	0.590	8.1×10^{-2}	59.0	0.0886	1.47	1.36
R-9	2.50	60	115.0	0.729	12.7×10^{-2}	72.9	0.0941		
R-10	3.00	60	24.0	0.783		78.3	0.0925	1.64	1.01
R-11	3.00	60	60.0	0.818		81.8	0.0964	1.67	0.57
I-1	0.74	25	4.0	0.363	0	98.1	0.0793		
I-2	2.50	25	20.0	0.856	0	85.6	0.0932	3.02	1.14
I-3	3.00	60	24.0	0.948	0	94.8	0.0958		
S-1	0.74	25	4.0	0.226	5.2×10^{-2}	61.1			
S-2	3.00	60	24.0	0.734	14.9×10^{-2}	73.4		2.94	0.68
C-1	2.00	25	24.0	0.365	0	77.6			
A-1	2.00	25	17.0	0.920	0	92.0			

[a] Yield % = 100(keto units)$_{exptl}$/(keto units)$_{theor}$. [b] Measured in DMF solution at 25 °C, for λ 5460 Å. [c] R = radical PMMA (I = 0.05, H = 0.37, S = 0.58); I, S = iso- and syndiotactic PMMA, respectively (triad purity ≥0.97); C = azeotropic radical sty-MMA copolymer (0.47 MMA mole fraction); A = radical poly(methyl acrylate).

(deduced from elemental analysis and NMR spectroscopy) may be attributed to carboxylic acid D units. An overnight treatment of the copolymer at room temperature with a slight excess of diazomethane allows a selective and quantitative methylation of the carboxylic acid functions. We have checked on 3,3-dimethyl-1-dimethylaminosulfonyl butanone (model 4) that the methylation, which should have led to the enol methyl ether,[17] does not occur to any appreciable extent in our experimental conditions:

$$-COCH_2SO_2N(CH_3)_2 \underset{H^+}{\overset{CH_2N_2}{\rightleftharpoons}} -\underset{\displaystyle OCH_3}{\underset{|}{C}}{=}CHSO_2N(CH_3)_2$$

The acidity determinations before and after selective methylation of the copolymer afford a fair estimation of carboxylic acid unit content (decrease of total acidity and simultaneous increase of the OCH_3 ester singlet in the ^1H-NMR spectrum).

Combination of elemental analysis and spectrometric and potentiometric measurements leads to an accurate determination of copolymer composition, as shown by the good self-consistency observed between the various methods (Table II).

Our experimental results are given in Tables III–VI.

(III) Discussion

(1) General Scheme of the Overall Reaction of a Primary Stabilized Organolithium Compound with PMMA.

Taking into account literature data related to monoesters[2,3,5,9] and 1,3-diesters,[4,10,11] the overall reaction of an organolithium compound RCH_2Li with PMMA may be described as in Table VII.

In no case does the process stop at the neutral keto stage, as a result of the initial S_N2 step (reaction 1), but it proceeds further through reactions 2–8. Reaction 2: keto–enolate formation through proton abstraction[2,3,5] by the most basic RCH_2Li species ($pK_A(COCH_2R) < pK_A(CH_3OH) < pK_A(RCH_3)$). Reaction 3: tertiary alcoholate formation by carbonyl addition.[9] Reaction 4: O-alkyl scission leading to carboxylate functions. Reaction 5: intramolecular cyclization in an ester–alcoholate diad into a δ-lactone ring, which may further react with RCH_2Li, leading to a keto–alcoholate diad. Reaction 6: classical open chain–hemiacetal ring tautomerism[18] characteristic of tertiary δ ketol structures. Reaction 7: intramolecular cyclization in an ester–ketoenolate diad into a β-diketo ring.[4,10] Reaction 8: intramolecular cyclization in a diketo–enolate diad into an α,β-ethylenic cyclic ketone.[11]

The most important feature of this general scheme is that the initial step always leads to an anionic species (ketoenolate or tertiary alcoholate), which gives to the macromolecular chain a strong anionic character. This effect restricts the solubility of the substituted PMMA to highly dipolar aprotic solvents (DMSO, HMPA), and it also implies autoretarded kinetics.[7,8] Within this general framework the various systems under study present only small differences, and they may be discussed all together from a mechanistic point of view.

Table IV
Reaction of $(CH_3)_2NSO_2CH_2Li$ with PMMA in Heterogeneous THF Solution

Run	$[RCH_2Li]/[ester]$	T, °C	Time, h	Molar fraction of		Yield,[a] %	dn/dc[b] dL/g	$\bar{M}_w \times 10^{-5}$	
				Keto units	Carbox. acids			Calcd	Found
R-12	0.324	25	2.5	0.138	0	94.8	0.0702	1.08	1.14
R-13	0.500	25	2.5	0.201	0	83.7			
R-14	0.596	25	2.5	0.224	0	81.5	0.0755	1.15	1.15
R-15	0.626	60	3.5	0.299	0.5×10^{-2}	95.5	0.0765	1.22	1.29
R-16	1.00	25	2.5	0.240	2.1×10^{-2}	51.4			
R-17[c]	1.00	25	4.0	0.280		56.0	0.0772	1.19	1.25
R-18	1.00	25	17.0	0.322		64.4	0.0794		
R-19	1.00	25	28.0	0.366	2.9×10^{-2}	73.2	0.0796	1.28	1.43
R-20[d]	1.20	25	40.0	0.376		63.2	0.0810	1.28	1.38
I-4	0.626	60	3.5	0.302		96.5			

[a,b] See Table III. [c] Reaction carried out in the presence of stoichiometric amounts of tetramethylethylenediamine. [d] Dimethoxyethane used instead of THF as reaction medium.

Table V
Reaction of $CH_3SO_2CH_2Li$ with PMMA in Homogeneous THF–DMSO Solution at 25 °C

Run	$[RCH_2Li]/[ester]$	Time, h	Molar fraction of keto units	Yield,[a] %	dn/dc,[b] dL/g	$\bar{M}_w \times 10^{-5}$	
						Calcd	Found
R-21	0.50	2.5	0.153	61.2	0.0748	1.05	1.08
R-22	0.70	13.5	0.287	82.0	0.0845	1.13	1.44
R-23	0.80	0.3	0.284	71.0	0.0825		
R-24	0.80	0.8	0.322	80.5	0.0867		
R-25	0.80	1.5	0.339	84.7	0.0875		
R-26	0.80	24.0	0.388	97.0			
R-27	1.00	17.0	0.515	100.0	0.0917		
R-28	1.20	1.0	0.316	52.6		1.14	1.05
R-29	1.20	3.0	0.356	59.3			
R-30	1.20	7.0	0.430	71.6	0.0905	1.21	1.34
R-31	1.50	4.0	0.517	69.0			
R-32	2.00	40.0	0.622	62.2	0.107	1.32	1.28
R-33[c]	3.00	24.0	0.736	73.6			
I-5	1.20	4.0	0.550	91.5	0.0960		
S-3	1.20	4.0	0.398	66.5			
C-2	2.50	24.0	1.00	100.0			
A-2	1.20	4.0	0.553	92.2			

[a,b] See Table III. [c] Reaction temperature, 60 °C.

(2) Ketoenolate vs. Tertiary Alcoholate Formation. These two competitive reactions are functions of the relative basicity and nucleophilicity of the organolithium compound RCH_2Li on one hand and on the structure and acidity of the β-functionalized ketone $COCH_2R$ on the other hand. In all cases, the reaction on PMMA straightly proceeds through steps 1 and 2 of the general scheme (Table VII) with selective formation of the keto enolate B^-.

$$-\overset{O}{\overset{\|}{C}}-OCH_3 + 2RCH_2^- \rightarrow CH_3O^- + RCH_3 + -\overset{O}{\overset{\|}{C}}-\bar{C}HR \ (B^-)$$

This was quite expected for $CH_3S(O)_xCH_2Li$ ($x = 1, 2$) and $(CH_3)_2NSO_2CH_2Li$ according to literature data[2-5] and to our previous studies[7] but not for the system $C_6H_5SCH_2Li$/PMMA. At −25 °C, methyl decanoate undergoes a twofold addition with $C_6H_5SCH_2Li$, giving bisphenylthiomethylcarbinol with a yield of 73%.[9] In a similar way, we have shown that the reaction of $C_6H_5SCH_2Li$ with methyl pivalate at 25 °C for $(C_6H_5SCH_2Li)/(ester) = 2$ is quantitative, and that about 15% of the ester is converted into the tertiary alcohol. Thus the selective formation of the ketoenolate for the system $C_6H_5SCH_2Li$/PMMA has to be considered as a specific feature of the polymeric chain; it may be tentatively assigned to the increased steric hindrance around the keto function in the macromolecular chain, which favors proton abstraction with respect to carbonyl addition.

(3) Intramolecular Cyclization Reactions. Intramolecular cyclizations readily occur during the condensation of dimethyl sulfoxide and dimethyl sulfone with 1,2- or 1,3-aromatic and aliphatic esters (steps 7 and 8 of the general scheme) but may be inhibited by steric hindrance. In most cases they lead to the α–β ethylenic ketone rather than to the β-diketone,[19] which may be considered as an intermediate.[11]

The comparison of spectrometric (IR and UV) and potentiometric data between the cyclic model molecules **9** and **10** and the substituted PMMA leads to the following conclusions: No cyclization occurs during the reaction of $(CH_3)_2NSO_2CH_2Li$ or $C_6H_5SCH_2Li$ with PMMA. This feature may be correlated with the lack of cyclization we noticed in the model systems $(CH_3)_2NSO_2CH_2Li$/dimethyl glutarate or 1,3-dimethyl-1,3-cyclohexane dicarboxylate/THF, 25 °C, for $[RCH_2Li]/[ester] = 1$ or 2 (synthesis of models **7** and **8**). In the case of $CH_3SO_2CH_2Li$, the UV spectra of the substituted PMMA in TFE definitely show a weak absorption around 238 nm, which may be assigned to the $\pi \rightarrow \pi^*$ transition of a cyclic conjugated ketone occurring in very low amounts (molar fraction ≤ 0.02). This is in sharp contrast with the behavior of the model system $CH_3SO_2CH_2Li$/dimethyl glutarate/DMSO, 25 °C, which readily leads to the expected cyclic α–β ethylenic ketone for $[RCH_2Li]/[ester] = 2$ (model **10**).

The lack of any significant cyclization during the substi-

Table VI
Reaction of $C_6H_5SCH_2Li$ with PMMA in THF Solution at 25 °C

Run	$[RCH_2Li]/[ester]$	Time, h	Molar fraction of keto units	Yield,[a] %	dn/dc,[b] dL/g	$\overline{M}_w \times 10^{-5}$ Calcd	$\overline{M}_w \times 10^{-5}$ Found
R-34	0.60	3.5	0.162	54.0	0.115	1.09	1.05
R-35	0.70	7.0	0.307	87.7	0.123	1.23	1.41
R-35	1.00	15.0	0.440	88.0			
R-37	1.50	24.0	0.623	83.1	0.159	1.50	1.60
R-38	2.00	24.0	0.801	80.1	0.1796	1.66	1.81

[a] See Table III. [b] Measured in dioxane solution at 25 °C, for λ 5460 Å.

tution on PMMA may appear a little surprising. The differences between our reaction conditions and those reported in literature for cyclization reactions[4,11] (mainly the use of lithium instead of sodium and potassium as counterions, and the lack of any protic solvent) do not seem sufficient to give a full account for the experimental data. It is difficult to assign the inhibition of the cyclization to steric hindrance only, since numerous intramolecular cyclizations on a polymethacrylic backbone are well known, chiefly for isotactic chains.[20,21] Since cyclization in a disubstituted diad of PMMA does occur in protic media (NaOH 0.1 N or MeONa/MeOH 0.1 N),[22] the strong influence of the nature of the solvent has to be emphasized; the process may be highly favored in protic medium by OH^- solvation in the key elimination step of the overall cyclization reaction.[23]

(4) *O*-Alkyl Scission. Formation of Carboxylate Units D. The uncommon *O*-alkyl scission of the ester group by nucleophilic reagents occurs mainly with highly sterically hindered reagents.[24] We have actually observed carboxylate formation in the reaction of diphenylmethyllithium with PMMA in THF solution at room temperature,[25] and more surprisingly, Harwood[20] reported the same ester cleavage during PMMA transesterification with ^{14}C labeled sodium methoxide.

With the organolithium compounds under study, the *O*-alkyl scission of the ester group remains always negligible, except in the case of dimethylaminosulfonylmethyllithium in THF + HMPA solution. Our experimental data (Tables III and IV) may be summarized as follows: No *O*-alkyl scission is detected for isotactic PMMA (*I* triad fraction >0.97), whatever the reaction conditions are. For syndiotactic (*S* triad fraction >0.97) and radical ($I = 0.05$, $H = 0.37$, $S = 0.58$) PMMA, carboxylate formation does occur to a measurable yet low extent, even at 25 °C and for moderate $\overline{DS}_m$ values; it increases with temperature, with initial ratio $(RCH_2Li)/(ester)$, and with time, and may reach a maximum molar fraction of 0.15 for the most substituted syndiotactic PMMA at 60 °C (0.73 M fraction of keto substituents).

This characteristic difference between isotactic and syndiotactic PMMA may be correlated with steric factors; lesser accessibility of the ester carbonyl in a syndiotactic triad favors the *O*-alkyl scission, chiefly for high substitution degrees, when steric hindrance and electrostatic repulsion have increased in the vicinity of the reaction sites.

(5) Reaction Yields and Limiting Conversions. (a) Reactions Carried out in Homogeneous Solution. $CH_3SO_2CH_2Li$–DMSO and $(CH_3)_2NSO_2CH_2Li$–THF + HMPA Systems. The reaction yields are fairly high and may be quantitative for $(RCH_2Li)/(ester) \leq 1.2$ ($\overline{DS}M \leq 0.6$) as was previously observed for the PMMA/$CH_3SOCH_2^-Na^+$/DMSO system.[7] The limiting conversions observed, practically independent of the organolithium reagent (Table VIII), reflect the reactivity of the ester functions in various configurational and chemical environments.[20,21,26,27]

For PMMA, the limiting conversion increases in a significant manner with its isotacticity and with temperature; the substitution is nearly quantitative for an isotactic PMMA at 60 °C. The higher reactivity of the isotactic PMMA may arise from the greater accessibility of the ester groups in isotactic triads AmAmAm, in good agreement with literature data.[20,28,29] Competitive carboxylate formation through *O*-alkyl scission tends in the same way to reduce limiting conversion in the case of syndiotactic PMMA.

The limiting conversions may be tentatively correlated with the characteristic autoretarded kinetics of the reaction process.

$$AA^*A \xrightarrow{k_0} ABA,\ AA^*B \xrightarrow{k_1} ABB,\ BA^*B \xrightarrow{k_2} BBB$$

with $k_0 \geq k_1 \gg k_2$.

When the rate constant k_2 of an ester surrounded by two already substituted units (BA*B) is zero, the limiting conversion is a slightly decreasing function of the ratio k_0/k_1 and has a maximum value of 0.666 for $k_0 = k_1$.[30] Our experimental results suggest that an ester group flanked on both sides by keto–enolate anions in syndiotactic or heterotactic triads is no more reactive at 25 °C, because of simultaneous effects of steric hindrance and of the electrostatic field around the reaction site.

In sharp contrast to PMMA, at 25 °C the substitution degree is nearly quantitative (0.92) for poly(methyl acrylate) (PMA) and it is as high as 0.80 for the azeotropic styrene–MMA copolymer; quantitative substitution is easily performed in the presence of an excess of the organolithium reagent. For styrene–MMA copolymer, the limiting conversion of 0.78 reached at 25 °C for $(RCH_2Li)/(ester) = 2$ may be tentatively correlated with the total fraction of A* units (0.77 as deduced from statistical calculations[31]) included in the following sequences:

$$SA^*S + SA^*AS + SA^*AA^*S + SA^*AAA^*S + SA^*AA^*AA^*S$$

Steric hindrance around the ester function, which is drastically reduced in PMA and styrene–MMA copolymers with respect to PMMA,[20,32] is thus probably the most important factor affecting the reaction processes. The reactivities of the central MMA unit in different triads may be thus classified as:

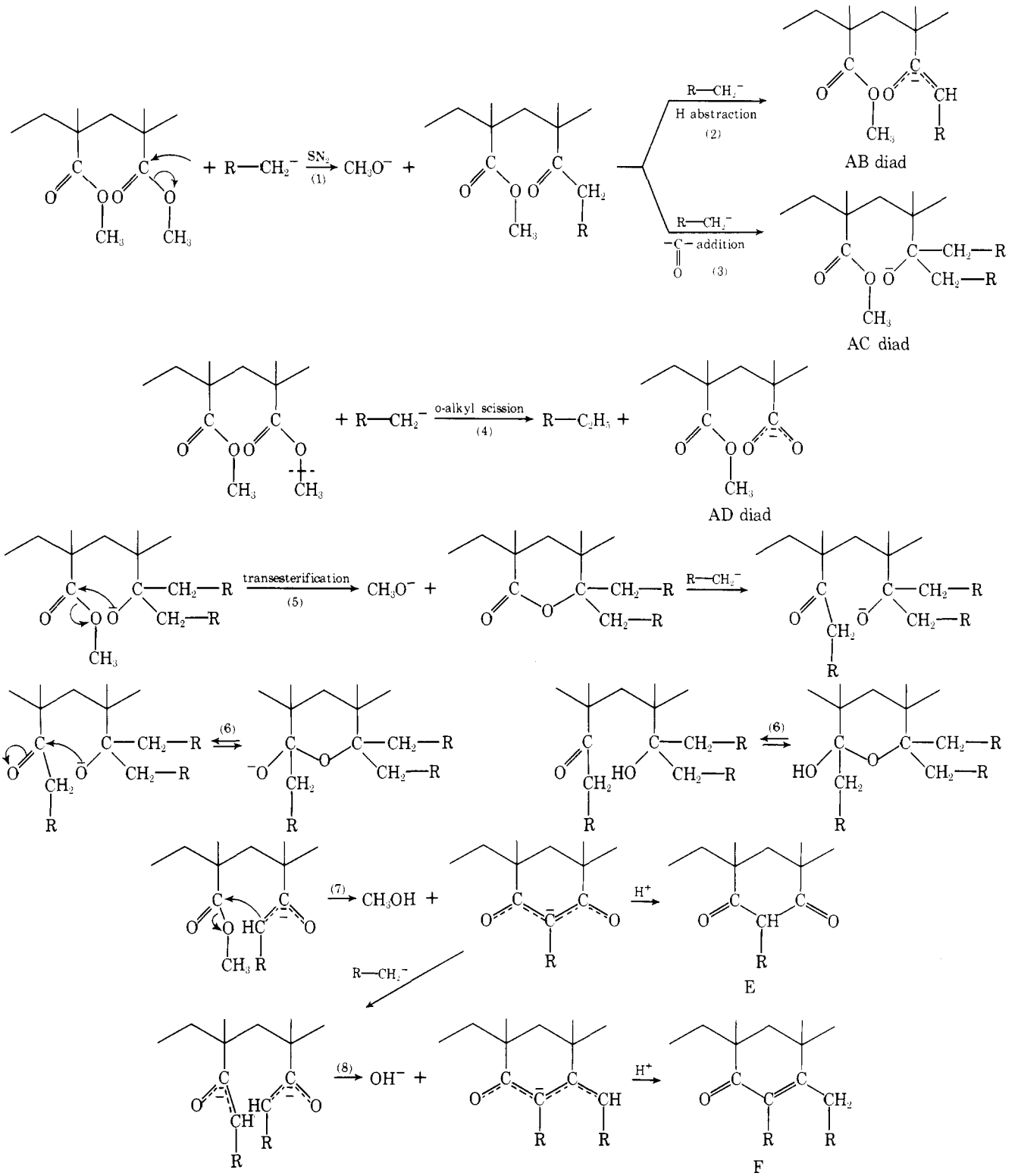
$$AmA^*mA > AmA^*rA > ArA^*rA \text{ and } SA^*S > SA^*A > AA^*A$$

in good agreement with literature data related to alkaline hydrolysis of styrene–MMA copolymers.[20,32]

(b) Reactions Carried out in Heterogeneous Solution. $(CH_3)_2NSO_2CH_2Li$, $C_6H_5SCH_2Li$, and $CH_3OSO_2CH_2Li$–THF Systems. The anionic modified PMMA becomes progressively insoluble in THF as its substitution degree increases, and the limiting conversions strongly depend on both the solubility and the reactivity of the organolithium reagent.

$(CH_3)_2NSO_2CH_2Li$ is insoluble in THF, and the copolymer precipitates for $\overline{DS}_m > 0.2$, except in the case of isotactic

Table VII
General Scheme of the Reaction of a Primary Organolithium Compound RCH_2Li with PMMA



PMMA at 60 °C[33] (Run I-4 in Table IV). The limiting conversion at 25 °C for radical PMMA is about 0.38. It cannot be significantly improved by the use of stoichiometric amounts of tetramethylethylenediamine (TMEDA) (strong complexing agent for Li^+ [34]) or of dimethoxyethane instead of THF (higher solvation power with respect to Li^+).

$C_6H_5SCH_2Li$ is soluble in THF at 25 °C, and there is no sharp phase separation as the $\overline{DS}_m$ increases; the copolymer is swollen enough to allow the reaction to proceed to high substitution degrees (0.80) with fairly high yield (80%).

A $CH_3OSO_2CH_2Li$ suspension in THF is stable only at −78 °C.[6] At this low temperature, synthesis of the model keto β-sulfonate **5** from methyl pivalate is still successful, but no reaction occurs at the sterically hindered ester group of PMMA or even of PMA. Carbanion activation through Li^+ complexation by crown ethers on cryptates[34,35] would probably be of major interest.

(6) Racemization. All the S_N2 substitutions on a polymethacrylic backbone under study occur without racemization;[26] this allows the preparation of co-isotactic or co-syn-

Table VIII
Limiting Conversions of RCH_2Li-Modified Ester Polymers

Initial polymer	T, °C	Limiting conversions into B units: Isotactic	Radical	Syndiotactic
PMMA	25	0.85[a]	0.60[a]	
	60	0.95[a]	0.80[a]	0.73[a]
PMA	25		0.92[b]	
STY-MMA	25		0.78[b]	
	25		1.00[a]	

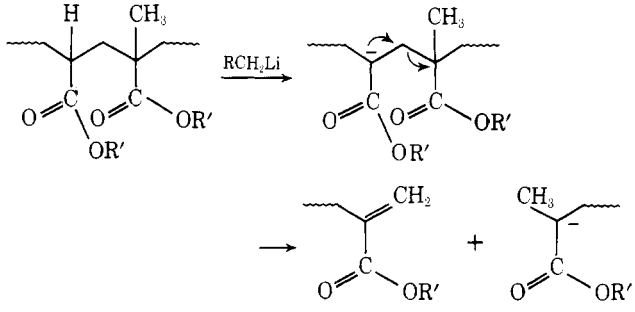
[a] $[RCH_2Li]/[ester] = 3$; reaction time = 20 h. [b] $[RCH_2Li]/[ester] = 2.0$; reaction time = 20 h.

diotactic copolymers from the corresponding PMMA. Epimerization would be normally expected with poly(methyl acrylate), because of tertiary hydrogen abstraction on the polymeric backbone.[26]

(7) Molecular Weights. The fluctuations in composition of the modified PMMA are quite negligible in all cases.[7,36] Thus the apparent molecular weight of the copolymers determined by light scattering may be considered as the true weight average molecular weight $\overline{M}_w$.[37] As expected all the refractive index increments (Tables III–VI) are a linear function of $\overline{DS}_w$.

At 25 °C, the maximum substitution degree of radical PMMA reached without degradation or cross-linking, as shown by the good agreement between experimental and calculated $\overline{M}_w$ values ($\overline{M}_w$(exptl) is an increasing linear function of $\overline{DS}_m$), is limited to about 0.6 for $(CH_3)_2NSO_2CH_2Li$/THF + HMPA (Tables III and IV) and $CH_3SO_2CH_2Li$/DMSO (Table V) systems, but it is as high as 0.8 for $C_6H_5SCH_2Li$/THF (Table VI) system. Degradation occurs in the two first cases in more drastic experimental conditions required to get $\overline{DS}_m$ values higher than 0.6; it is a complex function of temperature, reaction time, and initial ratio $[RCH_2Li]/[ester]$, and its precise mechanism remains yet to be elucidated.

The presence of a few ethylacrylate units (2 mol % in an industrial copolymer, $\overline{M}_w = 1.07 \times 10^5$) leads to strong degradation whatever the reaction conditions are ($\overline{M}_w$ decreases down to 2.5×10^4 for a $\overline{DS}_m$ of 0.25 obtained at room temperature) probably as a result of tertiary hydrogen abstraction.



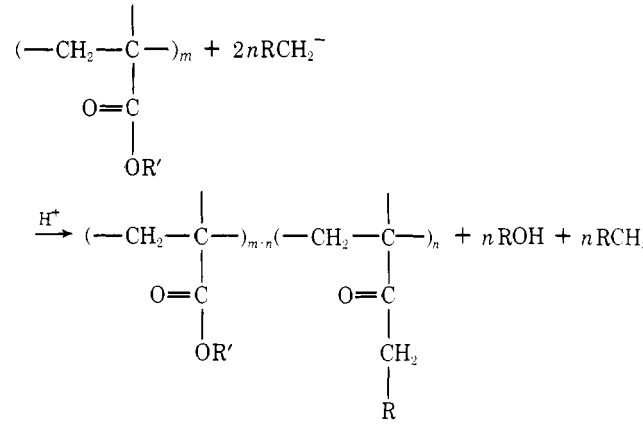
(8) Oxidation and Reduction Reactions at the Sulfur Group of Partially Modified PMMA. Stepwise or direct oxidation sulfide → sulfoxide → sulfone may be selectively and quantitatively performed on copolymers without any degradation or cross-linking using *m*-chloroperbenzoic acid as the oxidant at −15 and 25 °C, respectively.[38] On the contrary, the reduction $COCH_2SO \rightarrow COCH_2S$ carried out using stoichiometric amounts of dichloroborane[39] is not quantitative; moreover the Pummerer rearrangement $COCH_2SO \rightarrow COCH(OH)S$ may occur to some extent,[4] as deduced from IR spectrometry.

These selective and quantitative interconversion reactions afford a simple preparation of a series of homologous copolymers with different functional lateral groups and characterized by strictly identical $\overline{DP}_n$ and molecular weight distribution, tacticity, composition and compositional homogeneity, and unit distribution.

(9) Generalization of the Synthesis to Other Polymeric Substrates. The introduction of functional groups $COCH_2R$ from the corresponding organolithium compounds RCH_2Li on a polymeric chain may be considered as the general problem of the organolithium synthesis of ketones.[40,41] Thus any polymer bearing lateral nitrile, acyl chloride, anhydride, ester, tertiary amide, or carboxylate groups may be potentially a good precursor. The system organolithium/nitrile, the best fitted in most cases, cannot be readily transposed to polyacrylonitrile (PAN) or to polymethacrylonitrile (PMAN); CH_3SOCH_2Na induces the well-known cyclization of the nitrile groups with formation of ladder structure through conjugated C=N bonds,[42] and probably a strong degradation in PAN[43] as in poly(methyl acrylate). Among the acylated polymers, the ester function COOR′ remains the most suitable since the alkylpolymethacrylates offer an outstanding versatility as precursors in which most of the molecular parameters and properties may be readily monitored: $\overline{DP}_n$ and molecular weight distribution, tacticity, solubility ranging from water (R′ = $(CH_2)_2N(Et)_2$) to alkane (R′ = $(CH_2)_nCH_3$ with $n \geq 3$) solubility, glass transition temperature, coexistence of other functional groups compatible with carbanion chemistry (R′ = ether or tertiary amine).

(IV) Conclusions

Nucleophilic substitution of primary stabilized organolithium compounds RCH_2Li (R characterized by strong inductive effect) with polymethacrylic esters leads to structurally well-defined binary copolymers bearing lateral keto-β-functional groups $COCH_2R$ according to the simplified scheme:



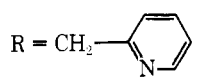
This general modification of a precursor polymer may be considered as a very promising route to a wide range of new model copolymers since it offers a number of advantages. The reaction is easy to carry out, quantitative up to a molar substitution degree of 0.60, and the composition of the ultimate copolymers is easily monitored by the initial ratio (RCH_2Li)/(ester); direct copolymerization could be troublesome owing to the complex structure of the corresponding comonomer $CH_2=C(CH_3)COCH_2R$. A series of structurally related copolymers of the same $\overline{DP}_n$ and same tacticity as the precursor polymethacrylate may be prepared, allowing the obtention of stereoregular copolymers. Variations on R′ afford a control of important characteristics of the precursor polymer which may be kept in part in the derived copolymers. Variations on R[44] allow selective introduction of complex $COCH_2R$ groups, which may be the sites of further reactions[2b,c,5,45,46] (selective reduction $COCH_2S(O)_xCH_3 \rightarrow COCH_3$ with $x = 1$ or 2 in particular is a possible way to stereoregular MMA–isopro-

Table IX
Oxidation and Reduction Reactions at Sulfur Groups of Modified Atactic PMMA

Initial substituent		Oxidized or reduced copolymer				
Molar fraction	Nature	Nature	Yield, %	dn/dc, dL/g at 5460 Å	$\overline{M}_w \times 10^{-5}$ Calcd	Exptl
0.307	$-CO-CH_2-S-C_6H_5$	$-CO-CH_2-SO-C_6H_t$	96	0.178[b]	1.27	1.45
		$-CO-CH_2-SO_2-C_6H_5$	100	0.171[b]	1.31	1.34
0.334	$-CO-CH_2-SO-CH_3$	$-CO-CH_2-SO_2-CH_3$	97	0.085[c]	1.14	1.09
		$-CO-CH_2-S-CH_3$	83[a]		1.05	*d*

[a] Deduced from the overall carbon acidity loss taking into account both the reduction and the eventual Pummerer rearrangement. [b] Acetone solution. [c] DMF solution. [d] No suitable solvent for light-scattering measurements, because of aggregation phenomena.

penyl methyl ketone copolymers[47]) or which present some specific properties (enolization for



ref 8 and 25.

(V) Experimental Section

Uncorrected melting points were taken on a Mettler FP 5 capillary melting point apparatus. IR, UV, and ^{1}H-NMR (chemical shifts expressed in ppm, δ, downfield from TMS) spectra were obtained respectively on a Perkin-Elmer 237, Beckman Acta V, and Varian HA-100 apparatus.

Potentiometric measurements in DMF were carried out under argon on a Methrohm E-436 potentiometer fitted with DMF-B glass (Tacussel) and calomel–DMF electrodes, using 0.1 N sodium methoxide in methanol–benzene or 0.1 N tetrabutylammonium hydroxide in benzene–2-propanol as titrant.

Specific index increments were measured at 25 °C on a Brice-Phoenix BP 1000 V differential refractometer for λ 5460 Å. Light-scattering measurements were performed on a FICA apparatus for the same wavelength at room temperature.

(1) Solvents, Reagents, and Polymers. After convenient drying and purification treatments (see below), solvents were directly distilled and stored under argon in Schlenk vessels:

THF, dioxane, dimethoxyethane, and benzene were distilled from disodiumbenzophenone dianion, HMPA from the Na–HMPA complex, and DMSO from CaH_2; DMF was purified according to literature.[48] *N,N'*-Dimethylmethanesulfonamide was prepared and crystallized according to literature;[2c] dimethyl sulfone and glutaric anhydride were recrystallized in $CHCl_3$–petroleum ether 9/1 v/v and in ethyl ether, respectively; diazabicyclooctane (DABCO) was sublimated; dimethyl glutarate, 1,3-dimethylcyclohexane dicarboxylate, tetramethylethylenediamine, methylmethane sulfonate, and methylthiobenzene were vacuum distilled in the presence of calcium hydride for the first three compounds; ether solutions of diazomethane were prepared and titrated according to literature.[49]

Polymers. Isotactic and syndiotactic PMMA were prepared in toluene solution at −78 °C using $AlLiH_4$ for iso-PMMA[50] and $Al(Et)_3$–$TiCl_4$ for syndio-PMMA.[51] Their stereochemical purity in triads is more than 97% (^{1}H-NMR measurements in *O*-dichlorobenzene at 120 °C). The radical PMMA sample obtained from ROHM-HAAS ($\overline{M}_w$ = 95 000, $\overline{M}_n$ = 65 000) has a predominantly syndiotactic structure (% I, 0.05; H, 0.37; S, 0.58). The azeotropic styrene–MMA copolymer (MMA molar fraction = 0.47) was obtained by radical polymerization in benzene solution at 60 °C in the presence of azobis(isobutyronitrile) (r_s = 0.53, r_{MMA} = 0.47[52]).

Organolithium Compounds. Experiments involving lithium and organolithium compounds were carried out under a slight pressure of purified argon in an all Pyrex glass reactor allowing the use of vacuum and argon sweeping cycles. Solvents and reagents may be introduced under argon from Schlenk vessels or through self-sealing rubber caps using syringe technique. Solutions of *n*-butyllithium in benzene were titrated in DMSO against acetanilid in the presence of triphenylmethane as a color index.[53] The organolithium reagents RCH_2Li were prepared according to literature, as solutions or suspensions over a 0.5–1.0 N concentration range, through metallation of the precursor R–CH_3 by stoichiometric amounts of *n*-Buli: $C_6H_5SCH_2Li$/THF, 0 °C, in the presence of stoichiometric amounts of DABCO;[1] $CH_3S(O)_xCH_2Li$ (x = 1,2)/THF–DMSO, 0 °C[2c], or /C_6H_6, 80 °C;[54] $CH_3OSO_2CH_2Li$/THF, −78 °C.[6]

(2) Synthesis of Model Compounds. The general procedure for the reactions of RCH_2Li with methyl pivalate (models **1–5**), glutaric anhydride (model 6), dimethyl glutarate (models 7 and **10**), and 1,3-dimethyl-1,3-cyclohexane dicarboxylate (model 8) follows: 0.04 mol of the neutral reagent, neat if liquid or dissolved in the minimum volume of THF if solid, is rapidly introduced into a solution (or a suspension) of the RCH_2Li reagent under efficient stirring, at room temperatures for all the carbanionic reagents, except for the CH_3O-SO_2CH_2Li reaction temperature being −75 °C. The stoichiometric ratio is always (RCH_2Li)/(ester or anhydride function) ≃ 2.05. After a reaction time of 3 h, the mixture is poured into an excess of chilled water and neutralized by diluted HCl solution to pH 5. The mixture is extracted with $CHCl_3$; the organic layer, washed with water and dried on anhydrous Na_2SO_4, yields the crude product by elimination of the solvent. Recrystallization gives the analytical sample required for further characterizations.

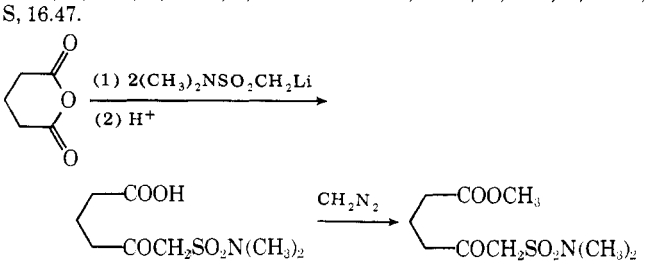
3,3-Dimethyl-1-phenylthio Butanone(1). Recrystallization in ethylacetate–petroleum ether afforded white needles, yield 70%; mp 25.4 °C, acidity equivalent 0. IR ($CHCl_3$) 1700 (C=O), 1580, 1475–730 cm^{-1} (C_6H_5). UV (ACN) λ_{max} 251 nm (ϵ 4100) with 310 nm shoulder (ϵ 160). NMR ($CDCl_3$) δ 7.7–7.0 (m, 5 H, C_6H_5), 4.0 (s, 2 H, $COCH_2S$), 1.18 (s, 9 H, $C(CH_3)_3$). Anal. Calcd for $C_{12}H_{16}OS$: C, 69.18; H, 7.74; O, 7.68; S, 15.39. Found: C, 69.07; H, 7.75; O, 7.70; S, 15.20.

3,3-Dimethyl-1-methylsulfinyl Butanone (2). Recrystallization at 0 °C in diethylether–petroleum ether afforded white crystals, 80% yield, mp 25.2 °C, acidity equivalent 0.98. IR ($CHCl_3$) 1730 (C=O), 1050 cm^{-1} (SO). UV (ACN) λ_{max} 293 nm (ϵ 63). NMR ($CDCl_3$) δ 4.0 (q, 2 H, $SOCH_2CO$), 2.72 (s, 3 H, $SOCH_3$), 1.18 (S, 9 H, $C(CH_3)_3$). Anal. Calcd for $C_7H_{14}O_2S$: C, 51.82; H, 8.70; O, 19.72; S, 19.76. Found: C, 51.93, H, 8.65; O, 19.74; S, 19.58.

3,3-Dimethyl-1-methylsulfonyl Butanone (3). Recrystallization in ethyl acetate–petroleum ether afforded long white needles, 90% yield, mp 62 °C, acidity equivalent 0.98. IR (KBr) 1720 (C=O), 1295 and 1135 (SO_2), 756 cm^{-1} (CSO_2–C). UV (ACN) λ_{max} 291 nm (ϵ 40). NMR ($CDCl_3$) δ 4.30 (S, 2 H, $COCH_2SO_2$), 3.95 (s, 3 H, SO_2CH_3), 1.18 (s, 9 H, $C(CH_3)_3$). Anal. Calcd for $C_7H_{14}O_3S$: C, 47.16; H, 7.92; O, 26.93; S, 17.99. Found: C, 47.19; H, 7.92; O, 26.93; S, 17.82.

3,3-Dimethyl-1-dimethylaminosulfonyl Butanone (4). Recrystallization in ethyl acetate–petroleum ether afforded white needles, 90% yield, mp 71.2 °C, acidity equivalent 1.00. IR ($CHCl_3$) 1720 (C=O), 1350 and 1155 (SO_2), 970 cm^{-1} (C–N). UV (ACN) λ_{max} 293 nm (ϵ 52). NMR ($CDCl_3$) δ 4.14 (s, 2 H, NSO_2CH_2CO), 2.90 (s, 6 H, $N(CH_3)_2$), 1.18 (s, 9 H, $C(CH_3)_3$). Anal. Calcd for $C_8H_{17}O_3SN$: C, 46.35; H, 8.27; O, 23.15; S, 15.47; N, 6.76. Found: C, 46.65; H, 8.46; O, 23.12; S, 15.44; N, 6.62.

3,3-Dimethyl-1-methoxysulfonyl Butanone (5). Recrystallization at 0 °C in diethyl ether–petroleum ether afforded a white crystalline powder, 90% yield, mp 33.1 °C, acidity equivalent 0.97. IR (KBr) 1720 (C=O), 1355 and 1175 (SO_2), and 960 cm^{-1}. UV (ACN) λ_{max} 289 nm (ϵ 36). NMR ($CDCl_3$) δ 4.30 (s, 2 H, OSO_2CH_2CO), 3.95 (s, 3 H, OCH_3) 1.18 (s, 9 H, $C(CH_3)_3$). Anal. Calcd for $C_7H_{14}O_4S$: C, 43.28; H, 7.26; O, 32.95; S, 16.51. Found: C, 43.36; H, 7.34; O, 32.80; S, 16.47.

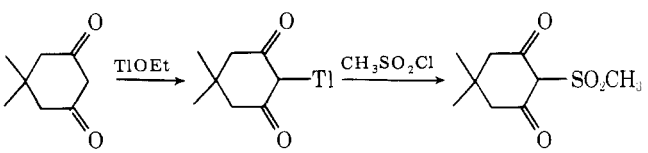


5-Dimethylaminosulfonylmethyl 1-Pentanoate (6). The crude acidic reaction product was dissolved in $CHCl_3$ and treated overnight at room temperature by an ether solution of diazomethane. After acidification with dilute HCl, the solution was washed with water and evaporated to dryness; then the residue was fractionated by column chromatography on silica; elution with petroleum ether–diethyl ether (5/95 v/v) afforded the purified product as a liquid at room temperature, yield 60%. IR (neat) 1735 (C=O ester), 1720 sh (C=O ketone), 1340 and 1155 (SO_2), 960 cm^{-1} ($CNSO_2$). UV (ACN) λ_{max} 286 nm (ϵ 51). NMR ($CDCl_3$) 3.90 (S, 2 H, $COCH_2SO_2N$), 3.60 (S, 3 H, OCH_3), 2.80 (S, 6 H, $N(CH_3)_2$), 1.6–2.8 (m, 6 H, $(CH_2)_3$). Anal. Calcd for $C_9H_{17}O_5SN$: C, 43.01; H, 6.82; O, 31.83; S, 12.76; N, 5.57. Found: C, 43.08; H, 6.80; O, 31.79; S, 12.58; N, 5.49.

1,3-Bis(dimethylaminosulfonylacetyl)propane (7). Recrystallization in $CHCl_3$ afforded white crystals, 75% yield, mp 123.8 °C, acidity equivalent 1.11. IR ($CHCl_3$) 1720 (C=O), 1345 and 1150 (SO_2), 970 cm^{-1} (C–N). UV (ACN) λ_{max} 290 nm (ϵ 88). NMR ($CDCl_3$) δ 3.95 (s, 4 H, $COCH_2SO_2N$), 2.89 (s, 12 H, N $(CH_3)_2$), 1.8–2.6 (m, 6 H, $(CH_2)_3$). Anal. Calcd for $C_{11}H_{22}O_6S_2N_2$: C, 38.58; H, 6.48; O, 28.03; S, 18.73; N, 8.18. Found: C, 38.68; H, 6.48; O, 28.02; S, 18.34; N, 8.14.

1,3-Bis(dimethylaminosulfonylacetyl)cyclohexane (8). Recrystallization in $CHCl_3$ afforded white crystals, 80% yield, mp 185 °C, acidity equivalent 1.03. IR and NMR: see model **7**. UV (ACN) λ_{max} 291 nm (ϵ 84). Anal. Calcd for $C_{14}H_{26}O_6S_2N_2$: C, 43.96; H, 6.85; O, 25.10; S, 16.77; N, 7.32. Found: C, 43.82; H, 6.87; O, 25.07; S, 16.46; N, 7.81.

2-Methylsulfonyl-3-methylsulfonylmethyl-Δ^2-cyclohexenone (10). Recrystallization in $CHCl_3$ afforded white powder, 60% yield, mp 105.2 °C, acidity equivalent 1.03. IR (KBr) 1695 (C=O, splited because of the presence of s-cis and s-trans isomers), 1600 (C=C), 1300 and 1150 cm^{-1} (SO_2). UV (TFE) λ_{max} 238 nm (ϵ 11 000) and 330 nm (ϵ 46). NMR ($CDCl_3$) δ 4.91 (s, 2 H, $=C-CH_2-SO_2$), 3.26 (s, 3 H, SO_2CH_3), 3.08 (s, 3 H, $CH_2SO_2CH_3$), 2.0–2.88 (m, 6 H, $(CH_2)_3$). Attempts to estimate the conjugated double bond by bromination were unsuccessful. Anal. Calcd for $C_9H_{14}O_5S_2$: C, 40.58; H, 5.30; O, 30.04; S, 24.08. Found: C, 40.42; H, 5.34; O, 29.99; S, 24.01.



5,5-Dimethyl-2-methylsulfonyl-1,3-cyclohexanedione (9). To a solution of 2.8 g (0.02 mol) of dimedone in 50 mL of diethyl ether was added dropwise 5 g (0.02 mol) of thallium ethylate;[55] the thallium salt precipitated quantitatively in a few minutes. To the suspension maintained at 30 °C, 2.26 g of mesyl chloride[56] (0.02 mol) was added dropwise and the suspension was stirred for 1 h. The suspension then concentrated was filtered and the homogeneous ether solution was washed with water and gave the crude product after elimination of the solvent. Recrystallization in $CHCl_3$–Et_2O afforded white crystalline powder, mp 50.2 °C, acidity equivalent 1.02. IR ($CHCl_3$) 1720–1675–1590 cm^{-1} (–CO–CH–CO–), 1310–1150 cm^{-1} (SO_2). UV (TFE) λ_{max} 272 nm (ϵ 14 000) with 315 nm shoulder (ϵ 44). NMR ($CDCl_3$) δ 11.0 (s, 1 H, CH), 3.3 (s, 3 H, SO_2CH_3) Anal. Calcd for $C_0H_{14}O_4S$: C, 49.52; H, 6.46; O, 29.32; S, 14.69. Found: C, 49.63; H, 6.51; O, 29.16; S, 14.32.

(3) Synthesis of Modified Polymers by Reaction with RCH_2Li. PMMA (3 g; 3×10^{-2} mol) in 60 mL of the appropriate solvent (THF, THF + DMSO, or THF + HMPA (1/1 v/v)) was rapidly added to the solution (or suspension) of the organolithium reagent under efficient stirring. The volume fraction of C_6H_6 arising from *n*-BuLi solution never exceeded 0.25. After a given reaction time, the reaction medium is acidified with dilute HCl to pH 5; the polymer is recovered by precipitation into a large excess of methanol, and it is purified by precipitation from acetone (or acetone + DMF for the highest $\overline{DS}_m$) solution acidified by 3 drops of dilute HCl into methanol.

(4) Oxidation and Reduction Reactions at Sulfur Groups in Copolymers. Oxidations were carried out in $CHCl_3$ solution, using stoichiometric amounts of purified *m*-chloroperbenzoic acid[57] (98.5% purity by iodometry), according to the following general conditions: S → SO, (peracid)/(S) = 1, −15 °C/15 h; SO → SO_2, (peracid)/(SO) = 1, −15 °C/1 h, then 25 °C/48 h; S → SO_2, (peracid)/(S) = 2, −15 °C/1 h, then 25 °C/48 h. The yields, calculated from elemental analysis, NMR, and acidity measurements on the recovered copolymers were always higher than 95%.

The reductions $COCH_2SO \rightarrow COCH_2S$ were performed in CH_2Cl_2 solution at 0 °C during 24 h, using stoichiometric amounts of dichloroborane ($(HBCl_2)/(SO) = 1$) prepared as a 1 M solution in CH_2Cl_2–THF (2/1 v/v) according to literature.[39] The extent of reaction was measured by potentiometry on the recovered copolymers, using the overall loss of carbon acidity arising both from the reduction $COCH_2SO \rightarrow COCH_2S$ and from the Pummerer rearrangement $COCH_2SO \rightarrow COCH(OH)S$ (intense absorption around 3500 cm^{-1} for ν(OH)).

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Metal Complexes of Poly(α-amino acids). A Potentiometric and Circular Dichroism Investigation of Cu(II) Complexes of Poly(L-lysine), Poly(L-ornithine), and Poly(L-diaminobutyric acid)[1]

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ABSTRACT: The conformational properties of cupric complexes of poly(L-lysine), poly(L-ornithine), and poly(L-diaminobutyric acid) have been investigated by potentiometric, visible and UV absorption, and circular dichroism (CD) techniques. The three polymers form two kinds of complexes stable at pH <8.5 (type I complexes) and at pH >8.5 (type II complexes). It has been found that in the low pH complexes of poly(L-diaminobutyric acid) at least one deprotonated amido nitrogen is coordinated to cupric ions. Type II complexes involve always amide nitrogens in the coordination sphere of Cu(II). Evidence is presented that the structure of such complexes is not compatible with the α-helical conformation of the peptide backbone.

The preparation and the catalytic properties of metal complexes of poly(α-amino acids) have been described in a number of papers.[2a] Particularly, copper complexes of amino acid polymers have been investigated in some detail both from the point of view of the catalytic activity and of the structural properties.[2b-5] Such compounds can be considered useful models in order to understand the way of action of copper-containing proteins. Addition of poly(L-histidine) ($[L\text{-His}]_n$) to several oxidation reactions was found to enhance the catalytic activity of copper toward neutral or negatively charged substrates.[3] Structural investigations on $[L\text{-His}]_n$ copper complexes revealed that two complexes are formed in aqueous solution.[3] In complex I, stable at pH 5, three imidazole nitrogens and one deprotonated amide nitrogen are coordinated to a copper ion. In complex II, formed at pH 14, four consecutive amide nitrogens have been suggested to occupy a distorted coordination square of the Cu(II) ion.[3]

Poly(L-arginine) forms three different copper complexes.[5] The first one is stable at pH <8, while the other two are formed between pH 8 and 10.5. In the last two complexes two guanido nitrogens and two peptide nitrogens have been suggested to occupy the corners of the coordination square of Cu(II).[5]

The poly(L-lysine) ($[L\text{-Lys}]_n$) copper complex has been described to behave as an asymmetrically selective catalyst for the oxidation of L-(3,4-dihydroxyphenyl)alanine (DOPA).[4] The structural properties of such a compound in aqueous solution have been recently investigated by Hatano et al.[4] Also in this case two complexes are formed. In the first one, stable at pH <8, four amino nitrogens have been suggested to occupy square-planar positions of Cu(II). In the second one, stable at pH >8, deprotonated amido nitrogens have been suggested as binding sites for Cu(II) ions.[4] Clearly, correlation between catalytic activity and complex structure is essential in order to understand the mechanism of action of such compounds, and in order to approach the problem of the way of action of copper-containing enzymes.

In view of the importance of such compounds on the effects of stereospecific catalysis and as models for copper proteins, we have reinvestigated the complex formation process between Cu(II) $[L\text{-Lys}]_n$, and the study has been extended to the copper complexes of poly(L-ornithine) ($[L\text{-Orn}]_n$) and poly(L-diaminobutyric acid) ($[L\text{-A}_2\text{bu}]_n$). The specific purpose of our work was to establish the relationship between complex structure and conformation of the polypeptide backbone.

Experimental Section

Materials. Reagent grade cupric chloride (Merck Chemical Co.) was used as obtained.

$[L\text{-Lys}]_n\cdot HCl$, $[L\text{-Orn}]_n\cdot HCl$, and $[L\text{-A}_2\text{bu}]_n\cdot HCl$ were prepared according to procedures described in the literature.[6] The intrinsic viscosities in 0.1 M KCl of the polymer samples used in the present work were the following: $[L\text{-Lys}]_n\cdot HCl$, $[\eta] = 0.24$ dL/g; $[L\text{-Orn}]_n\cdot HCl$, $[\eta] = 0.55$ dL/g; $[L\text{-A}_2\text{bu}]_n\cdot HCl$, $[\eta] = 0.67$ dL/g.

Carbonate-free potassium hydroxide was prepared from reagent grade KOH pellets (Merck Chemical Co.), according to the literature.[7]

Measurements. Potentiometric titrations were carried out at 25