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On M-Algebras, the Quantisation of Nambu-Mechanics, and Volume Preserving Diffeomorphisms[1]

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Dedicated to K. Hepp and W. Hunziker on the occasion of their 60th birthdays.

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Abstract: M-branes are related to theories on function spaces $\mathcal{A}$ involving M-linear non-commutative maps from $\mathcal{A} \times \cdots \times \mathcal{A}$ to $\mathcal{A}$. While the Lie-symmetry-algebra of volume preserving diffeomorphisms of T^M cannot be deformed when $M > 2$, the arising M-algebras naturally relate to Nambu's generalisation of Hamiltonian mechanics, e.g. by providing a representation of the canonical M-commutation relations, $[J_1, \cdots, J_M] = i\hbar$. Concerning multidimensional integrability, an important generalisation of Lax-pairs is given.

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1. Introduction

Generalizing fundamental concepts, such as Lie algebras or Hamiltonian dynamics, may have quite divers merits; it can lead to new, interesting possibilities, – or reassure oneself of our present notions. While the result that volume preserving diffeomorphisms of toroidal M-branes, as a Lie-symmetry algebra, cannot be deformed (if $M > 2$) is of the latter nature – the following ideas appear to be worthwhile persueing:
— Using a $*M$-deformation of the algebra of functions on some M-dimensional manifold for representing the M-linear analogue to Heisenberg's commutation relations that Nambu [1] encountered in multi-Hamiltonian dynamics.
— Generalizing the Jacobi identity for Lie algebras to a (2-bracket) identity involving $2M-1$ elements of a vectorspace V for which an antisymmetric M-linear map (M-commutator) from $V \times \cdots \times V$ to V is defined (in a dynamical context, an identity involving M, rather than 2, of the M-commutators, may be preferred).
— A potential relevance of M-algebras to the quantisation of space-time.
Perhaps most importantly (on a concrete, practical level), an explicit example is given (the multidimensional diffeomorphism-invariant integrable field theories found in [2]) for the usefulness (envisaged some time ago [3]) of generalizing Lax-pairs to -triples, ...

2. M-algebras from M-branes

A relativistic M-brane moving in D-dimensional space time may be described, in a light-cone gauge, by the VDiffΣ-invariant sector of ([4])

$$H = \frac{1}{2} \int_\Sigma \frac{d^M\varphi}{\rho(\varphi)} \left(\vec{p}^{\,2} + g\right) \tag{1}$$

where g is the determinant of the M×M matrix $(g_{rs}) := (\nabla_r x^i \nabla_s x_i)_{r,s=1\cdots M}$, x^i and p_i ($i = 1, \cdots, D-2 =: d$) are canonically conjugate fields, and ρ is a fixed non-dynamical density on the M-dimensional parameter-manifold Σ ($M = 1$ for strings, $M = 2$ for membranes,...). Generators of VDiffΣ, the group of volume-preserving diffeomorphisms of Σ (resp. the component connected to the identity), are represented by

$$K := \int_\Sigma f^r\, p_i\, \partial_r\, x^i\, d^M\, \varphi \tag{2}$$

with $\nabla_r f^r = 0$. g may be written as

$$g = \sum_{i_1<i_2<\cdots<i_M} \{x_{i_1}, \cdots, x_{i_M}\}\{x^{i_1}, \cdots, x^{i_M}\}, \tag{3}$$

where the 'Nambu-bracket' $\{\cdots\}$ is defined for functions $f_1, \cdots, f_M$ on Σ as

$$\{f_1, \cdots, f_M\} := \epsilon^{r_1\cdots r_M}\, \partial_{r_1} f_1 \cdots \partial_{r_M} f_M. \tag{4}$$

This trivial, but important observation suggests to consider Hamiltonians

$$H_\lambda := \frac{1}{2} Tr\Big(\vec{P}^{\,2} \pm \sum_{i_1<\cdots<i_M} [X_{i_1}, \cdots, X_{i_M}]_\lambda^2\Big), \tag{5}$$

resp.

$$H_\lambda = \frac{1}{2} \sum_{i=1}^{d} \beta\,(P_i, P_i) + \frac{1}{2} \sum_{i_1<\cdots<i_M} \beta\,([X_{i_1}, \cdots, X_{i_M}]_\lambda, [X_{i_1}, \cdots X_{i_M}]_\lambda), \tag{6}$$

where X^i and P_i are elements of (possibly finite dimensional, λ-dependent) vectorspaces V on which antisymmetric M-linear maps $[,\cdots,]_\lambda : V \times \cdots \times V \to V$ are defined, and β a positive definite hermitean form, preferably invariant with respect to some analogue of volume preserving diffeomorphisms (cp. (2)).

With

$$[T_{a_1}, \cdots, T_{a_M}]_\lambda = f^{a}_{a_1\cdots a_M}(\lambda)\, T_a \tag{7}$$

and

$$\beta(T_a, T_b) = \delta^a_b \tag{8}$$

for some (possibly λ-dependent) basis $\{T_a\}_{a=1}^{\dim V}$ of V, i.e.

$$f^{a}_{a_1\cdots a_M}(\lambda) = \beta(T_a, [T_{a_1}, \cdots, T_{a_M}]_\lambda), \tag{9}$$

(6) reads

$$H_\lambda = \frac{1}{2} p^*_{ia} p_{ia} + \frac{1}{2} (f^{a}_{a_1\cdots a_M}(\lambda))^* f^{a}_{b_1\cdots b_M}(\lambda) \frac{1}{M!} x^*_{i_1 a_1} \cdots x^*_{i_M a_M} x_{i_1 b_1} \cdots x_{i_M b_M}, \tag{10}$$

while (1) may be written as

$$H = \frac{1}{2} p^*_{i\alpha} p_{i\alpha} + \frac{1}{2} (g^{\alpha}_{\alpha_1\cdots\alpha_M})^* g^{\alpha}_{\beta_1\cdots\beta_M} \frac{1}{M!} x^*_{i_1\alpha_1} \cdots x_{i_M\beta_M}; \tag{11}$$

$$g^{\alpha}_{\alpha_1\cdots\alpha_M} := \int_\Sigma Y^*_\alpha \{Y_{\alpha_1}, \cdots, Y_{\alpha_M}\}\, \rho\, d^M\varphi \tag{12}$$

is defined with respect to some orthonormal basis of functions (on Σ) satisfying

$$\int Y^*_\alpha\, Y_\beta\, \rho\, d^M\varphi = \delta^\alpha_\beta \qquad \alpha, \beta = 1 \cdots \infty \tag{13}$$

(even for real x_i, it is often convenient to take a complex basis).

Obvious questions are:

1) Does there exist a 'natural' sequence of finite dimensional vectorspaces V_n with basis $\{T_a^{(n)}\}$ and antisymmetric maps $F_n : V_n \times \cdots \times V_n \to V_n$ such that for each $(M+1)$-tuple $(a\, a_1 \cdots a_M)$

$$\lim_{n\to\infty} f^a_{a_1\cdots a_M}(\lambda_n) \overset{?}{=} g^a_{a_1\cdots a_M} . \tag{14}$$

2) For which M do there exist finite dimensional analogues of (2), $K(n)$, leaving $(10)_{\lambda_n}$ invariant, such that, as $n\to\infty$, the full invariance under volume-preserving diffeomorphisms is recovered?

3) What about λ-deformations with infinite dimensional V's ?

Let us look at the case of a M-torus, $\Sigma = T^M$:
Choosing

$$Y_{\vec m} = e^{i\vec m\vec\varphi},\ \vec m = (m_1,\cdots,m_M) \in \mathbb{Z}^M,\ \rho \equiv 1, \tag{15}$$

one gets

$$g^{\vec m}_{\vec m_1\cdots\vec m_M} = i^M(\vec m_1,\cdots,\vec m_M)\,\delta^{\vec m}_{\vec m_1+\cdots+\vec m_M} \tag{16}$$

where $(\vec m_1,\cdots,\vec m_M) \in \mathbb{Z}$ denotes the determinant of the corresponding $M\times M$ Matrix (an element of $GL(M,\mathbb{Z})$).

Consider now the following '$*M$-product' (a deformation of the ordinary commutative product of M functions $f_1,\cdots,f_M$ on Σ):

$$(f_1\cdots f_M)_* := f_1\cdots f_M + \sum_{m=1}^{\infty} \frac{\left(\frac{(-i)^{M+1}\lambda}{M!}\right)^m}{m!} \cdots \begin{matrix}\epsilon^{r_1 r_1'\cdots r_1^{(M)}}\\ \epsilon^{r_m r_m'\cdots r_m^{(M)}}\end{matrix} \frac{\partial^m f_i}{\partial\varphi^{r_1}\cdots\partial\varphi_{r_m}} \cdots \frac{\partial^m f_M}{\partial\varphi^{r_1^{(M)}}\cdots\partial\varphi^{r_m^{(M)}}} . \tag{17}$$

One then finds that

$$(Y_{\vec m_1}\cdots Y_{\vec m_M})_* = \sqrt{\omega}^{\,-(\vec m_1,\cdots,\vec m_M)}\, Y_{\vec m_1+\cdots\vec m_M}$$
$$\sqrt{\omega} = e^{i\frac{\lambda}{M!}} . \tag{18}$$

Defining

$$[f_1,\cdots,f_M]_* := \sum_{\sigma\in S_M} (\text{sign}\,\sigma)\,(f_{\sigma 1}\cdots f_{\sigma M})_* \tag{19}$$

to simply be the antisymmetrized $*M$-product, one gets

$$[T_{\vec m_1},\cdots,T_{\vec m_M}] = \frac{-i}{2\pi\Lambda}\sin\left(2\pi\Lambda\,(\vec m_1,\cdots,\vec m_M)\right) T_{\vec m_1+\cdots+\vec m_M} \tag{20}$$

$$\text{with } \Lambda := \frac{\lambda}{2\pi M!} \quad\text{and}\quad T_{\vec m} := \lambda^{-\frac{1}{M-1}}\,Y_{\vec m}.$$

For $M>1$ arbitrary (but fixed), let V denote the vectorspace (over $\mathbb{C}$) generated by $\{T_{\vec m}\}_{\vec m\in\mathbb{Z}^M}$, $\mathbb{M}^\Lambda$ denote $(V,*)$ and $\mathbb{A}^\Lambda$ denote $(V,[\cdots]_*)$.

The hermitean form β (cp. (8),(9)),

$$\beta(T_{\vec m}, T_{\vec n}) = \delta^{\vec m}_{\vec n}, \quad \beta(c_i X_i, d_j X_j) = c_i^* d_j \, \beta(X_i, X_j),$$

will have the important property ('invariance') that (for $X_i = x_{i\vec m} T_{\vec m}$ with $x^*_{i\vec m} = x_{i-\vec m}$)

$$\beta\left(X, [X_{i_1}, \cdots X_{i_M}]\right) = -\beta\left(X_{i_r}, [X_{i_1}, \cdots, X_{i_{r-1}}, X, X_{i_{r+1}}, \cdots, X_{i_M}]\right),$$

as

$$\beta\left(T_{\vec m}, [T_{\vec m_1}, \cdots, T_{\vec m_M}]\right) = \frac{-i}{2\pi\Lambda} \, \delta^{\vec m}_{\vec m_1, + \cdots + \vec m_M} \, \sin\left(2\pi\Lambda(\vec m_1, \cdots, \vec m_M)\right).$$

For rational $\Lambda = \frac{\tilde N}{N}$ (assuming N and $\tilde N < N$ having no common divisor > 1) both $\mathbb{A}^\Lambda$ and $\mathbb{M}^\Lambda$ may be divided by an ideal of finite codimension, namely (using the periodicity of the structure-constants) the vectorspace I generated by all elements of the form $T_{\vec m} - T_{\vec m + N\,(\text{anything})}$. One thus arrives at considering (for arbitrary odd N)

$$V^{(N)} := \left\langle T_{\vec m} | m_r = -\frac{N-1}{2}, \cdots, +\frac{N-1}{2} \right\rangle_{\mathbb{C}} \quad r = 1 \cdots M \tag{21}$$

with a $*_M$ product on $V^{(N)}$ defined just as in (18):

$$\begin{aligned} (T_{\vec m_1} \cdots T_{\vec m_M})_* &:= \frac{-iN}{2\pi \tilde N M!} \, \omega^{-\frac{1}{2}(\vec m_1, \cdots, \vec m_M)} \, T_{\vec m_1 + \cdots + \vec m_M \,(\text{mod } N)} \\ \omega &= e^{4\pi i \frac{\tilde N}{N}}, \end{aligned} \tag{22}$$

and a corresponding alternating product,

$$\begin{aligned} [T_{\vec m_1}, \cdots, T_{\vec m_M}]_* &= \frac{-iN}{2\pi \tilde N} \sin\left(2\pi \frac{\tilde N}{N} (\vec m_1, \cdots, \vec m_M)\right) T_{\vec m_1 + \cdots + \vec m_M \,(\text{mod } N)} \\ \vec m_r &\in (\mathbb{Z}_N)^M. \end{aligned} \tag{23}$$

The 'structure constants' of the alternating finite dimensional M-algebras

$$\begin{aligned} \mathbb{A}_N &:= (V^{(N)}, [, \cdots,]_*), \\ f^{(N)\vec m}_{\vec m_1 \cdots \vec m_M} &:= \frac{-iN}{2\pi \tilde N} \sin\left(2\pi \frac{\tilde N}{N} \left(\vec m_1, \cdots, \vec m_M\right)\right) \cdot \delta^{\vec m}_{\vec m_1 + \cdots + \vec m_M \,(\text{mod } N)} \end{aligned} \tag{24}$$

satisfy (14) (up to an N and $\mathbb{Z}_N^M$-independent rescaling of the generators, resp. factors of i, which anyway drop out in (10) and (11); $n = N^M$, $f^{(N)} \triangleq f(\lambda_n)$, $\vec m \in \mathbb{Z}_N^M$ $V^{(N)} = V_{n=N^3}$, and $\lim_{N \to \infty} V^{(N)} = V$).

$$\begin{aligned} H_N = {} & \frac{1}{2} p_{i-\vec m} \, p_{i\vec m} \\ & + \frac{1}{2} \frac{N^2}{4\pi^2 \tilde N^2} \sin\left(2\pi \frac{\tilde N}{N} \left(\vec m_1 \cdots \vec m_M\right)\right) \cdot \sin\left(2\pi \frac{\tilde N}{N} \left(\vec n_1, \cdots \vec n_M\right)\right) \\ & \frac{1}{M!} \cdot x_{i_1 - \vec m_1} \cdots x_{i_M - \vec m_M} \, x_{i_1 \vec n_1} \cdots x_{i_M \vec n_M} \, \delta^{\vec m_1 + \cdots + \vec m_M}_{\vec n_1 + \cdots + \vec n_M \,(\text{mod } N)} \end{aligned} \tag{25}$$

could therefore be considered as a finite-dimensional analogue of (1).

3. Multidimensional Commutation Relations

Before turning to questions of symmetry, let me discuss in a little more detail the $*M$-algebras $\mathbb{M}^\Lambda$, with defining relations (cp. (18); note the slight change of notation/normalisation)

$$(T_{\vec{m}_1} \cdots T_{\vec{m}_M})_* \; = \; \omega^{-\frac{1}{2}(\vec{m}_1,\cdots,\vec{m}_M)} \, T_{\vec{m}_1+\cdots+\vec{m}_M} \; (*) \, ,$$

and as vectorspaces generated by basis-elements $T_{\vec{m}}$, $\vec{m} \in S$ (where $S = \mathbb{Z}^M$, $S = (\mathbb{Z}_N)^M$, or any combination thereof – in the M-brane context, depending on whether $\Sigma = T^M$, resp. a fully, or partially, discretized M-torus).

First of all note, that for any M elements, $A_1, \cdots A_M \in V$, any even permutation $\sigma \in S_M$ (the symmetric group in M objects), and any choice of S (even $\mathbb{R}^M$),

$$(A_1 \cdots A_M)_* \; = \; (A_{\sigma(1)} \cdots A_{\sigma(M)}) \quad (\text{sign}\, \sigma \; = \; +) \, , \tag{26}$$

and that $E := T_{\vec{0}}$ acts as a 'unity' in the sense that if one of the A_r is equal to $T_{\vec{0}}$, the $*M$-product becomes commutative (i.e. independent of the order of its M entries).

Using E, one may identify $T_{(m=\pm|m|,0,\cdots,0)}$ with the $|m|$-th power of $E_{\pm 1} := T_{(\pm 1,0,\cdots,0)}$,

$$T_{(m,0,\cdots,0)} \; = \; \underset{\substack{\uparrow \\ |m| \text{ brackets}}}{((((}E \cdots E E_{\pm 1})_* \cdots E E_{\pm 1})_* \cdots)_* \cdots E E_{\pm 1})_* \, , \tag{27}$$

so that one may wonder whether $\mathbb{M}^\Lambda$ can be thought of as being generated by

$$E \; = \; T_{\vec{0}}, \; E_{\pm 1} \; = \; T_{(\pm 1 \; 0 \cdots 0)}, \cdots, \; E_{\pm M} \; = \; T_{(0 \cdots 0 \; \pm 1)} \, .$$

This is indeed the case: Let $\mathbb{F}^M$ be the free (non associative) M-algebra generated by $2M+1$ elements $E, E_{\pm 1}, \cdots, E_{\pm M}$; define arbitrary powers $(E_r)^m$ of the generating elements as in (27) (from now on $E_{-r}^{|m|} =: E_r^{-|m|}$, a notation that will be justified via (29)), and let

$$E_{\vec{m}} \; := \; E_1^{m_1} \, E_2^{m_2} \, \cdots \, E_M^{m_M} \, . \tag{28}$$

Divide $\mathbb{F}^M$ by the ideal generated by elements

$$E_{\vec{m}'} \, E_{\vec{m}''} \cdots E_{\vec{m}^{(M)}} \; - \; \omega^{\gamma(\vec{m}',\vec{m}'',\cdots,\vec{m}^{(M)})} \cdot E_{\vec{m}'+\cdots+\vec{m}^{(M)}} \tag{29}$$

where $\omega = e^{4\pi i \Lambda}$ and

$$\begin{aligned} 2\gamma(\vec{m}', \cdots, \vec{m}^{(M)}) \; &:= \; (m_1 \cdot m_2 \cdot \; \cdots \; \cdot m_M) \; - \; (\vec{m}', \vec{m}'', \cdots, \vec{m}^{(M)}) \\ &\quad - \; \sum_{r=1}^{M} \Big(\prod_{s=1}^{M} m_s^{(r)} \Big) \end{aligned} \tag{30}$$

$$(\vec{m} \; := \; \vec{m}' \; + \; \vec{m}'' \; + \; \cdots \; + \; \vec{m}^{(M)}) \, .$$

This quotient then is isomorphic to $\mathbb{M}^\Lambda$, as can be seen by defining

$$T_{\vec{m}} \; := \; \omega^{\frac{1}{2} m_1 m_2 \cdots m_M} \, E_1^{m_1} \, E_2^{m_2} \cdots E_M^{m_M} \, , \tag{31}$$

which (due to (29) being zero in $\mathbb{F}^\Lambda/I$) satisfies (18) (with Y standing for T).

Note that

$$E_2^{m_2}\, E_1^{m_1}\, E_3^{m_3} \cdots E_M^{m_M} \;=\; \omega^{m_1 m_2 \cdots m_M} \cdot E_1^{m_1}\, E_2^{m_2} \cdots E_M^{m_M}, \tag{32}$$

in particular:

$$E_2\, E_1\, E_3 \cdots E_M \;=\; \omega\, E_1\, E_2 \cdots E_M \tag{33}$$

(while any even permutation does not alter the product, cp. (26)).

In order to get a feeling for (29)/(30) it may be instructive to consider $M = 3$: due to (29),

$$\begin{aligned} & (E_1^{n_1}\, E_2^{n_2}\, E_3^{n_3})(E_1^{l_1}\, E_2^{l_2}\, E_3^{l_3})(E_1^{k_1}\, E_2^{k_2}\, E_3^{k_3}) \\ = \;& E_1^{n_1+l_1+k_1}\, E_2^{n_2+l_2+k_2}\, E_3^{n_3+l_3+k_3} \\ & \cdot\, \omega^{n_1 l_3 k_2 + n_2 l_1 k_3 + n_3 l_2 k_1} \\ & \cdot\, \sqrt{\omega}^{\,n_1(l_2 l_3 + k_2 k_3) + n_2(l_1 l_3 + k_1 k_3) + n_3(l_1 l_2 + k_1 k_2)} \\ & \cdot\, \sqrt{\omega}^{\,n_1 n_2(l_3+k_3) + n_1 n_3(l_2+k_2) + n_2 n_3(l_1+k_1)} \; . \end{aligned} \tag{34}$$

The general rule (30) can hence be stated as follows:

Consider all possible triples (resp. M-tuples) containing powers of each of the $E_r (r = 1 \cdots M)$ exactly once. If the 'contraction' picks out exactly one factor from each of the 3 (resp. M) factors in (34) it does not contribute if they are already in the correct order, modulo even permutations (cp. 26), (like $E_1^{n_1}\, E_2^{l_2}\, E_3^{k_3}$, or $E_2^{n_2}\, E_3^{l_3}\, E_2^{k_1}$), while they contribute a factor $\omega^{(\text{product of the } E-\text{powers})}$, when they are not in the correct (modulo even permutation) order (like $E_2^{n_2}\, E_1^{l_1}\, E_3^{k_3}$). Contractions entirely within one of the factors don't contribute, while mixed contractions (involving at least 2, but not all, of the factors in (34)), all contribute a factor $\sqrt{\omega}^{(\text{product of the } E-\text{powers})}$, irrespective of their order.

Due to (32), all 'monomials' are proportional to one of the elements $E_{\vec{m}}$ (cp. (28)) – which therefore form a basis (with the convention $E_{\vec{0}} \equiv E$). Note that $2\pi M!\Lambda = \lambda \to 0$ is a 'classical limit' (resp. $\lambda \neq 0$ a 'quantisation' of the classical Nambu-structure) as, formally,

$$[\ln E_1, \ln E_2, \cdots, \ln E_M] \;=\; i\,\lambda\, E\; . \tag{35}$$

Having obtained this relation, one could of course start with objects $\ln E_r =: J_r$, $[J_1, J_2, \cdots, J_M] = i\,\lambda\, E$, and derive generalized 'Hausdorff-formulae' for products involving the $e^{i\, m_r\, J_r}$.

Of course, (35) cannot be true in any M-algebra containing only finite linear combinations of the basis-elements $E_{\vec{m}}$, as $T_{\vec{0}} = E$ never appears on the r.h.s. of (20); this is similar to the fact that the canonical commutation relations of ordinary quantum mechanics, $[q, p] = i\,\hbar\, \mathbf{1}$, cannot hold for trace-class operators. (35) may be justified by formally expanding $\ln E_r \;=\; -\sum\limits_{n_r=1}^{\infty} \sum\limits_{k_r=0}^{n_r} \binom{n_r}{k_r} \dfrac{(-)^{k_r}}{n_r}\, E_r^k$, using

$$[E_1^{k_1}, E_2^{k_2}, \cdots, E_M^{k_M}] \;=\; \frac{M!}{2}\,(1 - \omega^{k_1 \cdots k_M})\, E_1^{k_1} \cdots E_M^{k_M}$$

and then resumming recursively, after the first step obtaining

$$\frac{M!}{2}\ln E_1\cdots\ln E_M - \frac{M!}{2}\sum_{\substack{n_r,k_r\\ r>1}}{}'\cdots\ln(E_1\omega^{k_2\cdots k_M})E_2^{k_2}\cdots E_M^{k_M} = \frac{M!}{2}(\ln\omega)\cdot E\,, \tag{36}$$

as formally,

$$\sum_{n_r=1}^{\infty}\sum_{k_r=1}^{n_r}\binom{n_r}{k_r}\frac{(-)^{k_r}}{n_r}\,k_r\,E_r^k = E_r\cdot\sum_{n'=0}^{\infty}(E-E_r)^{n'} = E\,.$$

4. Breakdown of Conventional Symmetries

Let us now discuss the question, whether theories like (5) or (6) can have symmetries reminiscent of volume preserving diffeomorphisms; in particular whether the generators (2) may be 'translated' to finite dimensional analogues. * For simplicity, consider again $\Sigma = T^M$.

As $f^r = \partial_s\omega^{rs} = \epsilon^{rsr_1\cdots r_{M-2}}\partial_s\omega_{r_1\cdots r_{M-2}}$ for non-constant (divergence-free) vector-fields on T^M, (2) may be written in the form

$$K_{r_1\cdots r_{M-2}} = \int d^M\varphi\,\omega_{r_1\cdots r_{M-2}}\,\{p_i, x^i, \varphi^{r_1},\cdots,\varphi^{r_{M-2}}\}\,, \tag{37}$$

resp., in Fourier-components,

$$K^{\vec{l}}_{r_1\cdots r_{M-2}} = \sum_{\substack{\vec{m},\vec{n}\\ \in\mathbb{Z}^M}}\delta^{\vec{l}}_{\vec{m}+\vec{n}}\,p_{i\vec{m}}\,x_{i\vec{n}}\,(\vec{m},\vec{n},\vec{e}_{r_1},\cdots,\vec{e}_{r_{M-2}}) \tag{38}$$

(where $\vec{e}_r$ denotes the unit vector in the r-direction).

Suppose the deformed theory was invariant under transformations that are still generated in a conventional way by phase-space functions of the form

$$K^{\vec{l}} = \sum_{\vec{m},\vec{n}\in S} p_{i\vec{m}}x_{i\vec{n}}\,\delta^{\vec{l}}_{\vec{m}+\vec{n}}\,c_{\vec{m}\vec{n}}\,. \tag{39}$$

Using $[x_{i\vec{m}}, p_{j\vec{n}}] = \delta_{ij}\delta^{-\vec{n}}_{\vec{m}}$, while leaving open whether $S=\mathbb{Z}^M$ or $S=(\mathbb{Z}_N)^M$ as well as (independently) whether δ is defined mod N, or not, one has

$$[K^{\vec{l}}, \tilde{K}^{\vec{l}'}] = \sum_{\substack{\vec{m}_1\vec{n}\\ \in S}} p_{i\vec{m}}x_{i\vec{n}}\,\delta^{\vec{l}+\vec{l}'}_{\vec{m}+\vec{n}}\,\tilde{\tilde{c}}_{\vec{m}\vec{n}}$$

with (40)

$$\tilde{\tilde{c}}_{\vec{m}\vec{n}} = \sum_{\vec{k}\in S}\left(\delta^{\vec{l}-\vec{m}}_{\vec{k}}\,\delta^{\vec{l}'-\vec{n}}_{-\vec{k}}\,c_{\vec{m}\vec{k}}\,\tilde{c}_{-\vec{k}\vec{n}} - \begin{pmatrix}\vec{l}\leftrightarrow\vec{l}'\\ c\leftrightarrow\tilde{c}\end{pmatrix}\right),$$

*For $M=2$, this question was already considered in [4] and answered positively.

while $\dot{K}^{\vec{l}} = 0$ would require $c_{\vec{m}\vec{n}} = - - - - c_{\vec{n}\vec{m}}$ and

$$\begin{aligned} &\sin(2\pi\Lambda(\vec{a}_1, \cdots, \vec{a}_M)) \sin(2\pi\Lambda(\vec{a}_1 + \cdots + \vec{a}_M, \vec{a}_2{}', \cdots, \vec{a}_M{}')) \\ &\cdot c_{\vec{a}_1 + \cdots \vec{a}_1{}' + \cdots \vec{a}_M{}', \vec{a}_1{}'} \cdot x_{i_1 \vec{a}_1} x_{i_1 \vec{a}_1{}'} \cdots x_{i_M \vec{a}_M} x_{i_M \vec{a}_M{}'} = 0 \end{aligned} \tag{41}$$

(where for (41) consistency of the δ-functions used in (39) and $(25)_\Lambda$ with the index set S was assumed).

The effect of the $x_{i\vec{m}}$-factors in (41) is to make the product sin · sin · c, symmetric under any interchange $\vec{a}_r \leftrightarrow \vec{a}_r{}'$, as well as any simultaneous interchange $\vec{a}_r \leftrightarrow \vec{a}_s$, $\vec{a}_r{}' \leftrightarrow \vec{a}_s{}'$. Choosing, e.g., $\vec{a}_r{}' = \vec{a}_r (r = 1 \cdots M)$, with $\sin(2\pi\Lambda(\vec{a}_1 \cdots \vec{a}_M)) \neq 0$, (41) requires that

$$\sum_{\sigma \in S_M} c_{\vec{a}_{\sigma 1} + 2(\vec{a}_{\sigma 2} + \cdots + \vec{a}_{\sigma M}), \vec{a}_{\sigma 1}} = 0 . \tag{42}$$

This condition is insensitive to any alteration of the deformation: replacing the sine-function in (41) (resp. $(25)_\Lambda, \cdots$) by any other function of the determinant will still result in (42) as a necessary condition. Apart from $M = 2$ ($c_{\vec{a}_1 + 2\vec{a}_2, \vec{a}_1} + c_{\vec{a}_2 + 2\vec{a}_1, \vec{a}_2} = 0$ is trivially satisfied by any odd function) (42) is <u>not</u> satisfied by

$$c_{\vec{m}\vec{n}} = \sin(2\pi\Lambda(\vec{m}, \vec{n}, \vec{k}_1, \cdots, \vec{k}_{M-2})) , \tag{43}$$

- - - - nor would (40) be a linear combination of the generators (39), for such a $c_{\vec{m}\vec{n}}$; for $M = 3$, e.g., one would obtain

$$\begin{aligned} &\approx{c}_{\vec{m}\vec{n}}(\vec{l}\vec{l}'; \vec{k}\vec{k}') \\ = \; &\sin\left(2\pi\Lambda\left(\vec{l}, \vec{l}', \frac{\vec{k} + \vec{k}'}{2}\right)\right) \\ &\cdot \sin\left(2\pi\Lambda\left(\left(\vec{m}, \vec{n}, \frac{\vec{k} + \vec{k}'}{2}\right) + \left(\vec{m} - \vec{n}, \frac{\vec{l} - \vec{l}'}{2}, \frac{\vec{k} - \vec{k}'}{2}\right)\right)\right) \\ - \; &\sin\left(2\pi\Lambda\left(\vec{l}, \vec{l}', \frac{\vec{k} - \vec{k}'}{2}\right)\right) \\ &\cdot \sin\left(2\pi\Lambda\left(\vec{m}, \vec{n}, \frac{\vec{k} - \vec{k}'}{2}\right) + \left(\vec{m} - \vec{n}, \frac{\vec{l} - \vec{l}'}{2}, \frac{\vec{k} + \vec{k}'}{2}\right)\right) \end{aligned} \tag{44}$$

- - - - which means that the algebra closes only for $\vec{k}' = \vec{k}$ (for $\Lambda = \frac{1}{N}$ this would give N^3 closed Lie algebras, each of dimension N^3; in fact, each consisting of N copies of $gl(N)$). – In any case, if $c_{\vec{m}\vec{n}}$ was a function of $(\vec{m}_1 \vec{n}_1 \vec{k}_1, \cdots, \vec{k}_{M-2})$, one could let $\vec{a}_2, \vec{a}_3, \cdots \vec{a}_M$ differ only in the ('irrelevant') $\vec{k}_1, \cdots \vec{k}_{M-2}$ directions and obtain

$$f\,(((2M - 2)\vec{a}_2, \vec{a}_1, \cdots)) + (M - 1) f\,((2\vec{a}_1, \vec{a}_2, \cdots)) = 0 , \tag{45}$$

which eliminates all $c_{\vec{m}\vec{n}}$ that are non-linear functions of the determinant.

Interestingly, $c_{\vec{m}\vec{n}} = (\vec{m}, \vec{n}, \text{something})_{\text{if } M>2}$ is suggested by yet another consideration: replacing $\{p_i, x_i, \varphi^3, \cdots, \varphi^M\}$ (cp. (37); for notational simplicity taking $r_1 = 3, \cdots, r_{M-2} = M$) by

$$[P_i, X_i, \ln E_3, \cdots, \ln E_M] , \tag{46}$$

(with $P_i = p_{i\vec{m}} T_{\vec{m}}, X_i = x_{i\vec{m}} T_{\vec{m}}$) formally expanding the logarithms in a power series, using (20), and then (formally) summing again, one obtains something proportional to

$$p_{i\vec{m}}\, x_{i\vec{n}}\, T_{\vec{m}+\vec{n}} \cdot (m_1 n_2 - m_2 n_1)\,. \tag{47}$$

$$\begin{aligned}
&[P_i, X_i, \ln E_3, \cdots, \ln E_M] \\
&= p_{i\vec{m}}\, x_{i\vec{n}}\, (-)^{M-2} \sum_{n_3=1}^{\infty} \sum_{k_3=0}^{n_3} \cdots \sum_{n_M=1}^{\infty} \sum_{k_M=0}^{n_M} \binom{n_3}{k_3} \cdots \binom{n_M}{k_M} \frac{(-)^{k_3+\cdots+k_M}}{n_3 \cdots n_M} \\
&\quad \cdot [T_{\vec{m}},\, T_{\vec{n}},\, E_3^{k_3}, \cdots, E_M^{k_M}] \\
&\sim \sum \cdots \sin\left(2\pi\Lambda\,(\vec{m}, \vec{n}, k_3\,\vec{e}_3, \cdots, k_M\,\vec{e}_M)\right) \cdot T_{\vec{m}+\vec{n}+\vec{k}} \\
&\sim \sum \cdots \left(\sqrt{\omega}^{\,k_3 \cdots k_M\, z} - \sqrt{\omega}^{\,-k_3 \cdots k_M\, z}\right) (\sqrt{\omega})^{\prod_{r=1}^{M}(m_r+n_r+k_r)}\,. \\
&\quad \cdot E_1^{m_1+n_1}\, E_2^{m_2+n_2}\, E_3^{m_3+n_3+k_3} \cdots E_M^{m_M+n_M+k_M} \\
&\sim \sum \cdots \Big(\ln\Big(\sqrt{\omega}^{\,k_4 \cdots k_M\, z + \prod_{r\neq 3}(m_r+n_r+k_r)}\, E_3\Big) \\
&\qquad - \ln\Big(\sqrt{\omega}^{\,-k_4 \cdots k_M\, z + \prod_{r\neq 3}(\cdots)}\, E_3\Big)\Big) \cdot \sqrt{\omega}^{\,(m_3+n_3)\cdot \prod_{r\neq 3}(\cdots)} \\
&\qquad \cdot E_1^{m_1+n_1}\, E_2^{m_2+n_2}\, E_3^{m_3+n_3}\, E_4^{m_4+n_4+k_4} \cdots E_M^{m_M+n_M+k_M} \\
&\begin{pmatrix} z := (\vec{m}, \vec{n}, \vec{e}_3, \cdots, \vec{e}_M) = m_1 n_2 - m_2 n_1 \\ \vec{k} = (0,\, 0,\, k_3, \cdots, k_M) \end{pmatrix} \\
&= (\ln\omega)\, p_{i\vec{m}}\, x_{i\vec{n}}\, z\,(\vec{m}, \vec{n})\, \sqrt{\omega}^{\prod_1^M (m_r+n_r)}\, E_1^{m_1+n_1} \cdots E_M^{m_M+n_M} \\
&= (m_1\, n_2 - m_2\, n_1)\, p_{i\vec{m}}\, x_{i\vec{n}}\, (\ln\omega) \cdot T_{\vec{m}+\vec{n}} \\
&\quad \text{where (for } r > 3) - \sum_{n=1}^{\infty} \sum_{k=0}^{n} \binom{n}{k} \frac{(-)^k}{n}\, k \cdot E_r^k \cdot (\omega^{\cdots})^k = E \text{ was used.}
\end{aligned}$$

However,

$$c_{\vec{m}\vec{n}} = (\vec{m}, \vec{n}, \text{ anything}) \tag{48}$$

does <u>not</u> satisfy (41). Moreover, even if one considers more general deformations of the Hamiltonian, i.e. replacing the sine-function in (41) by an arbitrary odd (power-series) function f of the determinant, the corresponding condition,

$$\begin{aligned} f(\vec{a}_1, \cdots, \vec{a}_M)\, f(\vec{a}_1 + \cdots + \vec{a}_M,\, \vec{a}'_2, \cdots, \vec{a}'_M) \cdot (\vec{e}, \vec{a}'_1, \cdots) &= 0 \\ + (M \cdot 2^M - 1) \text{ permutations}\,, \end{aligned} \tag{49}$$

$\vec{e} = \sum_{r=1}^{M} (\vec{a}_r + \vec{a}'_r)$, can never be satisfied by any non-linear function f – as on can see, e.g., by choosing $\vec{a}'_r = \mu_r \vec{a}_r$. Supposing $f(x) = \alpha x + \beta x^{2n+1} = \cdots$, and denoting $(\vec{a}_1, \cdots, \vec{a}_M)$ by z, $\prod_{r=1}^{M} \mu_r$ by μ, the terms $\mu_1, \alpha\, z\, \beta\, (\mu\, z)^{2n+1}$, e.g., (occurring only twice, with the same sign) could never cancel.

The preceding arguments possibly suffice to prove that, independent of the above dynamical context, the Lie algebra of volume-preserving diffeomorphisms of $T^{M>2}$ does not possess any non-trivial deformations.*

5. Rigidity of Canonical Nambu-Poisson Manifolds

For the multilinear antisymmetric map (4), and $2M-1$ arbitrary functions $f_1,\cdots,f_{2M-1}$, one has (cp. [5]):

$$\begin{aligned}&\{\{f_M,f_1,\cdots,f_{M-1}\},\ f_{M+1},\cdots,\ f_{2M-1}\}\\&+\{f_M,\{f_{M+1},f_1,\cdots,f_{M-1}\},f_{M+2},\cdots,f_{2M-1}\}\\&+\cdots+\{f_M,\cdots f_{2M-2},\{f_{2M-1},f_1,\cdots,f_{M-1}\}\}\\&=\{\{f_M,\cdots,f_{2M-1}\},f_1,\cdots,f_{M-1}\}\ .\end{aligned} \tag{50}$$

Takhtajan [5], stressing its relevance for time-evolution in Nambu-mechanics [1], named (50) 'Fundamental Identity (FI)', and defined a 'Nambu-Poisson-manifold of order M' to be a manifold X together with a multilinear antisymmetric map $\{\cdots\}$ satisfying (50) and the Leibniz-rule

$$\{f_1\tilde{f}_1,f_2,\cdots,f_M\}\ =\ f_1\{\tilde{f}_1,f_2,\cdots,f_M\}\ +\ \{f_1,\cdots,f_M\}\,\tilde{f}_1 \tag{51}$$

for functions $f_r : X \to \mathbb{R}$ (or $\mathbb{C}$).

Without (51), i.e. just demanding (50) for an antisymmetric M linear map: $V\times\cdots\times V\to V$, V some vectorspace, Takhtajan defines a 'Nambu-Lie-gebra' [5], – also called 'Fillipov [6] Lie algebra' [7]). I would like to point out various other identities satisfied by canonical Nambu-Poisson brackets (4), and show that all of them – including (50)! – do not allow deformations (of certain natural type), if $M>2$.

At least from a non-dynamical point of view, all identities involving Nambu-brackets obtained from antisymmetrizing the product of two determinants formed from $2M$ M-vectors,

$$(\vec{a}_1\cdots\vec{a}_M)(\vec{a}_{M+1}\cdots\vec{a}_{2M}) \tag{52}$$

with respect to $M+1$ of the $\vec{a}_\alpha(\alpha=1\cdots 2M)$ should be treated on an equal footing. For $M=3$, e.g., one has – apart from

$$\begin{aligned}&(\vec{a}\,\vec{b}\,\vec{c}_1)(\vec{c}_2\,\vec{c}_3\,\vec{c}_4)\ -\ (\vec{a}\,\vec{b}\,\vec{c}_2)(\vec{c}_3\,\vec{c}_4\,\vec{c}_1)\\&+(\vec{a}\,\vec{b}\,\vec{c}_3)(\vec{c}_4\,\vec{c}_1\,\vec{c}_2)\ -\ (\vec{a}\,\vec{b}\,\vec{c}_4)(\vec{c}_1\,\vec{c}_2\,\vec{c}_3)\ =\ 0\ ,\end{aligned} \tag{53}$$

which gives rise to $(50)_{M=3}$ for functions $f\in T^3$ – also

$$(a\,\vec{c}_{[1}\,\vec{c}_2)(\vec{c}_3\,\vec{c}_{4]}\,\vec{b})\ =\ 0\ , \tag{54}$$

*M. Bordemann has informed me that apparently an even more general statement of this nature has recently been proven in [19].

yielding the following 6-term identity $(\mathrm{FI})_6$ (which can of course also be proven by using just the definition (4), $\{f,g,h\} = \epsilon_{\alpha\beta\gamma}\, \partial_\alpha f\, \partial_\beta g\, \partial_\gamma h$, rather than (54); i.e. not necessarily specifying the manifold X):

$$\{\{f,\ f_{[1},\ f_2\}\ f_3,\ f_{4]}\} = 0 \tag{55}$$

as well as the 4-term identity $(\widetilde{\mathrm{FI}})$,

$$\begin{aligned}&\{\{f,f_1,f_2\},\ g,f_3\}\\ &+\{\{f,f_2,f_3\},\ g,f_1\}\\ &+\{\{f,f_3,f_1\},\ g,f_2\} = -\{f,g,\ \{f_1,f_2,f_3\}\}\end{aligned} \tag{56}$$

- - - - each of which is independent of $(50)_{M=3}$ (while any 2 of the 3 identities yield the 3rd).

Naively, one would think that (56) should follow from $(50)_3$ alone, as (54) follows from (53) (perhaps one should note that for general M, a theorem concerning vector invariants [8] states, that any (!) vector-bracket identity is an algebraic consequence of

$$(\vec{a}_{[1}\,\vec{a}_2\,\cdots\,\vec{a}_M)\,(\vec{a}_{M+1]}\,\cdots\,\vec{a}_{2M}) = 0\,;$$

however, in the proof of (56) via vector-bracket identities, one in particular needs (54) for the special case $\vec{a} = \vec{b}$ – which cannot be stated as an identity between functions on X .) Curiously (with respect to a statistical approach to M-branes), vector-bracket identities ('Basis Exchange Properties' [9]) also play an important role in combinatorical geometry.

From an aesthetic point of view, the most natural quadratic identity for (4) is

$$\sum_{\sigma\in S_{2M-1}} (\mathrm{sign}\,\sigma)\{\{f_{\sigma1},\cdots,f_{\sigma M}\}\ f_{\sigma M+1},\cdots,f_{\sigma 2M-1}\} = 0\,. \tag{57}$$

For $M = 3$, e.g., one could see this to be a consequence of $(50)_3$ and (56) by grouping the 10 distinct terms in (57) according to whether $\{f_{\sigma1},f_{\sigma2},f_{\sigma3}\}$ contains both f_4 and f_5 (3 terms, 'type A'), only one of them (3 'B-terms' and 3 'C-terms') or none of them (1 term, 'type D'); for the B (resp. C)-terms one can use (56) while (50) for the A-terms, to get $\pm\ \{f_4,f_5,\{f_1\, f_2\, f_3\}\}$ for each of the 4 types, and for the B and C-terms with a sign opposite to the one obtained from the D (and A) term(s). (57) (taken without the derivation-requirement) is a beautiful generalisation of Lie-algebras ($M = 2$), and has recently started to attract the attention of mathematicians – mostly under the name of $(M-1)$-ary Lie algebras [10 - 13]. *

Unfortunately, all identities (50), (55)–(57), can be shown to be rigid, in the following sense: assuming that

$$[T_{\vec{m}_1},\cdots,T_{\vec{m}_M}]_\lambda = g_\lambda\left((\vec{m}_1,\cdots,\vec{m}_M)\right)\, T_{\vec{m}_1+\cdots+\vec{m}_M} \tag{58}$$

with $g_\lambda(x)$ a smooth odd function proportional to $x + \lambda^n\, c\, x^n$ as $\lambda \to 0$ $(n > 1)$ any of the above identities will require the constant c to be equal to zero (I have proved this

*I would like to thank W. Soergel for mentioning refs. [10]/[11] to me and J.L. Loday for sending me a copy of [10] and [12]; also, I would like to express my gratitude to R. Chatterjee and L. Takhtajan for sending me their papers on Nambu Mechanics (cp. [5]).

only for $M = 3$, and in the case of (57) – the a priori most promising case – for general $M > 2$).

Concerning

$$\begin{aligned} & g_\lambda\left((\vec{a},\vec{b},\vec{c}_1)\right)\, g_\lambda\left((\vec{a}+\vec{b}+\vec{c}_1,\vec{c}_2,\vec{c}_3)\right) \\ + \; & g_\lambda\left((\vec{a},\vec{b},\vec{c}_2)\right)\, g_\lambda\left((\vec{a}+\vec{b}+\vec{c}_2,\vec{c}_3,\vec{c}_1)\right) \\ + \; & g_\lambda\left((\vec{a},\vec{b},\vec{c}_3)\right)\, g_\lambda\left((\vec{a}+\vec{b}+\vec{c}_3,\vec{c}_1,\vec{c}_2)\right) \\ \overset{!}{=} \; & g_\lambda\left((\vec{c}_1,\vec{c}_2,\vec{c}_3)\right)\, g_\lambda\left((\vec{c}_1+\vec{c}_2+\vec{c}_3,\vec{a},\vec{b})\right) \;, \end{aligned} \tag{59}$$

i.e. the deformation of $(50)_{M=3}$, one could assume $z := (\vec{c}_1, \vec{c}_2, \vec{c}_3) \neq 0$, $\vec{a} = \sum_1^3 \alpha_r \vec{c}_r$, $\vec{b} = \sum_1^3 \beta_r \vec{c}_r$, such that $g(y) := \bar{g}_\lambda(y) := g_\lambda(zy)$ must satisfy

$$\begin{aligned} & g\,(\alpha_2\,\beta_3 - \alpha_3\,\beta_2) \,\cdot\, g\,(1 + \alpha_1 + \beta_1) \\ & \quad + \text{cyclic permutations} \\ & \quad = g\,(1) \,\cdot\, g\,(\alpha_2\,\beta_3 - \alpha_3\,\beta_2 \,+\, \text{cycl.}) \end{aligned} \tag{60}$$

for all α_r, β_r; which is clearly impossible for any nonlinear g of the required form. (e.g., as in next to lowest order in λ the terms $\alpha_1(\alpha_2\,\beta_3)^{n>1}$ appear only once).

Similarly, the deformation of (56) is impossible due to the analogous requirement

$$\begin{aligned} & g\,(\alpha_3)\; g\,(\beta_2 - \beta_1 \,+\, (\alpha_1\,\beta_2 \,-\, \alpha_2\,\beta_1)) \,+\, \text{cycl.} \\ & \quad \overset{!}{=} \; -\,g\,(1)\; g\,((\alpha_1\,\beta_2 \,-\, \alpha_2\,\beta_1) \,+\, \text{cycl.}) \;. \end{aligned} \tag{61}$$

Finally, concerning possible deformations of (57), let $(\vec{a}_1, \cdots, \vec{a}_M) \neq 0$, and

$$\vec{a}_{M+\bar{r}} \;=\; \sum_{s=1}^{M} \alpha_s^{(\bar{r})}\, \vec{a}_s \;\; (\bar{r} = 1, \cdots, M-1);$$

$$\text{then } g\,(1 + \alpha_1^{(1)} + \cdots + \alpha_1^{(M-1)}) \,\cdot\, g \underbrace{\begin{pmatrix} 1 & & \\ 0 & \vec{\alpha}^{\,(1)} \cdots & \vec{\alpha}^{\,(M-1)} \\ \vdots & & \\ 0 & & \end{pmatrix}}_{=:\;[1]} ,$$

e.g., contains (in next to lowest order in λ) a term $\alpha_1^{(1)} \cdot \alpha_1^{(2)} \cdot [1]$ (of total degree $(M+1)$ in the $\alpha_s^{(\bar{r})}$), which cannot appear anywhere else (in the same order in λ), – in contradiction to the assumption that (57) should hold for $[\cdots]_\lambda$ (cp. (58)) replacing the curly bracket (4).

6. A Remark on Generalized Schild Actions

Consider

$$S := -\int d\varphi^0 \, d^M\varphi \, f(G) \,, \tag{62}$$

where $G := (-)^M \det (G_{\alpha\beta})$, $G_{\alpha\beta} := \frac{\partial x^\mu}{\partial \varphi^\alpha} \frac{\partial x^\nu}{\partial \varphi^\beta} \eta_{\mu\nu}$, $\eta_{\mu\nu} = \mathrm{diag}\,(1, -1, \cdots, -1)$, $\alpha, \beta = 0, \cdots, M$ and f some smooth monotonic function like G^γ ($\gamma = 1$ resp. $\frac{1}{2}$ corresponding to a generalized Schild-, resp. Nambu-Goto, action for M-branes). Apart from a few subtleties (like $\gamma = 1$ allowing for vanishing G, while $\gamma = \frac{1}{2}$ does not) actions with different f are equivalent, in the sense that the equations of motion,

$$\partial_\alpha \left(f'(G) G \, G^{\alpha\beta} \, \partial_\beta \, x^\mu \right) = 0 \qquad \mu = 0 \cdots \cdot D-1 \tag{63}$$

are easily seen to imply

$$\partial_\alpha \, G = 0 \qquad \alpha = 0, \cdots, M \tag{64}$$

(just multiply (63) by $\partial_\epsilon x_\mu$ and sum) – unless $f(G) = \text{const.} \sqrt{G}$, in which case (62) is fully reparametrisation invariant and a parametrisation may be assumed in which $G =$ const. (such that (63) becomes proportional to $\partial_\alpha(G^{\alpha\beta} \, \partial_\beta x^\mu)$ also in this case). Due to

$$G = \sum_{\mu_1 < \cdots < \mu_{M+1}} \{x^{\mu_1}, \cdots, x^{\mu_{M+1}}\} \, \{x_{\mu_1}, \cdots, x_{\mu_{M+1}}\} \tag{65}$$

(63) may be written as (cp. [14] for strings, and [15] for membranes, in the case of $\gamma = 1$ resp. $\frac{1}{2}$)

$$\left\{ f'(G) \{x^{\mu_1}, \cdots, x^{\mu_{M+1}}\}, \, x_{\mu_2}, \cdots, x_{\mu_{M+1}} \right\} = 0 \,, \tag{66}$$

whose deformed analogue (note the similarity between $G =$ const. and condition (3.9) of [16])

$$\left[[x^{\mu_1}, \cdots, x^{\mu_{M+1}}], \, x_{\mu_2}, \cdots, x_{\mu_{M+1}} \right] = 0 \tag{67}$$

looks very suggestive when thinking about space-time quantization in M-brane theories.

7. Multidimensional Integrable Systems from M-algebras

Several ideas used in the context of integrable systems are based on bilinear operations. Our problems to extend results about low (especially 1+1) dimensional integrable field theories to higher dimensions may well rest on precisely this fact. Already some time ago, attempts were made to overcome this difficulty by generalizing Lax-pairs to -triples ([3], p. 72) and Hirota's bilinear equations for 'τ-functions' [17] to multilinear equations ([3], p. 107-111).

At that time, good examples were lacking, and – not being an exception to the rule that generalisations involving the number of dimensions (of one sort or an other) are usually hindered by implicitely low dimensional point(s) of view – the proposed generalisation of

Hirota-operators may have still been too naive; while hoping to come back to the question of multidimensional τ-functions in the near future, I would now like to give an example ($M > 3$ will then be obvious) for an equation of the form

$$\dot{\mathcal{L}} = \frac{1}{\rho}\{\mathcal{L}, \mathcal{M}_1, \mathcal{M}_2\} \tag{68}$$

being equivalent to the equations of motion of a compact 3 dimensional manifold $\widehat{\sum} \subset \mathbb{R}^4$ (described by a time-dependent 4-vector $x^i(\varphi^1, \varphi^2, \varphi^3, t)$), moving in such a way that its normal velocity is always equal to the induced volume density $\sqrt{g}$ (on $\widehat{\sum}$) devided by a fixed non-dynamical density $\rho(\varphi)$ ('the' volume density of the parameter manifold):

$$\begin{aligned}
\dot{x}_1 &= \frac{1}{\rho}\{x_2, x_3, x_4\} \\
\dot{x}_2 &= -\frac{1}{\rho}\{x_3, x_4, x_1\} \\
\dot{x}_3 &= \frac{1}{\rho}\{x_4, x_1, x_2\} \\
\dot{x}_4 &= -\frac{1}{\rho}\{x_1, x_2, x_3\}\ .
\end{aligned} \tag{69}$$

With the curly bracket defined as before (cp. (4)), it will be an immediate consequence of (68) that

$$Q_n := \int_{\Sigma} d^3\varphi\, \rho(\varphi)\, \mathcal{L}^n \tag{70}$$

is time-independent (for any n).

In [2] evolution-equations of the form (69) (in any number of dimensions) were shown to correspond to the diffeomorphism invariant part of an integrable Hamiltonian field theory (as well as to a gradient flow); one way to solve such equations is to note ([18], [2]) that the time at which the hypersurface will pass a point $\vec{x}$ in space will simply be a harmonic function.

In any case, the (a) form of $(\mathcal{L}, \mathcal{M}_1, \mathcal{M}_2)$ that will yield the equivalence of (69) with (68) is:

$$\begin{aligned}
\mathcal{L} &= (x_1 + ix_2)\frac{1}{\lambda} + (x_3 + ix_4)\frac{1}{\mu} + \mu(x_3 - ix_4) - \lambda(x_1 - ix_2) \\
\mathcal{M}_1 &= \frac{\mu}{2}(x_3 - ix_4) - \frac{1}{2\mu}(x_3 + ix_4) \\
\mathcal{M}_2 &= \frac{\lambda}{2}(x_1 - ix_2) + \frac{1}{2\lambda}(x_1 + ix_2)
\end{aligned} \tag{71}$$

(involving two spectral parameters, λ and μ). Surely, this observation will have much more elegant formulations, and conclusions.

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