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RESEARCH IN ELEMENTARY PARTICLE PHYSICS

MASTER

Technical Progress Report

Lawrence E. Kirsch and Howard J. Schnitzer

Department of Physics
Brandeis University
Waltham, Massachusetts 02254

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TECHNICAL PROGRESS REPORT

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Under this contract, research has been performed on both the theoretical and experimental properties of elementary particles. A brief description of work which has either been completed or is in progress is given below:

EXPERIMENT

MULTIPARTICLE SPECTROMETER PROGRESS

The analysis of data from two experiments at the Multiparticle Spectrometer (MPS) facility at Brookhaven has been the focus of the Brandeis experimental effort during the last year.

The experiments, E673 and E682, both utilize the three dimensional correlation device RAM[1] in conjunction with a high pressure ($\gamma_{threshold} \sim 10$) Cerenkov counter to select high momentum positive particles. For E682 this is combined with a second atmospheric pressure Cerenkov counter to trigger on the reaction

$$\pi^- p \rightarrow \begin{Bmatrix} p \\ K^+ \end{Bmatrix}_f + X$$

at an incident beam momentum of 16 GeV/c. The f subscript indicates kaons in the range 7 to 20 GeV/c and protons in the range 9 to 13 GeV/c. The raw flux yields a sensitivity of 62 ev/nb.

The other experiment, E673, triggers on the reaction

$$\begin{Bmatrix} K^- \\ \bar{p} \end{Bmatrix} p \rightarrow \begin{Bmatrix} p \\ K^+ \end{Bmatrix}_f + X$$

at a beam momentum of 5.0 GeV/c and the f subscript indicates kaons or protons above 1.3 GeV/c, without separation. The raw flux yields a sensitivity of 12 ev/nb for the K^- data and 6 ev/nb for the antiproton data.

I. BARYONIUM PRODUCTION

With a high level of sensitivity, both experiments have failed to observe the production of narrow final states in the $p\bar{p}$ system; a contradiction of earlier results reported by the CERN Ω spectrometer[2]. E682 set a limit of 5 nb,[3] five times lower than the CERN result in the same channel with a similar trigger. E673 set an effective limit of similar magnitude.[4] These experiments conclusively rule out the narrow baryonium states reported by CERN.

It now seems likely that if there exists four quark states which are coupled to baryon or meson exchange they are likely to be broad (~150MeV). However, baryonium which couples to exotic states may, due to color symmetry, be narrow (>10 MeV). This possibility has been explored in the reactions:

$$\pi^- p \rightarrow (\bar{p}p\pi^+)_f \; X^- \qquad (1)$$

$$\rightarrow (\bar{p}\Lambda^\circ\pi^+)_f \; X^\circ \qquad (2)$$

from E682.[5] The production of the forward meson requires exchange of an I=2 (or I=3/2) exotic state. No signal is observed. Assuming a width of Γ=30 MeV/c^2, the upper limit for baryonium production (95% confidence) is 10-40 nanobarns in the mass range 2.3-2.8 GeV/c^2.

II. INCLUSIVE HYPERON PRODUCTION

a) Λ°(E682)

A sample of two hundred thousand Λ°'s produced by 16 GeV/c pions is being used to measure the invariant cross section and polarization. Various quark models[1] predict that the invariant differential cross section as a function of the Feynman x variable behave as

$$E\frac{d^3\sigma}{dp^3} = f(p_\perp)(1-x)^n$$

where $p_\perp$ is the transverse momentum. The exponent n is determined by quark counting rules, and has a value between 2.0-3.0. This data yields a value of $n = 1.51 \pm 0.11$ where the error is only statistical.

The polarization of the Λ° in this data sample is also of interest due to the unexpected observation of a significant degree of Λ° polarization in pp inclusive reactions independent of energy and Feynman x. The experiments[7] measure an increasing Λ° polarization with increasing transverse momentum.

A preliminary analysis of our data indicates that the Λ°'s produced by pions are unpolarized up to a transverse momentum of 1 GeV.

b) Ξ^-(E673)

The data reduction for this experiment has been completed yielding a sample of ~150,000 events of the reaction

$$K^-p \rightarrow \Xi^-X$$

These events are being used to obtain the Feynman x dependence of the cascade polarization. The polarization measurements determine properties of the Regge exchanges which are not accessible to unpolarized cross sections. The data also addresses the question of the transverse momentum dependence of the hyperon polarization in a lower energy region.

III. E° PRODUCTION

Interest in the measurement of the E°(1420) derive from the suggestion[8] that there may be both an $s\bar{s}$ state and a bound state of gluons at this mass.

From the E673 data a study is underway on the reactions

$$\bar{p}p \rightarrow E_f^\circ X^\circ$$

$$K^-p \rightarrow E_f^\circ X^\circ$$

where the E° decays to $K^+K^\circ\pi^-$. Preliminary results suggest that the cross section for the production of E° from antiprotons is higher than that from kaons.

If the E° is a conventional $s\bar{s}$ quark state, then kaon exchange in the forward region should contribute copiously to the cross section. Conversely the strange quarks needed in antiproton annihilation must be created from the sea, hence suppressing the reaction. One resolution of this paradox is that the E° is a glueball, and that quark annihilation into gluons is favored by the antiproton reaction whereas quark exchange is favored by the kaon reaction.

IV. TECHNICAL PROGRESS

A) Lead Glass Hodoscope

A significant amount of effort was required to prove the feasibility of our proposal (E751) to study hyperon radiative decay, and then to acquire adequate data to complete the design of the lead glass hodoscope. The principal problem is to design a hodoscope which gives energy resolutions on the order of $12\%/\sqrt{E}$ and which can operate in the magnetic fringe field of the MPS. Shielding of the photomultipliers can be accomplished passively using a light pipe matched to the tube diameter covered by a μ-metal and iron shield. Active shielding requires a coil on each photomultiplier with the local field adjusted to cancel the MPS field.

The first tests were run behind the MPS during the fall of 1980. The tests were undertaken in response to the concerns of the high energy advisory committee that the experiment was unfeasible due to high photon rates and the fringe field. Using a pulsed LED it was shown that either the passive or active shielding technique was adequate; however, it was determined that lucite light pipes resulted in an unacceptable loss of light at the lead glass interface. A measurement of the photon rate produced by a heavy target indicates a trigger rate of less than twenty events per pulse in agreement with earlier calculations in the E751 proposal.

The second series of tests utilized the Brookhaven A2 test beam facility. These tests include the following: a single lead glass block mounted in (and out of) a Helmholtz coil to study magnetic field effect, and a seven lead glass block array, mounted on a remotely controlled table, to study position dependence of the energy resolution and shower sharing characteristics. Equipment for these tests was designed and built at Brandeis.

The tests have already indicated the need for thermal stability of the array and extreme care in photomultiplier base design. Preliminary results suggest that the lead glass light pipes result in a loss of 1-2% in energy resolution independent of whether a 2" or 4" length is used. Further measurements include a determination of the absolute energy resolution and the effect of lateral shower spread on the energy resolution. Analysis of this data is continuing.

B) MPS II Development

Contributions are being made to the software required for MPS II. In addition to overall system design the Brandeis group is developing modules for machine independent magnetic tape formatting, and beam reconstruction. Work is also underway on a Monte Carlo package which can be used for experimental design and the evaluation of pattern recognition algorithms in the drift chambers.

Footnotes

1) "Programmable Combinational Logic Trigger System for High Energy Particle Physics Experiments" (Brandeis, BNL, and CCNY), Nucl. Instrum. Methods 140,. 549 (1977).

2) Benkheire, et al, Phys. Lett. 65B, 483 (1977).

3) "Search for Narrow $\bar{p}p$ States in the Reaction $\pi^- p \to p\pi^- \bar{p}p$ at 16 Gev/c" (Brandeis, BNL, CCNY, SMU, and UMass), Phy. Rev. Lett. 45, 1611 (1980).

4) "Search for Narrow $\bar{p}p$ States in the Reaction $\bar{p}p \to \bar{p}p\pi^0$ and $\bar{p}p\rho^0$ at 5 GeV/c" (Brandeis, BNL, U. of Cincinnati, FSU, and SMU), Phys. Rev. Lett. 46, 395 (1981).

5) "Search for Narrow Structures in $p\bar{p}\pi^+$ and $\Lambda\bar{p}\pi^\pm$ Systems" (Brandeis, BNL, CCNY, SMU, and UMass). Submitted to Phys. Rev. Lett.

6) S. J. Brodsky and J. F. Gunion, Phys. Rev. D17, 848 (1978).

7) F. Lomanno, et al, Phys. Rev. Lett. 43, 2905 (1979) and references therein.

8) M. Chanowitz, Phys. Rev. Lett. 46, 981 (1981); K. Ishikawa, Phys. Rev. Lett. 46, 978 (1981).

THEORY

During the past contract year the theoretical physics group pursued research in quantum field theory and phenomenology. A major part of the program concentrated on effective field theories, subconstituent theories of quarks and leptons, quantum chromodynamics at finite temperature, grand unified theories, and calculational techniques in gauge theories. A summary of this research follows.

I. EFFECTIVE FIELD THEORIES

In earlier work Ovrut and Schnitzer developed a systematic discussion of effective field theories describing a given subset of fields of a quantum field theory and their low energy processes. This phase of the program concentrated on scalar field theories with broken symmetry, and dealt with subtleties of mixed light-heavy graphs. During the year under review, Ovrut and Schnitzer extended their methods to gauge theories, in a series of detailed studies. In this entire body of work, minimal coupling renormalization was employed, with an important aspect of the program the demonstration that a mass-independent subtraction scheme was compatible with the Appelquist-Carazzone decoupling theorem. Previous workers had employed the more cumbersome momentum-space subtraction schemes, as it had not been clear how to use a mass-independent subtraction scheme in the construction of effective field theories. Therefore, the presentation of effective field theories within the context of minimal subtraction renormalization represents a genuine simplification in methodology, and a clarification of the issues relating to decoupling theorems.

In detail, it was shown explicitly to the two-loop level, that the decoupling theorem of Applequist and Carazzone is valid, and a consistent light particle effective field theory exists, for quantum electrodynamics (QED) in arbitrary covariant α-gauges, and in non-Abelian gauge theory in $\alpha=0$ Landau gauge, renormalized by minimal subtraction. In a sequel to this work, these methods were then extended to arbitrary covariant gauges in non-Abelian theories as well. The demonstration of these results involved explicit two-loop calculations. Further, an inductive algorithm was presented which showed how to obtain a local low-energy effective field theory valid to n-loops, from knowledge of the effective theory and the complete theory at the (n-1) loop level.

These results were further elaborated in a study which presented a set of rules to be observed in the calculation of light-field, low-momentum processes using our method of effective field theory defined by minimal subtraction renormalization. The concept of the invariant charge, and its relevance to the problem of decoupling in theories renormalized by minimal subtraction, was discussed. These rules were applied to the calculation of the invariant charge and its associated beta-function in a non-Abelian theory with both massless and massive fermions. The threshold behavior of the beta-function appropriate to the invariant charge was displayed and analyzed.

The body of work reviewed above focused on the portion of the effective Lagrangian of dimension four and less. Ovrut and Schnitzer also considered the contribution of mixed light-heavy graphs for operators with dimension > 5 by considering a model problem. The contribution of heavy fermions (muons) to the electron anomalous magnetic moment in QED was considered within the context of effective field theories, constructed by means of functional integration, correct to order $\alpha^2\ m^2/M^2$. Although no violation of decoupling was found, it was shown that the leading contribution of the muon to the electron magnetic moment is incorrectly given by the <u>local</u> effective Lagrangian obtained from functional integration. It was also shown that this effective Lagrangian, with terms of arbitrary order in $(1/M^2)$, has the wrong analyticity in this variable in that the electron magnetic moment has a term of order $\alpha^2 m^4/M^4 \ln M^2/m^2$ which cannot be obtained from the local effective Lagrangian, even if the infinite series of non-renormalizable but local terms are retained. One must compute a graph of the complete theory (a mixed light-heavy graph) if the correct result is to be obtained.

Hagiwara studied extensions of two well-known examples of non-linear field theories by considering them to be effective Lagrangian theories. He first considered an Abelian gauge theory with various matter fields, and by integrating out the massive matter fields of the full theory, obtained an effective Lagrangian describing low energy multiphoton processes. The resulting model is an extension of the Euler-Heisenberg Lagrangian. He then examined constraints on the complete theory so that the residual effective Lagrangian exhibited additional symmetry. As a model example he assumed that the effective Lagrangian was the simplest non-polynomial Born-Infeld Lagrangian, and formulated an eigenvalue problem that must be satisfied by the complete theory for this to be valid. Unfortunately, if one restricts the matter fields to have spins of at most one, then the eigenvalue problem has no solution. Only the two-, four-, and six-photon effective interactions of the Born-Infeld theory are reproduced by a suitable choice of mass and coupling parameters of the matter fields. The higher photon interactions of the Born-Infeld Lagrangian are not reproduced.

As a side-product of the above research, Hagiwara found a non-Abelian generalization of the Abelian Born-Infeld Lagrangian. He also discussed some of the classical solutions of the non-Abelian equations of motion. Most notably, the classical non-Abelian Born-Infeld theory is a finite theory at the origin of coordinates, due to presence of an intrinsic mass-parameter.

II. SUBCONSTITUENT MODELS

In earlier work, Grisaru and Schnitzer derived necessary conditions for all the gauge bosons and elementary fermions of an arbitrary renormalizable non-Abelian gauge theory with gauge group G to lie on a Regge trajectory. The Reggeization of all the elementary gauge bosons requires that the Lie algebra of G be semi-simple, so that G can have no U(1) factors. The corresponding condition for the fermions requires that there be no massive fermion singlet under G. Based on these results, Schnitzer argued that in a properly unified gauge theory all particles of a given spin lie on Regge trajectories, in which case the particles in the Lagrangian will be simultaneously elementary and composite. If a gauge theory does not satisfy these criteria, it is at best only partially unified. [The Weinberg-Salam SU(2) x U(1) electroweak theory is an example of a partially unified gauge theory in this sense.] In order for a partially unified theory to be properly unified, additional degrees of freedom are required. These may arise from either 1) embedding in a larger theory, such as the embedding of the electroweak theory in a grand unified theory (GUT), or 2) subconstituents of the constituents in the partially unified Lagrangian, or 3) both. For example, it was shown that the effective Lagrangian for the observed strongly interacting vector mesons, the ρ, ω, ϕ, K*, J/ψ, Υ, D*, F*, cannot be properly unified in our sense by embedding and that subconstituents (quarks) are required to achieve a properly unified theory. A consideration of the general pattern of Regge trajectories in field theories leads one to propose a search for spin 3/2 quarks and leptons and spin 2 weak gauge bosons in the Tev region, a proposal not unique to our point of view. However, the correct interpretation of such a hypothetical discovery will require correlation with the Higgs boson mass, as well as features typical of strong interaction physics. Work in progress is also focusing on possible phenomenological implications from this point of view.

During the past year Grisaru and Schnitzer began a study of the possible Regge structures in O(8) supergravity. It is known that O(8) supergravity can not contain the phenomenological SU(2)xU(1)xSU(3) theory as a subgroup. However, there is also a (hidden) local SU(8) structure in O(8) supergravity. It has been speculated by Ellis, Gaillard, Maiani, and Zumino that SU(8) invariance characterizes the bound-state structure of O(8) supergravity, and that these bound-states are in fact the quarks, gauge bosons, and scalar mesons of phenomenological GUT theories. Thus the fields of O(8) supergravity would be the subconstituents of the "observed" quarks, leptons and gauge bosons. The calculation in progress is extremely difficult, and no results are available as yet. This calculation is approximately at the half-way point after several months of work, and Grisaru and Schnitzer hope to have useful results in the next contract year. Because of the importance of the issue, this work will be pursued vigorously in spite of the length and difficulty of the analysis.

Abbott and Farhi have constructed a preon model of the weak interactions based on the standard $SU(2)_L \times U(1)$ gauge Lagrangian, which accounts for the observed weak interactions as a residual interaction between fermions which are bound-states of the confined preons. The preons are confined since the parameters of the model are chosen so that the Higgs bosons do <u>not</u> get vaccuum expectation values. As a result the Higgs bosons and fundamental gauge bosons are confined as well, and the observed states transform as <u>singlets</u> of the underlying $SU(2)_L$ group. The bound-states of the model have a global SU(2) symmetry and a local U(1) electromagnetic interaction. This model can account for the low-energy charged and neutral current interactions. In addition, it is an interesting preon model of quark and lepton structure which satisfies the 't Hooft consistency conditions, and gives the correct quark and lepton masses and quantum numbers.

III. FINITE TEMPERATURE QCD

Anishetty has concentrated on understanding quantum chromodynamics (QCD) at finite temperature. He has focused on two particular aspects of the subject, which we review.

Asymptotic freedom implies that perturbation theory is valid for QCD at high temperatures. Since it is a theory of massless interacting bosons (gluons), perturbation theory is subject to infrared divergences at any finite temperature. It has been speculated that the theory cures itself of this difficulty by generating masses for the gluons. Furthermore, it is believed that this mechanism may play a dominant role in understanding the suppression of magnetic monopoles in the early big-bang cosmology. The nature of these infrared divergences is common to all theories of massless interacting bosons. However since gluons carry conserved color charge, a macroscopic ensemble of gluons is constrained to obey the conservation of this charge. This implies that the thermal fluctuation of gluons is constrained in color space, with the constraint imposed throught the introduction of a chemical potential. It has been realized that a non-vanishing chemical potential at finite temperature cures the infrared divergence by making (N^2-2) gluons massive in a SU(N) non-Abelian gauge theory. Work is in progress to determine the chemical potential at very high temperatures for a color singlet statistical ensemble of gluons.

It has been argued that macroscopic systems of confined quarks at high temperatures may undergo a phase transition to free quarks. A possible way to produce such macroscopic systems is by means of central collisions of heavy ions such as U^{238} at energies of the order of 50 GeV/nucleon or more in the center of mass frame. Anishetty, in collaboration with Glendenning, Guylassy, Koehler, and McLerran, have computed the thermodynamic properties of the resulting fireball, including strange particles, in three different models: a) quark-gluon matter at very high temperatures, b) nuclear matter with all known excited resonances at finite temperatures, and c) nuclear matter modified by Hagedorn exponential spectrum for excited resonances at finite temperatures. The results are:

1) A crude estimate of the nature of the phase transition from nuclear matter (confined quarks) to free quarks, based on perturbation theory, shows it to be weakly first order.

2) The ratio of strange to anti-strange mesons $(K^+ + K^\circ)/(K^- + \bar{K}^\circ)$ inside the fireball can vary from 1.5 in nuclear matter to 5 in quark-gluon matter at fireball center of mass energies of the order of 5-10 GeV/baryon

3) The ratio of strange baryons to the total number of baryons in the fireball are of the order of 0.3 in nuclear matter, 0.4 in quark matter, and 0.1 in Hagedorn matter with fireball center of mass energies of 5-10 GeV/ baryon. Hagedorn matter seems to be clearly distinguishable from the other possibilities in this regard. However, quark matter and nuclear matter with all known resonances become sufficiently different to be distinguished only when fireball energies reach approximately 15 GeV/nucleon.

IV. GRAND UNIFIED THEORIES

Most grand unified theories predict that the proton will decay with a lifetime which will soon be accessible to experiments. Rates and branching ratios for the 2-body decay modes have been calculated by many people. Abbott, Wise, and Blankenbecler have extended these results to the 3-body decays of the proton using current algebra and final-state rescattering techniques. Their results indicated that the 3-body modes could constitute a substantial fraction of the total proton decay modes.

In the standard big-bang cosmology, the early universe is characterized by very high temperatures at which the gauge symmetries of electroweak and grand unified models were presumably unbroken. As the universe cooled, phase transitions took place which brought these theories to their present form as spontaneously broken gauge theories. If these phase transitions were first order, extreme supercooling might have occurred with interesting cosmological consequences. Abbott studied the example of SU(5) broken by means of the Coleman-Weinberg mechanism. In this model supercooling occurs, and the SU(5) phase transition is controlled, i.e., either driven or suppressed by gravitational effects. It is unusual and interesting to see gravity playing such an important role in elementary particle field theory.

V. CALCULATIONAL TECHNIQUES IN GAUGE THEORIES

The background field method is a technique for calculating in gauge field theories without losing explicit gauge invariance, and hence makes gauge theory calculations easier both technically and conceptually. Abbott presented a new derivation of the method and derived relations between quantities calculated using the background field technique and the conventional functional approach. Feynman rules were presented, and it was shown that the renormalization program can be carried out without any reference to the fields appearing inside closed loops. As an example, Abbott computed the two-loop β-functions of Yang-Mills theory, a calculation which clearly demonstrated the power of the method.

Publications from May 1, 1980 to April 30, 1981

Experimental

1) "Search for Cascade Resonances," BAPS 25, 580 (1980).

2) "Peripheral Production and Decay of $K_s^0K_s^0$ in the Reaction $\pi^-p \to K_s^0K_s^0$ + Neutrals at 15.4 GeV/c" (with Syracuse University, Brookhaven National Laboratory, and University of Cincinnati), Phys. Rev. D22, 1503 (1980).

3) "Search for Narrow $\bar{p}p$ States in the Reaction $\pi^-p \to p\pi^-\bar{p}p$ at 16 GeV/c" (with Brookhaven National Laboratory, City College of New York, Southeastern Massachusetts University, and University of Massachusetts), Phys. Rev. Lett. 45, 1611 (1980).

4) Search for Narrow $\bar{p}p$ States in the Reaction $\bar{p}p \to \bar{p}p\pi^0$ and $\bar{p}p\rho^0$ at 5 GeV/c" (with Brookhaven National Laboratory, University of Cincinnati, Florida State University, and Southeastern Mass. University), Phys. Rev. Lett. 46, 395 (1981).

5) "Search for Narrow Structures in $\bar{p}p\pi^+$ and $\Lambda\bar{p}\pi^{\pm}$ System" (with Brookhaven National Laboratory, City College of New York, Southeastern Massachusetts University, and University of Massachusetts), submitted to Phys. Rev. Lett.

Theoretical

Effective Field Theories

6) "Decoupling Theorems and Effective Field Theories" (Ovrut and Schnitzer), pg. 445 Proceedings of the 20th International Conference on High Energy Physics Madison, Wisc. June 1980, ed. by L. Durand and L.G. Pondrom.

7) "The Decoupling Theorem and Minimal Subtraction" (Ovrut and Schnitzer), Phys. Lett. B100, 403 (1981).

8) "Gauge Theories with Minimal Subtraction and the Decoupling Theorem" (Ovrut and Schnitzer), Nucl. Phys. B179, 381 (1981).

9) "Low Energy and Threshold Calculations Using Effective Field Theory" (Ovrut and Schnitzer), Nucl. Phys. B184 109 (1981).

10) "Effective Field Theories and Higher Dimensional Operators" (Ovrut and Schnitzer), submitted to Phys. Rev. D.

11) "Gauge Theory and Effective Lagrangians" (Ovrut and Schnitzer), submitted to Nucl. Phys. B.

12) "An Effective Lagrangian for Multiphoton Processes and a Non-Linear Born-Infeld Lagrangian" (Hagiwara), Nucl. Phys. B (to be published).

13) "A Non-Abelian Born-Infeld Lagrangian" (Hagiwara), J. Phys. A (to be published).

Subconstituent Models

14) "Radial and Regge Excitations in Unified, Grand Unified, and Subconstituent Models" (Schnitzer), submitted to Nucl. Phys. B.

15) "Are the Weak Interactions Strong?" (Abbott and Farhi), Phys. Letters B101, 69 (1981).

16) "A Confining Model of the Weak Interactions" (Abbott and Farhi), submitted to Nucl. Phys. B.

Supersymmetry

17) "Regularizations and Super-Conformed Anomalies" (Hagiwara, Pi, Tsao), Ann. of Phys. (N.Y.) 130, 282 (1980).

Finite Temperature QCD

18) "Central Collisions between Heavy Nuclei at Extremely High Energies: The Fragmentation Region" (Anishetty, Koehler, and McLerran), Phys. Rev. D22, 2793 (1980).

Grand Unified Theories

19) "Three-Body Decays of the Proton" (Abbott, Wise, and Blankenbecler), Phys. Rev. D23, 1591 (1981).

20) "Gravitational Effects on the SU(5) Breaking Phase Transition for a Coleman-Weinberg Potential" (Abbott), Nucl. Phys. B (to be published).

Calculational Techniques

21) "The Background Field Method Beyond One Loop" (Abbott), Nucl. Phys. B (to be published).

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