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The Teaching of High Energy Physics in British Universities

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Abstract

An analysis is given of a survey of the teaching of High Energy Physics in British universities. The subject changes quickly, and there is a continual conflict between new and old material. Different courses may deal with this in different ways. To find out what is actually being taught to students, details were obtained from all 50 University Physics departments in the UK by means of a questionnaire. This covered the course structure – whether it was optional or compulsory or contained both elements – the number of lectures given, and the topics covered in the syllabus. The replies give a comprehensive picture of the state of undergraduate teaching of High Energy Physics in the UK.

1 Introduction

Designing a lecture course in Particle Physics for undergraduates is a difficult business. There are lots of new and exciting results and ideas to be included, but also a great deal of more traditional material that one is reluctant to discard. The course designer receives inevitable criticism from the Extreme Applied ("But what *use* are quarks to industry?") to the Extreme Academic ("But *surely* you teach them the Dirac equation?"). It's very hard to decide what to leave in and what to leave out, and how it can all be fitted together: whether to teach the course in historical order, from the atom down to the quarks, or in logical order, from the quarks up to the atoms.

As well as these long-standing considerations, we now have to consider the place of HEP teaching within the proposed new system of 4 year degree courses [1]. It is temptingly easy to pontificate on what one considers should be taught in such a course, on the basis of one's own judgement. The working party on Higher Education have indeed made such a suggestion (op. cit. Annex 2). The Institute of Physics HEP/Education subgroup felt that an important preliminary input to such any discussions would be to find out what was actually being taught in UK universities, and that those who were faced with the task of designing (or defending) their own syllabus would find this information helpful.

2 The Questionnaire

The questionnaire was sent out to all 50 UK universities with Physics departments. 28 replied, and a further 18 replied after a polite reminder. A slightly less polite reminder elicited replies from 3 of the remaining 4, and one final recipient succumbed only after a third prompting.

Replies are inevitably subjective. It was asked what topics were 'covered' in the course, defining this to mean

> 'that the student has been exposed to it at some level, in lectures or wherever: not necessarily very deeply but more than just a mention of the name'

but even this is somewhat elastic. As an interesting and unintended control, at one institute the questionnaire was filled in twice by different people, and there were significant differences between the two independent responses. Hopefully these discrepancies are exceptional, given the obvious lack of co-ordination in this instance. But this emphasises that replies should be taken as showing general patterns, and the figures should not be taken at their face accuracy.

Strict anonymity was guaranteed, in order to obtain honest replies, therefore the results tabulated here do not name particular institutions. In the same spirit of avoiding league tables and value judgements, there is no attempt to distinguish the teaching patterns of those universities with and without active research groups in HEP.

[1] "The Future Pattern of Higher Education in Physics"; Final report of the Higher Education Working Party of the IoP, the Standing Conference of Physics professors, and the Committee of Heads of Physics in Polytechnics, August 1990

3 Course Structures

Of the 50 institutes, one does no teaching in HEP; it teaches only service courses for other departments and does not offer a physics degree. (A second department is similarly placed at present, but it has plans to resume in the near future and these data were used). Of the 49 that do teach HEP, 45 give a set of core lectures which are taken by all students (for the Open University the Science Foundation course was included under this heading). Of these, 23, including most of the larger institutions, also offer further lectures available as an optional specialist course or courses, and the other 22 do not. ('Optional' is used here in the sense that the student may choose it from a range of alternatives offered; once chosen the course is assessed in the usual compulsory way.) The remaining 4 offer an optional course, but do not teach HEP in the core lectures, so in these it is possible for a physicist to graduate without having been taught any High Energy Physics. However for most of the optional HEP courses (whether preceded by a compulsory course or not) the take-up rate is fairly high, so there are few such students.

This confirms the result of a previous survey, done by the Open University, that HEP is in the mainstream of undergraduate teaching. A graduate in physics has almost certainly been taught some amount of HEP, whatever university they come from, and has probably been offered the chance of more specialised study.

It was asked how many lectures were devoted to HEP. Many topics cross subject boundaries and may be taught under different headings in different places: the Yukawa exchange theory, for example, may be regarded as part of Nuclear Physics, and Synchrotron Radiation is often taught as part of Electromagnetism. Thus the number of lectures 'on HEP topics' is subject to differences of interpretation (and no such measure is available for the OU courses). Figure 1 shows a histogram of the results for those places where core lectures are given but no specialised option offered. The numbers vary widely, between about 10 and 30 lectures. Those courses with only a few lectures are generally at institutes offering only some form of joint 'Physics with ...' degrees. Where a further optional course is provided the core tends to be rather shorter, perhaps around 10 lectures, as displayed in Figure 2. The length of an optional course, as shown in Figure 3, displays more consensus at around 20 lectures.

4 Syllabus Content

A list of topics was given, and it was asked whether they were taught. (The much more difficult question of what students *learnt* was not considered.) Topics that were taught were then subdivided into those that formed part of a core taken by all students, and those only available in a specialised option. (The option in question may be labelled 'HEP' or something else). We did our best to define the terms by saying

> 'By a topic taught to "all" students, we mean that all, or virtually all, students taking a single honours physics degree will have met it in their mainstream, core, compulsory courses.'

Results are presented and discussed here. (The order has been rearranged for purposes of presentation.) A few replies added topics we failed to list, but these are not included as there is no systematic way of collating such information.

4.1 Accelerators

Topic	Core	Option
Motion of charged particles in Magnetic fields	39	5
The Cyclotron	29	6
The Synchrotron	28	8
Colliding Beam accelerators	20	12
Synchrotron radiation	17	12
Real accelerators (LEP,HERA, etc)	14	12
Strong Focussing	10	5

This shows that virtually all students have been taught about the behaviour of a charged particle in a magnetic field – hardly surprising, as this is basic electromagnetism. Most have covered the ideas of circular particle accelerators. Many, but not all, have met (possibly in a specialist course) practical details like synchrotron radiation and the need for colliding beam machines to increase the effective energy, and considered some real modern accelerators. Detailed technical points, like strong focussing, are studied only by a few.

4.2 Detectors

Topic	Core	Option
Bubble chambers	24	9
Scintillators	23	13
Cloud chambers	18	3
The Bethe-Bloch formula	16	8
Radiation Length	16	7
Spark Chambers	14	9
Cherenkov Counters	14	13
Silicon and Solid State detectors	14	10
Photographic emulsions	13	6
Drift Chambers	9	14
Calorimetry	5	10

Bubble chambers are very popular, possibly because they produce pedagogically useful pictures. Perhaps more surprisingly, scintillators are also widely taught. Other detectors are also taught to varying extents: typically the student will meet bubble chambers, scintillators and two or three other techniques. Some places go into the details of the processes: the Bethe-Bloch formula for energy loss, and the definition of Radiation Length, but many do not.

Some courses appear to be victims of history, describing cloud chambers and photographic emulsions but not more modern techniques. The drift chamber and calorimetry, the main detectors in today's experiments, are comparatively neglected.

4.3 Theoretical ideas

Topic	Core	Option
Antiparticles	40	6
Relativistic Kinematics	35	8
Virtual Particles	33	12
Feynman Diagrams (as pictures)	31	14
Yukawa Potential	28	11
Symmetries, Invariance and Conservation laws	28	18
The photon, W, Z and gluon as Gauge Bosons	21	21
Helicity	15	15
The Gauge Principle	12	13
The Big Bang	11	17
The Lagrangean	11	10
The Klein-Gordon Equation	9	17
The Dirac Equation	8	21
SU_2 and SU_3 (by name)	7	17
The Higgs model	8	10
GUTS	8	9
The Inflationary Universe	5	11
Least Action principle (path integrals)	4	7
Group theory	2	21

There is general agreement that students should know about relativistic kinematics (invariant masses etc.) and have an idea of particles, antiparticles, the symmetries and invariance principles describing them, and how they interact by exchanging Yukawa-style virtual particles, and the use of Feynman diagrams to describe this.

Some topics, like helicity, the Higgs, GUTS, and the big bang (before and after the first 3 minutes) seem to be regarded as optional extras, put into a course if there's room as they're interesting, but left out of others without harming them. Many replies pointed out that although they cover such topics they do so only in a qualitative way.

Differences appear in the treatment of basic theoretical ideas: Least Action, The Lagrangean, the Gauge Principle, the Klein-Gordon and Dirac equations, SU_2, SU_3, and group theory in general. These are nothing if not fundamental: one can use them as a basis for a course, or one can ignore them completely; they are not such optional inclusions as the topics of the previous paragraph. (Yet many courses manage to use the idea of a 'gauge boson' without a discussion of the principle of gauge invariance.) There is no consensus here. Many places include such topics in specialised courses. Others regard them as fundamental and include them in their compulsory core. Others ignore them completely, even for their specialised courses. The 'theoretical theory' content of courses varies very widely from place to place, and one cannot lay down any expectations as to what a graduate will have met.

4.4 General Phenomenology

Topic	Core	Option
The hierarchy of 4 forces	42	5
Simple quark model of Hadrons	40	7
Nomenclature: Leptons and Hadrons	39	8
Nomenclature: Mesons and Baryons	38	8
Lepton Number	37	9
Baryon number	36	10
Strange particles	36	10
Strangeness conservation	32	13
Associated production	30	11
Cross sections and event rates	30	10
Fermi's Golden rule – what it is	23	12
Fermi's Golden rule – derivation	13	11
C parity	14	16
Phase space factor	13	14
2 body phase space calculations	7	11
G parity	4	13
3 body phase space: Dalitz plots	2	11
n body phase space	0	1

The classification of forces (strong, electromagnetic, weak, and gravitational) and particles (hadrons, mesons, leptons, baryons) are taught essentially everywhere, together with the appropriate conservation laws. Students are told that hadrons are made of quarks, and meet the strange particles as an instance of this.

They are also introduced to the idea of a cross section as a measure of reaction rate, and have usually been shown how to obtain this from Fermi's Golden Rule (often, but not always, with the derivation of this using time dependent perturbation theory). They may well have met the phase space factor, but are unlikely to have done calculations with it, or have used the idea of a phase-space (Dalitz) 3 body plot for investigation of resonances etc, unless they have taken a specialised course.

Charge Parity, as an operation/conserved quantum number, is a reasonably popular topic. G parity is understandably less so, but still quite common in specialist courses.

4.5 The Weak Interactions – General

Topic	Core	Option
Neutrinos: their production and detection	31	9
Weak decays of strange particles	28	14
Discovery of the W and the Z	27	16
The Z and the number of generations	21	12
Measurements of the Z at LEP	18	10
Properties of the τ lepton	9	12
The Cabibbo angle	5	15
The Z and precision asymmetry measurements	3	3
The Kobayashi-Maskawa Matrix	1	10

Weak interactions of neutrinos and strange particles are regarded as important and taught in most places. (The list did not include topics on β decay as, rightly or wrongly, it was felt to be 'nuclear' physics.) More modern developments: the discovery if the W and Z, and the measurements at LEP that measured the number of generations (with massless neutrinos) are well covered, though few places appear to consider future precision measurements at LEP to be worth the difficulty of explanation.

Not much attention is paid to the τ lepton, or other members of the third generation, as will appear in a subsequent section.

It is hardly surprising that Kobayashi-Maskawa mixing is treated by few places, and then only as a specialised topic. More surprising is that the simpler Cabibbo mixing is disdained to almost the same extent.

4.6 The weak interactions–P and CP

Topic	Core	Option
Parity	29	13
Parity violation	27	16
The ^{60}Co experiment	24	16
The $K^0 - \overline{K^0}$ system	13	17
CP violation	11	17
The $\tau - \theta$ paradox	9	16

Parity and its violation are obviously treated as an important piece of physics. The ^{60}Co experiment is still taught, despite the fact that it was done in 1957, before today's students were born, it is still a dramatic and beautiful effect. The $\tau - \theta$ paradox, by contrast, is now relatively downplayed; despite its historical importance it is less pedagogically useful.

The $K^0\overline{K^0}$ system and CP violation are often treated in specialised courses where they are not covered in the core.

4.7 Quarks in hadrons

Topic	Core	Option
The Quark model of hadrons - Multiplets	31	11
Discovery of the Ω^-	29	9
Isospin classification	28	13
The Charm quark - the J/ψ	26	12
Hadron resonances - ρ, Δ, K^* etc	22	16
Quarks as partons:Deep inelastic scattering	16	14
The Breit-Wigner formula	16	13
The SU_3 analysis of multiplets	12	14
The Charm quark - D mesons	12	13
Angular momentum and angular distributions	11	15
Partial wave analysis	8	12
Isospin - Clebsch-Gordan coefficients	7	11
Properties of the b quark and B hadrons	7	11
Structure functions	5	8
Properties of the t quark	4	9
SU_6 multiplets	0	4
Regge Poles	0	1

Most courses extend the simple quark model (c.f. section 4.4) to the description in terms of multiplets (octets, decuplets, etc). Sometimes this involves going into details of the SU_3 classification, but in many cases this is not done. SU_6 is rarely mentioned. The success of the model in the prediction and discovery of the Ω^- is widely covered.

Particle classification using isospin is widely taught, though the numerical use of Clebsch-Gordan coefficients for calculations in this topic is much less common.

The resonance description of strongly-unstable hadrons is widespread, usually, but not always, with the numerical description using the Breit-Wigner formula. Angular distributions and their links with angular momentum are covered in about half the courses, and this is sometimes continued to the description of partial wave analysis.

The charm quark in the form of the J/ψ particle is very widely covered: in the form of the D mesons rather less so. The b and t quarks are, like the τ, not widely studied.

The pointlike nature of quarks in the nucleon is fairly widely covered, though usually without by a discussion of the details of the actual structure functions.

One valiant lecturer is teaching undergraduates about Regge poles – though it was added that this course is in the process of a thorough revision.

5 Other points

Several replies raised (quite spontaneously) the issue of a textbook. That of Perkins [2] is often felt to be too advanced for the courses and students involved. Many courses use Hughes [3] though this has now gone out of print.

A final question asked was 'Are you and your students generally happy with the content and structure of the course'. Most (35) replied 'Yes' to this, often adding that the students found the material interesting and stimulating, though there were several comments on the problems of packing a lot of material into too few lectures, often resolved by treating interesting but difficult material qualitatively. Perhaps, as one reply suggested, we concentrate too much on knowledge-content and should think more about what skills we are trying to teach.

6 Conclusions

An area of consensus emerges: one can draw up a list of topics covered by most courses

- The 4 forces
- Yukawa theory
- Feynman diagrams at the pictorial level
- antiparticles
- the simple quark model in terms of multiplets
- strangeness
- isospin classification
- baryon and lepton number and conservation laws
- neutrinos
- strange particle decays
- a bit about the W and the Z
- parity and its violation
- circular accelerators
- bubble chambers and scintillators
- what a cross section is

[2] D. H. Perkins: *Introduction to High Energy Physics*, 3rd Edition, Addison-Wesley 1987
[3] I. S. Hughes: *Elementary Particles*, 2nd Edition, Cambridge 1985

Most graduating physicists will have met most of these. Anyone designing a particle physics course should reckon to include them if they wish to produce students whose study of particle physics is in accord with general practice. But such areas are obvious, and their inclusion does not form a great constraint. However even this modest list goes some way beyond the syllabus suggested by the Higher Education Working Party and suggests that they may have been over-cautious.

Outside these limited and basic set of topics, particularly in the specialist option courses, there are great variations in the content of the syllabus. So any course designer can choose what topics make best sense, in view of their own preference, the types of students involved, and preparatory and follow-on courses at that institution, without worrying that by doing so they are out-of-line. It is hoped that the results of this questionnaire will help such lecturers rebut criticisms of the 'But you must include ...' variety, and also of the 'Surely ... is far too obscure' type. If you think you should cover synchroton radiation, say, or solid state detectors or C parity in your course, then you are in good and numerous company. On the other hand, if you wish to omit such items you are in good company there too.

This variation in specialised courses makes for difficulties at the post-graduate level, but this is a price that has to be paid. It is worth noting that the take-up rate of these optional courses is high; several hundred students every year take such a 'specialist' course, of which only a few dozen will go on to further study in the field. For most students this will be the final course they receive on HEP, and one should concentrate on making it complete and satisfactory in itself. Inclusion of topics solely because they'll be needed if the students go on to postgraduate work in the field should be resisted.

There is some evidence, particularly in the areas of detectors, that historical techniques may be being overemphasised at the expense of the new. But in most cases older material is being retained where it is clearly of use in teaching (such as bubble chambers and the ^{60}Co experiment), and disappearing to specialised courses or altogether where it is of less relevance. It is clear that new, recent, material is being included in the courses taught in typical UK universities. 'I change it slightly every year, to try to keep up to date' as one respondent commented, from a University that is not active in HEP research.

7 Acknowledgements

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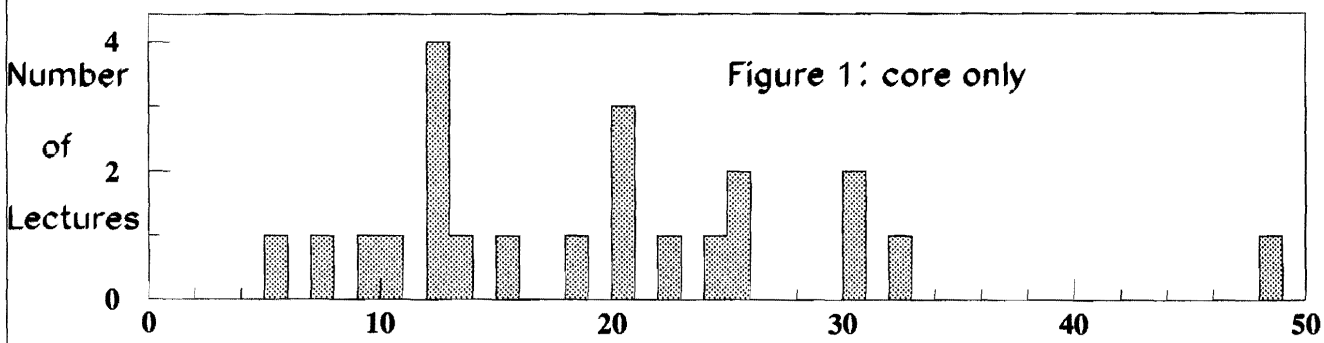

Figure 1: core only

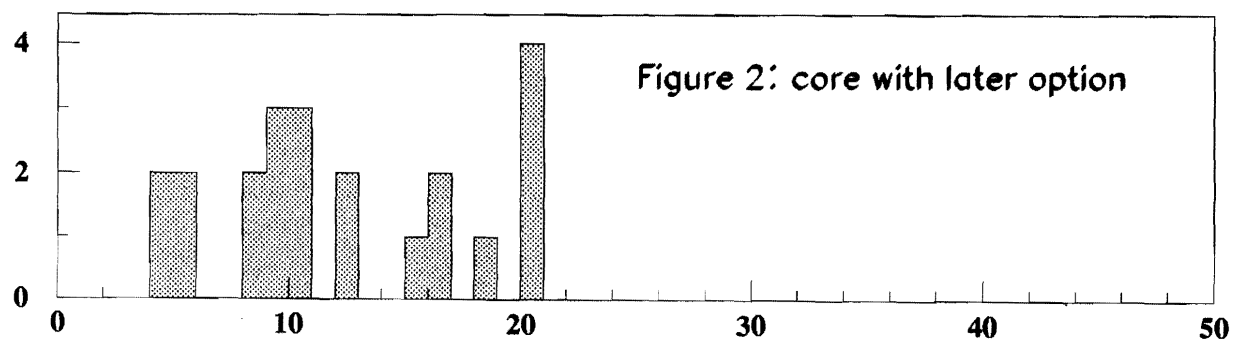

Figure 2: core with later option

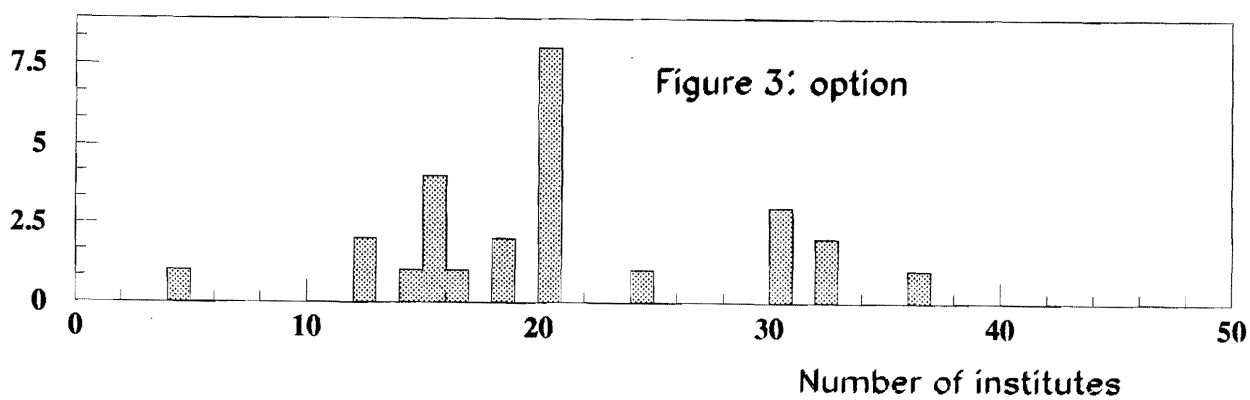

Figure 3: option