HIGH ENERGY PHYSICS
AND
NUCLEAR STRUCTURE

PROCEEDINGS OF THE
SECOND INTERNATIONAL CONFERENCE
ON HIGH ENERGY PHYSICS AND NUCLEAR STRUCTURE
HELD AT THE WEIZMANN INSTITUTE OF SCIENCE
REHOVOTH - FEBRUARY 27 - MARCH 3, 1967

Organised by
CERN AND THE WEIZMANN INSTITUTE OF SCIENCE

Under the Auspices of
THE ISRAEL ACADEMY OF SCIENCES AND HUMANITIES
AND
THE INTERNATIONAL UNION OF PURE AND APPLIED PHYSICS (IUPAP)

Edited by
GIDEON ALEXANDER

1967

NORTH-HOLLAND PUBLISHING COMPANY-AMSTERDAM

Library of Congress Catalogue Card Number 67-25031

Publishers:
NORTH-HOLLAND PUBLISHING CO. – AMSTERDAM

PRINTED IN THE NETHERLANDS

CONTENTS

Session I. *Hyperon interactions and hypernuclei*

Session II. *Interactions of electrons, mesons and nucleons with nuclei (including mesic atoms), experimental*

Session III. *Interactions of electrons, mesons and nucleons with nuclei (including mesic atoms), theoretical*

Session IV. *Nuclear astrophysics*

Session V. *Diffraction phenomena in nuclear and elementary particle interactions*

Session VI. *Composite structure of elementary particles*

Session VII. *Interactions of elementary particles with nuclei (theoretical)*

Summary session of "opening session"

HIGH ENERGY PHYSICS AND NUCLEAR STRUCTURE, NORTH-HOLLAND (1967)

REMARKS ON NUCLEAR STRUCTURE AND HIGH ENERGY PHYSICS

A. DE-SHALIT
Nuclear Physics Department,
Weizmann Institute of Science, Rehovoth, Israel

The rapid expansion in physics in the last decade on the one hand, and the slight slowing down in the rate of increase in the support of research on the other, demand that we stop and think for a moment where are we actually heading, and what is it that we are looking for. To be sure a good part of the progress of science is due to careful observations of unexpected phenomena, and many of the outstanding achievements would have not been obtained if research would have been "planned" too much. Still, the identification of some of the outstanding open problems in a given field may help in directing our attention to avenues which are possibly more promising. It is with this aim in mind that I want to make some remarks on the field of nuclear structure and its possible interaction with high energy physics.

The basic problem in nuclear physics is still that of the extent of validity of the description of the nucleus as a system of A interacting nucleons governed by a Schrödinger equation. That this is not a precise description of the nucleus is, I believe, generally accepted. In fact even in atomic physics, where the interactions are better understood, we have to invoke concepts beyond those of electrons obeying the Schrödinger or the Dirac equation when we reach the level of precision affected by the Lamb-shift. The question in the nuclear case can therefore be formulated in the following way: How far can one describe the nucleus by means of an A-particle wave-function, what is the equation that this wave-function satisfies, and how are the "parameters" in this equation such as mass, charge, moments, interaction, etc. related to those of the free nucleons.

This question is relevant not just for the clarification of nuclear structure, but perhaps also for the better understanding of quantum mechanics as well. The Schrödinger equation, which is believed to govern the behaviour of quantum mechanical systems at least at the non-relativistic limit, has really been fully tested only for the electro-magnetic interactions in atomic and in solid state physics. This is basically a very simple interaction, and it is not impossible that the more general case, i.e. that covering nuclear interactions as well, is more complex.

Partial answers are known, of course, to this question, and to a crude level of accuracy it is established that nuclei are governed by a Schrödinger equation with the free nucleon basic parameters. The main task before us is, therefore, that of pushing the tests to higher accuracies. Let us see what is known today.

The nuclear Schrödinger equation

$$H = \sum T_i + \sum_{i<j} V_{ij}$$

poses two problems; the one has to do with its being a finite many-body problem and the other has to do with the determination of V_{ij}. Let us assume, for the moment, that V_{ij} is known, and let us confine ourselves to bound states only. An approximate solution to the equation $H\psi = E\psi$ very often has the density of the system as a parameter, whose best value is determined in one way or another. Since the total energy E involves big cancellations between positive kinetic energies and negative potential energies it happens very often that approximate solutions to $H\psi = E\psi$ lead to rather large uncertainties in the density of the system. A better insight into the validity of the description of nuclear structure by means of a Schrödinger equation is therefore obtained by starting from an approximation which *assumes* the observed density, and starts from an approximate ψ which has this density built into it.

In the case of nuclear matter this is obtained by fixing the Fermi momentum and one knows that a whole set of nuclear properties are then rather well accounted for. We can ignore any additional effects of the interaction and obtain a good estimate to about 30% of such quantities as the symmetry-energy of nuclear matter, the surface energy for a semi-infinite nucleus and the surface thickness of such nuclei.

In finite nuclei we can go into further details as well. A very instructive study in this connection has been carried out by Krieger, Baranger and Davis [1]. To assure a proper density for the nuclear system these authors propose to deal with a modified Schrödinger equation of the type

$$H = -\frac{\hbar^2\nabla^2}{2m} + \frac{c}{\rho_0^2}\rho^2(\boldsymbol{r},\boldsymbol{r}) + \tfrac{1}{2}U(\boldsymbol{r},\boldsymbol{r}') .$$

Here $U(\boldsymbol{r},\boldsymbol{r}')$ is the non-local Hartree-Fock potential derived from an interaction $V(ij)$, and

$$\rho(\boldsymbol{r},\boldsymbol{r}') = \sum_{i=1}^{A} \phi_i(\boldsymbol{r})\,\phi_i^*(\boldsymbol{r}')$$

is the one-body density matrix. ρ_0 is the observed average density of nuclear matter and c is a parameter chosen so that a Hartree-Fock treatment of the *nuclear matter* problem will lead to an average equilibrium density ρ_0. Thus, once the "central" nuclear density is determined by a proper choice of c, the problem has got no further free parameter. For the two-body interaction V_{ij} they take a velocity dependent potential of the form

$$V(r) = A_S\,\mathrm{e}^{-\alpha_S r^2} + A_T\,\mathrm{e}^{-\alpha_T r^2} + B_S(p^2\,\mathrm{e}^{-\alpha_S r^2} + \mathrm{e}^{-\alpha_S r^2}\,p^2)$$
$$+ B_T(p^2\,\mathrm{e}^{-\alpha_T r^2} + \mathrm{e}^{-\alpha_T r^2}\,p^2) ,$$

where S and T stand for singlet and triplet respectively and A_S, A_T etc. include the appropriate spin projection operators. p is the relative momentum. The parameters A_S, A_T, α_S etc., are made to fit the observed effective range and scattering lengths in the singlet and triplet nucleon-nucleon scattering, so that $V(r)$ reproduces the low energy scattering data. Krieger et al. [1] then carry out Hartree-Fock self-consistent calculations for various nuclei and obtain rather interesting results for the single particle energies. For instance in ^{28}Si their results are:

	1s	1p	2s	1d
Theory	57 MeV	31.7 MeV	9.1 MeV	10.2 MeV
Experiment	59 MeV	26 MeV	14 MeV	16 MeV

Considering the fact that this is a theory without free parameters except the density, we may conclude that once we fix the density, then introducing the free two nucleon-interaction into an A-body Schrödinger equation, gives a fair account of the "single particle" energy levels in finite nuclei. It seems that within the range of agreement expected from such a crude theory, the results are not too sensitive to the details of the two-body interaction $V(r)$, and the numerical results given above are characteristic of the accuracy with which we can claim today the validity of a Schrödinger equation approach to nuclear structure.

The complexity of the nuclear many body problem has led to a quasi phenomenological approach in the analysis of some nuclear properties: In addition to the assumption that ψ represents a system of a given density one assumes also that it can be simply expressed in terms of single particle wave-functions, ascribing to these particles various "effective" properties. The success of Talmi and others in thus interrelating energies and other properties of nuclear levels is well known. However, the relation between these quasi-particles, with their effective intrinsic properties, and the "real" free nucleons has recently become less obvious. Most attempts to arrive at a nuclear wave-function from "first principles" leads to wave-functions with a rather large configuration mixing, and why these thoroughly admixted states lend themselves to a simple description in terms of quasi-particles is not clear at the moment.

Two avenues seem to be open to tackle this class of questions. One has to do with better determination of spectroscopic factors of various nuclear states. Since a spectroscopic factor is connected with the removal of a real nucleon from the nuclear wave-function its proper determination is a good experimental tool for the determination of the structure of nuclear wave-functions in terms of real nucleons. There have been suggestions by Kerman and others of testing the structure of the tail of nuclei by stripping and pick-up reactions in which the colliding particles are below their mutual Coulomb barrier both before and after the collision. The cross-sections are low, but the reliability of the theoretical analysis is high. At ordinary nuclear physics energies the cross sections are substantially more convenient, but the analysis of the data in terms of DWBA suffers from serious uncertainties. Thus it has not been possible to derive the same spectroscopic factor for a given situation arrived at by different reactions. The best study is possibly that of Bromley and his collaborators (Heidelberg Conference 1966), who determined the spectroscopic factors for the breakup of ^{11}B into $^{10}B + p$ and $^{11}B + n$; using different reactions to determine these spectroscopic factors and employing DWBA for their analysis, variations of up to a factor two are obtained. It therefore seems that in determining spectroscopic factors one wants to go to high energies where the theoretical uncertainties may be less severe.

Another approach to the study of nuclear structure is to concentrate on the lightest nuclei, where detailed calculations are becoming now more and more feasible. Here, however, one is faced with another difficulty since the lightest nuclei have very few bound states. One is thus faced with the problem of relating the parameters of resonances with the ingredients put into the fundamental theory. The study of these theoretical problems can be expected to benefit much from the similar problems encountered in the analysis of elementary-particle resonances.

These and other problems are basically connected with the many-particle nature of the nuclear Hamiltonian. There is, however, another fundamental problem to be solved even before we start tackling the many-body Schrödinger equation. The nuclear interaction $V(ij)$ cannot, at this stage of our knowledge, be derived from field theory. We thus have got no first principles for determining its structure and functional form. Under these circumstances one tries to determine $V(ij)$ from two-body scattering data. Apart from the fact that the two-body processes may be more sensitive to one part of $V(ij)$, while the 3- or 4-body data may be sensitive to another, we are faced with the fundamental difficulty that 2-body collisions test $V(ij)$ only on the energy-shell, whereas for the many-body system we need its elements off the mass shell as well. The latter could be determined, in principle, in a nucleon-nucleon bremsstrahlung experiment, but the theoretical calculations of this process are presently uncertain and a more thorough study is required before we can draw definite conclusions about the "best" interaction $V(ij)$. It has been shown by F. Low many years ago that the bremsstrahlung cross section for the emission of a photon of energy k, and for small values of k, behaves like

$$\sigma(k) = \frac{\sigma_{-1}}{k} + \sigma_0 + \sigma_1 k + \dots ,$$

and that both σ_{-1} and σ_0 depend only on the elastic, i.e., on energy shell, matrix elements of $V(ij)$. It is very desirable that calculations which claim to analyze the experimental data will also be checked against this fundamental theorem.

Even if we were to know the interaction $V(ij)$ perfectly both on and off the energy shell, any discrepancy between a many body calculation using this $V(ij)$ and experiment could be attributed to the presence of many body forces. Had we had a field theoretic derivation of $V(ij)$, the same theory would have also given us the exact form and strength of the many body forces. However, as things stand we should look for other ways of determining the extent to which many body forces do or do not contribute to a given nuclear property. Some experience in this direction can probably be gotten through the study of hyperfragments where 3-body forces can be expected to play a relatively important role. In this respect the contribution of Gal to this conference is of special interest since it brings rather strong evidence in favour of the actual observation of such forces in hyperfragments. His argument is based on the observation that in hypernuclei like ${}_{\Lambda}^{13}B$ and ${}_{\Lambda}^{13}C$ the two-body Λ-nucleon forces should lead to roughly the same Λ-binding energy, since the single-nucleon densities of the host nuclei in both cases are roughly the same. However, due to the higher space symmetry of the ${}^{12}C$ core of ${}_{\Lambda}^{13}C$ as compared with the ${}^{12}B$ core of ${}_{\Lambda}^{13}B$, the contributions of the ΛNN-forces will be markedly different in both cases. A big difference in the Λ-binding energy is therefore a possible indication of important 3-body forces contribution.

The existence of 3-body forces is an important corollary of the field theoretic explanation of interactions among particles. The hopes of detecting 3-body electro-magnetic forces are rather meager as can be seen from an order of magnitude estimate. Their detection in baryon systems is therefore of great fundamental importance.

In conclusion I want to stress again that some of the most fundamental questions pertaining to nuclear structure are still open, and that the use of high energy projectiles, the use of other elementary particles and the employment of theoretical methods of high energy physics, may contribute significantly to the clarification of the situation.

REFERENCE

[1] S. J. Krieger, M. Baranger and K. T. R. Davies, Phys. Letters 22 (1966) 607.

HIGH ENERGY PHYSICS AND NUCLEAR STRUCTURE, NORTH-HOLLAND (1967)

NUCLEAR STRUCTURE RESEARCH ON THE CERN ACCELERATORS

B. P. GREGORY
CERN, Geneva

1. INTRODUCTION

In the spring of 1963 a first conference on High-Energy Physics and Nuclear Structure was held at CERN. It was organized by Professor Weisskopf and Professor de-Shalit and had a great influence in introducing a new field in the programme of physics at CERN. Three years ago, an experiment on nuclear structure at one of the CERN accelerators was an exception. At the present time, over 80% of the research programme at the 600 MeV synchro-cyclotron at CERN deals with nuclear structure.

Among the factors which contributed to this development we may quote:

1) The stimulating interest shown by some theorists regarding the possibility of using pion beams as probes of nuclear structure. Professor M. Jean and Professor T. Ericson contributed very much in this respect.

2) The initiative of several groups working in low-energy nuclear physics in European laboratories who decided to come to CERN as visiting teams to carry out the experimental programme.

3) The steady improvement in beam quality and beam intensity of the synchro-cyclotron and the increase in the efficiency of the machine operation allowing the simultaneous operation of many experiments.

4) Finally, new techniques have been made available: disc Čerenkov counters; filmless, position sensitive spark chambers; the new germanium-lithium drifted detectors with a resolution better by one order magnitude than the old NaI detector; on-line mass spectrometers.

In the following, a short survey of the present CERN programme will be given.

2. THE SYNCHRO-CYCLOTRON OF CERN AND ITS BEAMS

The current internal proton intensity of the 600 MeV CERN synchro-cyclotron is around 2 μA very similar to the Berkeley and Dubna machines. The extracted proton beam has an intensity of 0.1 μA. Fig. 1 shows the general lay-out of the experimental areas. The pion beams come either from internal targets in the so-called neutron room (Charpak, MSS and muon channel Backenstoss) or from external targets (Tanner-Measday lines) placed in the so-called proton room. Typical intensities are of the

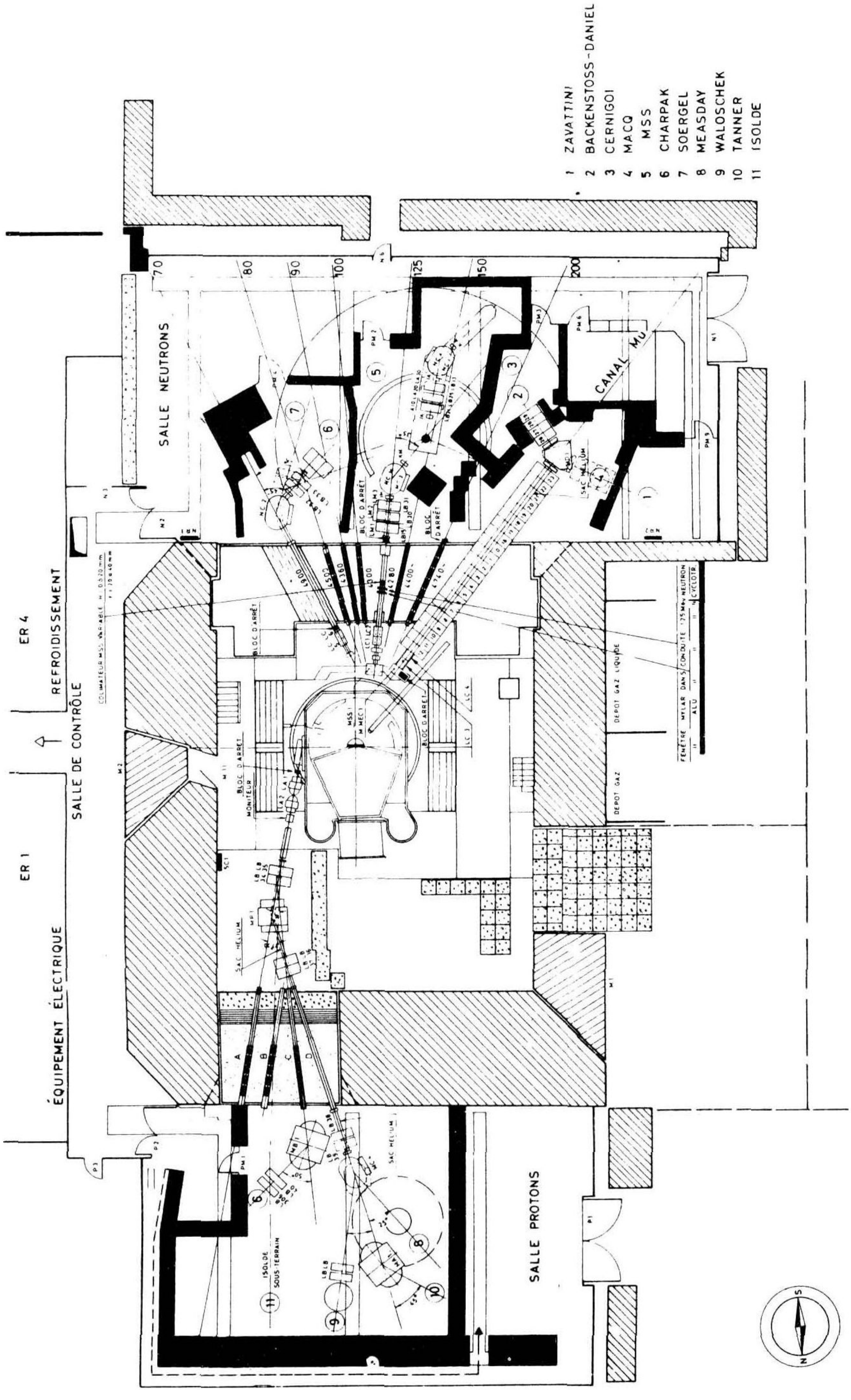

Fig. 1. General lay-out of the experimental area.

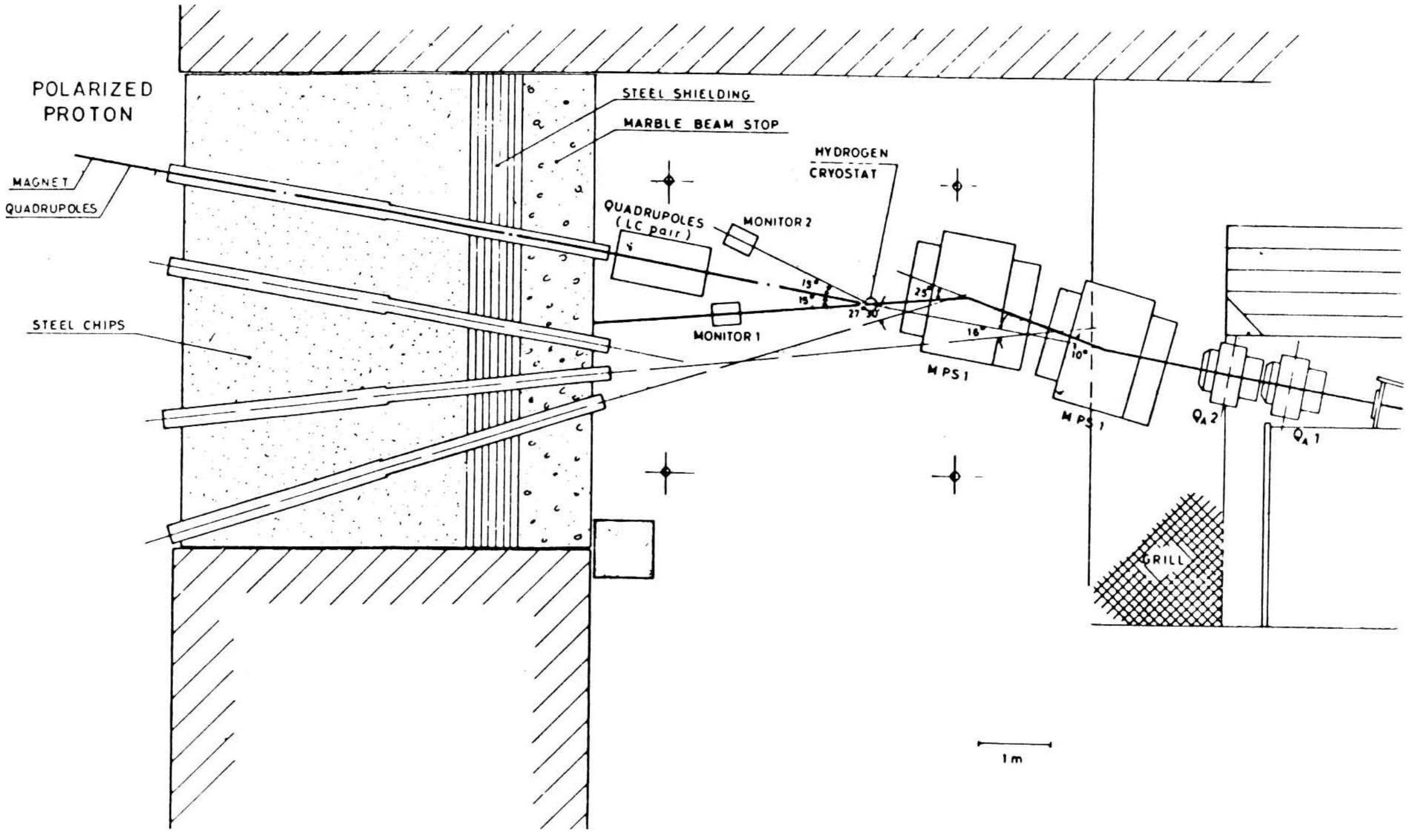

Fig. 2. Polarized proton beam obtained by scattering the extracted protons on hydrogen at a fixed angle.

order of or slightly less than 10^5 pions/sec in an energy range of 70 to 300 MeV. The rate of stopping pions is of the order of 600/g sec. Fig. 2 shows the polarized proton beam obtained by scattering the extracted protons on hydrogen at a fixed angle. This beam produces an intensity of the order of 10^7 protons per second at 550 MeV with a polarization of about 50%. Polarized neutrons can also be obtained in this way.

3. μ MESIC AND π MESIC ATOMS

The development of the germanium-lithium drifted detectors has enabled precise measurement to be made in this field. It is well known that the cascade process brings down a stopping μ meson in matter to the 1s orbit which lies roughly a factor m_μ/m_e closer to the nucleus than the corresponding electronic orbit. The mesic X-ray energies corresponding to the last step of the cascade process (3d → 2p, 2p → 1s) are affected by the charge distribution in the nucleus.

Table 1 shows some recent results for spherical nuclei for which the values of the transition are interpreted in terms of the charge distribution characterized by a radius parameter and a surface thickness. The results

Table 1
Muonic 2p-1s transition energies and deduced nuclear radii.

	E_m (keV)		RMSR (fm)	
				Electron scattering
$^{10}_{5}$B	52.05 ± 0.15		3.36 ± 0.7	2.40 ± 0.15
$^{11}_{5}$B	51.92 ± 0.13		4.23 ± 0.6	2.50 ± 0.20
$^{12}_{6}$C	75.25 ± 0.1		2.40 ± 0.38	2.42 ± 0.03
$^{14}_{7}$N	102.29 ± 0.10		2.68 ± 0.17	2.45 ± 0.05
$^{16}_{8}$O	133.55 ± 0.08		2.62 ± 0.09	2.65 ± 0.04
		^{18}O-^{16}O: 0.016 ± 0.020	0.095 ± 0.021	
$^{18}_{8}$O	133.56 ± 0.08		2.71 ± 0.09	2.77
$^{19}_{9}$F	168.4		2.85 (± 0.1)	
$^{23}_{11}$Na	250.2		2.95 (± 0.05)	
$_{12}$Mg	296.5		3.02 (± 0.04)	2.98 ± 0.06
$^{27}_{13}$Al	346.8		3.03 (± 0.03)	2.91 ± 0.10
$^{32}_{16}$S	515.8		3.27 (± 0.02)	3.19 ± 0.06

are compared to those obtained from the electron scattering experiments. More precise data are obtained with mesic X-rays in heavy nuclei. Very recently some promising first results have been obtained for deformed nuclei where hyperfine structure can be observed.

Finally, μ mesic X-rays can also reveal electronic excitation of a nucleus, isomer shifts, etc. Fig. 3 shows an example of a type of data one may observe. The delayed line is due to the gamma-ray emission of the nucleus produced by the μ capture in Bi. The width of this line gives an experimental measure of the resolution obtained.

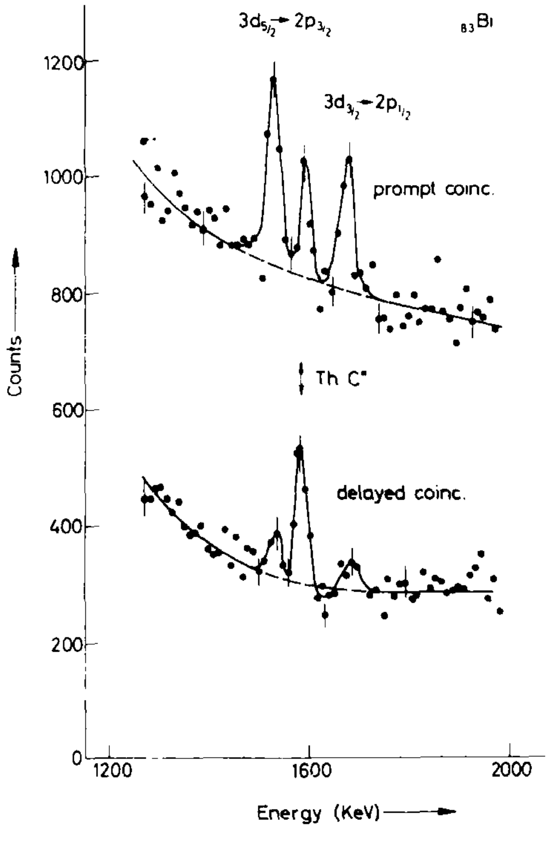

Fig. 3. Type of data one may observe.

Stopped muons can also be used as a tool to solve a well-defined problem of nuclear structure, as shown by a recent measurement by a group from Louvain. It is well known that the β decay from the ground state of ^{11}Be to ^{11}B has a much slower rate than the one that would be deduced from a naive application of the shell model which assigns $1P_{\frac{1}{2}}$ to ^{11}Be and $1P_{\frac{3}{2}}$ to ^{11}B. A possible explanation would be an inversion of the levels in ^{11}Be which would give a $2S_{\frac{1}{2}}$ assignment for the ground state. The idea of Professor Macq and his collaborators was to use the μ^- capture to test this hypothesis. The rate of muon capture would then be much higher to the first excited level of ^{11}Be than to the ground state. The experiment shows that both transitions are equally inhibited. This opens up anew the problem of the assignments of the ground and first excited states of ^{11}Be.

The capture of the π^- meson is more complicated since nuclear forces enter in shifting and broadening the lines observed. Results will be presented in this conference on this subject.

4. 20 GeV PROTON NUCLEI COLLISIONS

The experiment was done at the CERN PS on the differential elastic cross-section of protons on various nuclei at 20 GeV. In spite of the very long spectrometer used in order to minimize the angular and momentum

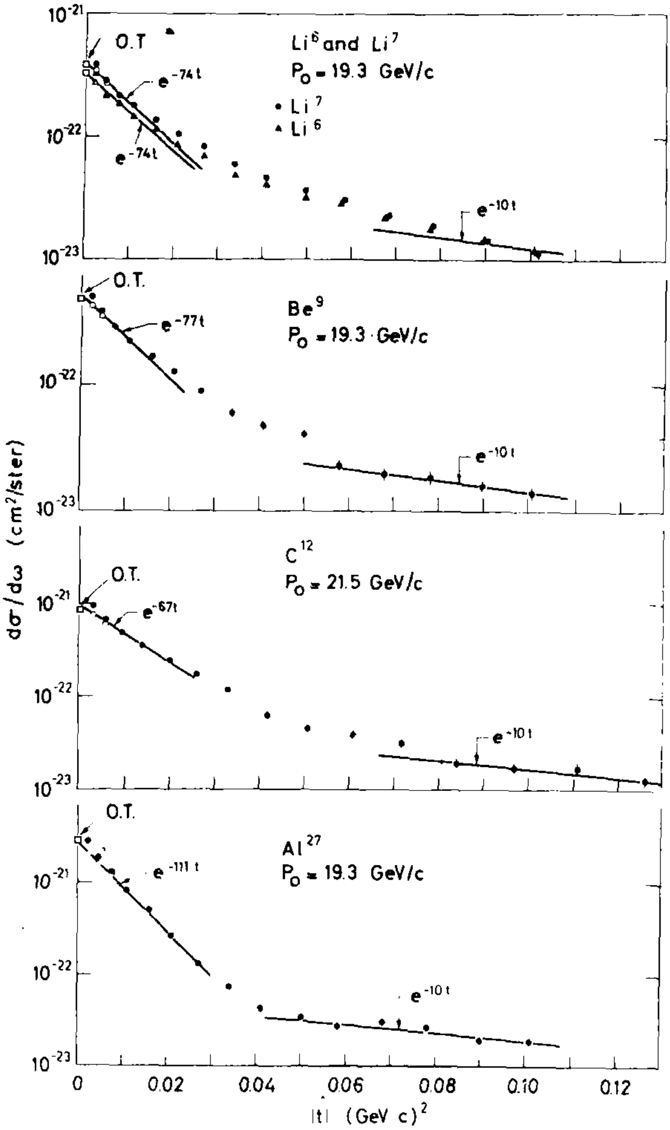

Fig. 4. Main results on central peak.

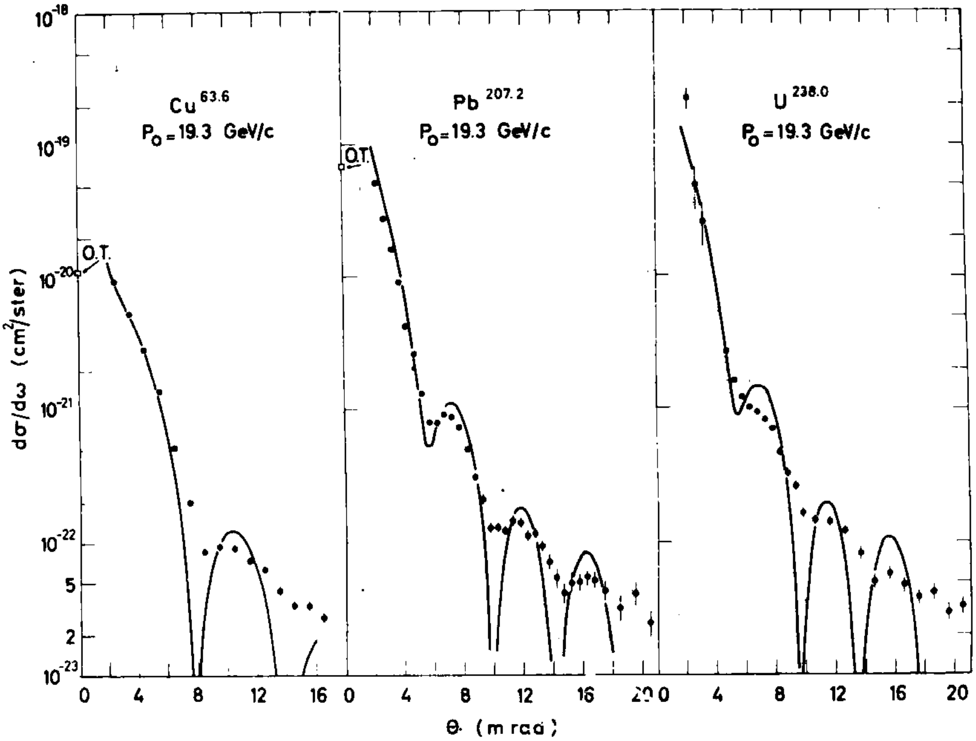

Fig. 5. Main results on central peak.

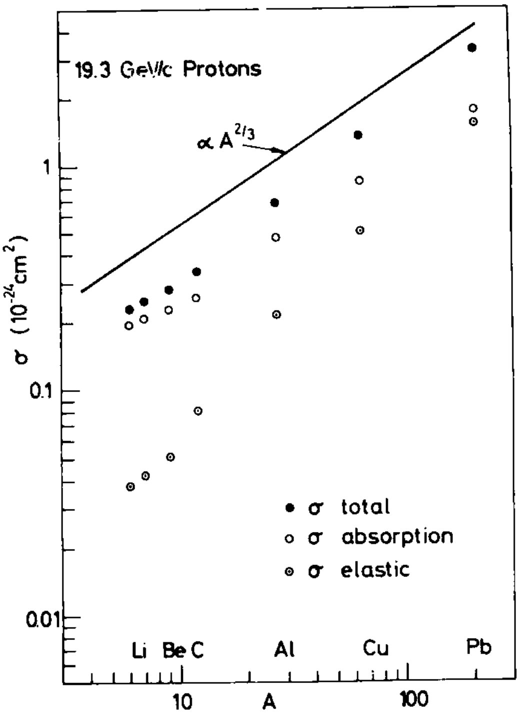

Fig. 6. Data combined with a complementary experiment giving the total cross-section.

errors, excited levels up to 50 MeV cannot be separated from elastic scattering. Figs. 4 and 5 show the main experimental results: the central peak is due to coherent proton nucleus scattering with a slope characteristic of the radius of the nucleus. For the heavier nuclei the angular pattern shows diffraction minima and maxima. The angular distribution at large angles is much flatter with a slope characteristic of the radius of a nucleon. This is presumably a surface phenomenon and decreases in relative importance when the atomic number of a nucleus increases.

In fig. 6 the data are combined with a complementary experiment giving the total cross-section. It is seen that the lighter nuclei are quite transparent and the heaviest ones behave as opaque objects. During the past years, a number of computations were made on these data to try to correlate them with the electron-proton scattering data.

5. NUCLEAR REACTIONS INDUCED BY π MESONS

This is a new technique in nuclear structure studies which is only just beginning to yield some results. The interest of π mesons in nucleon interactions as compared with the more conventional fast particles: protons, deuterons, α and γ rays, comes from the following well-known properties.

The *I* spin 1 allows single and double charge exchange interactions; the π meson is a boson field particle which can release a large energy to two or more nucleons in the nucleus. Its light mass has for consequence that for a given energy release one has low momentum transfer and low angular momenta. The π meson has spin 0 and is not identical to the nucleon, and finally it has a very different interaction, the scattering length being much smaller than that of the proton.

Three different approaches made at CERN will be briefly described:

1) A very precise measurement of the incoming and outgoing π momentum allows a measurement of the change of energy from the target to the final excited nucleus. A new beam has been built at CERN that has a final resolution of 0.5 MeV. During the past years, attempts to discover possible bound states of the four-neutron system by double charge exchange of π^- mesons on ^{4}He were made using this technique.

2) The use of filmless, position sensitive spark chambers allows an accurate determination of the momentum of 2 outgoing protons in an interaction in which a fast π^+ meson is absorbed in a nucleus. More specifically, the interaction $\pi^+ + {}^6\mathrm{Li} \rightarrow {}^4\mathrm{He} + p + p$ was studied giving the experimental result shown in fig. 7. One observes a narrow peak on the ground state of ^{4}He and a broad resonant-like distribution centered around 30 MeV above the ground state. Whether this is due to a new excited state of He or to a production mechanism will be discussed by Dr. Zupančič in these proceedings. Measurements are also being carried out at CERN in which one of the measured outgoing nucleons is a neutron or both are neutrons.

3) In still another way, the reactions of pions with nuclei can be identified by the residual radioactivity following bombardment. On fig. 8 the cross-section for $^{12}\mathrm{C}(\pi^+\pi^+n)^{11}\mathrm{C}$ is plotted against energy; the effect of the 3-3 resonance is quite visible.