EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PH III-67/1
2 January 1967

PHYSICS III COMMITTEE

NUCLEAR EXCITATION IN MUONIC ATOMS AND STUDY OF NUCLEAR VOLUME EFFECTS

PROPOSAL FOR AN EXPERIMENT AT CERN

by

P. Brix, R. Engfer, E. Kankeleit, K. Wien

Institut für Technische Kernphysik der
Technischen Hochschule Darmstadt

(Proposal submitted 12 December 1966)

* *
*

A muon captured in one of the excited states of the muonic atom cascades down to the lowest 1s level. As observed in a number of experiments in which the muonic X rays have been studied (for literature see Ack 66) there is a considerable probability for E2 excitation of the nucleus from the ground to an excited state. This effect has also been treated theoretically in a number of publications (Wil 54, Ack 66).

It is the aim of the proposed experiment to search for nuclear excitations by direct observation of the γ ray from the decaying nucleus, as opposed to the usual observation of the X rays.

The purpose of this study is summarized in the following points listed in proposed chronological order.

1) Study of multipole excitation (E_0, E1, M1 etc.) of nuclei in muonic atoms in addition to E2 excitation.

2) Muonic isomer shift of nuclear levels in muonic atoms.

3) Effects on electron conversion and X-ray emission due to the presence of the muon.

The main interest will be in point no. 2 the muonic isomer shift. The results of point no. 1 will be necessary for an estimation of the feasibility of the observation of the muonic isomer shift. The effects mentioned under point no. 3 must be considered speculative and will not be discussed in the following.

TIME SCHEDULE

The experiment will be performed in cooperation with the existing Heidelberg-Karlsruhe group. During the first half of 1967 some test runs should be made. 10 shifts would be needed for this purpose. If these tests are successful and indicate that it is possible to perform the proposed experiment without major changes of the experimental set up it is then intended to ask for about 20 shifts in the second half of 1967. It depends on the results of the first measurements how many shifts will be needed in 1968.

HISTORICAL BACKGROUND

During the year 1961 a joint group from CERN (Backenstoss, Goebel, Stadler) and Darmstadt (Brix, Engfer, Hegel, Quitmann) carried out studies on muonic X-rays at the muon channel of the synchro-cyclotron. The results of these measurements are published in the literature (Bri E 62, Qui 63, Eng 64, Bac G 65, Ack M 65). These measurements in particular have been included in the recently published review article (Qui 66) in which a survey is given of the change at the nuclear radius following the addition of a proton. A second result of these earlier measurements was the determination of intensities of high-energy K-X-rays.

These experiments were originally planned for a limited amount of time and accordingly were finished after one year.

FACILITIES

The Institut für Technische Kernphysik of the T.H. Darmstadt has since worked on related problems. Elastic-electron-scattering experiments, carried out at the 60-MeV LINAC determined the charge distribution of nuclei (Eng 66, The E 66). Due to the low primary-electron energy, it was possible to study the second moments of the nuclear charge distribution, a result which can also be obtained from muonic-X-ray experiments (Nif E 66, Eng 66a).

The nuclear-spectroscopy group of the Institute developed and used Ge(Li) detectors for the measurement of γ-ray spectra. Many isotopes, whose level structures were previously only poorly known, were produced using the LINAC for activation.

The problem of exact calibration lines has been considered recently by Wien (Wien 66) in a γ-ray measurement of Ga^{66}. In addition, there exists a group at the Institute involved in Mössbauer spectroscopy. A number of Mössbauer experiments have been performed in which an isomeric shift has been observed (for ref. see Stei 66 and Hüfk 65). In some cases, determination of the electron density at the nucleus was possible using optical data. These cases will be of particular interest in the study of muonic atoms since a direct comparison of nuclear charge radii can be made.

EXPERIMENTAL SET-UP

The experimental set-up is similar to thatfor muonic X-ray studies. Some modifications are necessary due to the energy region of 50-150 keV of the nuclear γ rays instead of the several MeV energies of the muonic X rays. Because of self-absorption the target thickness should not exceed ~ 0.2 g cm^{-2}. Since the range curve of the muon beam has a width of ~ 6 g cm^{-2} only a small number of muons can be stopped in such a thin target. An arrangement of two thin targets, in a roof-shaped fashion, can increase the stopping rate by a factor 4 without increasing the self-absorption. The energy shift can simply be measured as the energy difference between this nuclear γ ray and the γ ray from the same transition in a radioactive source.

The possibility of confining the muon beam to a smaller area by a strongly inhomogeneous axially-symmetric field (magnetic bottle) is being studied. In such a field the muons will spiral around the flux lines and the path length within the thin target will be considerably increased. It is hoped that such an arrangement will reduce the amount of isotopically enriched target material necessary. In principle, however, the experimental observation of the nuclear γ rays in muonic atoms does not depend on such a magnetic device.

APPENDIX

To point 1 / Study of multipole excitation of nuclei in muonic atoms.

In nuclei with large deformations there exist low-energy rotational levels which have large quadrupole transition probabilities to the ground state. "For these nuclei, the excitation matrix elements are comparable in magnitude with the static quadrupole interaction...this provides a large probability that after the meson reaches the atomic ground state, the nucleus be left in an excited state and subsequently emits a nuclear γ ray" (Wil 54). Up to now, these nuclear γ rays have not been observed experimentally but the influence of the excited levels is inferred from the hyperfine splittings of the K_α and L_α X-rays in deformed nuclei. The analyses of experimental quadrupole hyperfine splittings yield excitation probabilities of up to 60% (Wit B 66). An experimental observation of the intensities of the nuclear γ rays is a valuable check of the theoretical calculations and of the recent calculations of Pieper which are based on the rot.-vib. model (Piep 66). In the rot.-vib.-model the intensities of excited nuclear levels or the excitation probabilities of nuclear levels by the muon are strongly fixed by the energies of the rotational band. There exist so far no estimates for other electric and magnetic multipole exitations (e.g. of single-particle levels). If these excitations could be observed they would provide detailed information on specific nuclear models.

To point 2/ Muonic isomer shift of nuclear levels in muonic atoms.

The Coulomb interaction of the atomic nucleus with the bound electrons can shift the energy of the nuclear levels. This effect is known as the "isomeric shift" and has been measured with the Mössbauer effect for many nuclei, mainly in the region of the rare-earth elements.

These measurements determine the difference in the mean square radii, $\delta < r^2 >$, between the excited $< r^2 >_{ex}$ and the ground state $< r^2 >_g$ of a nucleus. The isomeric shift in chemical compounds is proportional to the electron density at the nucleus.

$$\delta E = \left(\frac{2\pi}{3}\right) Z e^2 \{ [\varphi_1(0)]^2 - [\varphi_2(0)]^2 \} \delta \langle r^2 \rangle \qquad (1)$$

$[\varphi_1(0)]^2$ and $[\varphi_2(0)]^2$ are the densities of all electrons at the nucleus of two chemical compounds.

In an atom the energy shifts are very small, 10^{-6} eV e.g. for Eu (Stei 66); therefore, they can only be measured with the help of the Mössbauer effect. Unfortunately, the interpretation of the experimental shifts is very uncertain since it is difficult to determine the differences of electron densities in chemical compounds. In many cases, rather the uncertainty of the interpretation than the experimental errors determines the accuracy of the experimental $\delta \langle r^2 \rangle$.

These uncertainties of interpretation do not occur in muonic atoms. At the nucleus the density of a 1s muon is approximately $(200)^3$ times larger than the density of a 1s electron. It is therefore to be expected that the isomeric shift can be directly observed with a high-resolution Ge(Li) detector. As an example, using data from Mössbauer experiments it can be estimated that in Eu^{151} (Stei 66) this shift may be approximately 15 keV ($\delta \langle r^2 \rangle = 0.17$ fm^2).

Since the muon density is not constant over the region of the nucleus, it is to be expected that in addition to $\langle r^2 \rangle$, other moments of the nuclear charge radius will be also of importance.

The requirements for the experimental observation of the isomeric shift are:

1) During the de-excitation of the nuclear levels the muon must be bound in the 1s state. This condition can easily be fullfilled in the following way: a muon which is captured in the higher orbits of the atom cascades down with emission of the Auger electrons or X rays to the 1s state. During this process there exists a certain probability that low-energy nuclear levels will be excited. The excitation of the lowest rotational levels in deformed nuclei by quadrupole interaction was first calculated by Wilets in 1954 (Wil 54).

2) The lifetime of the nuclear level must be larger than the time required for the muon to cascade down to the 1s level ($\sim 10^{-12}$ sec). Otherwise,

the emission of the nuclear γ ray occurs under conditions of undefined muon density.

3) The lifetime of the muon bound in the 1s state (0.5 to 2×10^{-6} sec) must be larger than the lifetime of the nuclear level. Since most of the rotational levels have lifetimes of the order of 10^{-9} sec the last two requirements are automatically fullfilled.

Besides the abovementioned contribution to the isomer shift on different static radii of the nuclear ground states and excited states an additional effect due to the polarization of the nucleus by the bound muon is expected. The influence of this polarization on the muonic X rays is calculated by Greiner, Marschall (GreM 61, Gre 61), Scheck (Schec 63) and Nuding (Nud 57); up to now there has been no other possibility to check these calculations experimentally. Therefore a verification of these effects by the proposed experiment would provide valuable information. For rotational levels it is known that the difference of the rms radii of the various levels is very small; this means an energy shift of rotational levels is mainly due to a polarization of the nucleus. As an example, calculations of Pieper (Pie 66) based on the rot.-vib. model show an energy shift of 0.85 keV for the 50-keV level in U^{238}, which could be readily observed.

REFERENCES

Ack 66 H.L. Acker,(submitted to Nuclear Physics, 1966).

AckM 65 H.L. Acker, H. Marschall, G. Backenstoss and D. Quitmann, Nucl. Phys. 62, 477 (1965).

BacG 65 G. Backenstoss, K. Goebel, B. Stadler, U. Hegel and D. Quitmann, Nucl. Phys. 62, 449 (1965).

BriE 62 P. Brix, R. Engfer, U. Hegel, D. Quitmann, G. Backenstoss, K. Goebel and B. Stadler, Phys. Letters 1, 56 (1962).

Eng 64 R. Engfer, Nuckleonik 6, 199 (1964).

Eng 66 R. Engfer, Z. Physik 192, 29 (1966).

Eng 66a R. Engfer, Proc. Scuola Int. di Fisica, Enrico Fermi, Varenna (1966).

Gre 61 W. Greiner, Z. Physik 164, 374 (1961).

GreM 61 W. Greiner and H. Marschall, Z. Physik 165, 171 (1961).

HüfK 65 S. Hüfner, P. Kienle, D. Quitmann and P. Brix, Z. Physik 187, 67 (1965).

E. Steichele, S. Hüfner, P. Kienle, Phys. Letters 21, 220 (1966).

P. Brix, S. Hüfner, P. Kienle, D. Quitmann, Phys. Letters 13, 140 (1964).

NifE 66 G.J.C. van Niftrik and R. Engfer, Phys. Letters 22, 490 (1966).

Nud 57 E. Nuding, Z. Naturforsch. 12a, 187 (1957).

Pie 66 W. Pieper, Dissertation Universität Frankfurt (1966).

Qui 66 D. Quitmann, Habilitation TH Darmstadt (1966), Inst. für Techn. Kernphysik.

Qui 63 D. Quitmann, Z. Physik 172, 263 (1963).

QuiE 64 D. Quitmann, R. Engfer, U. Hegel, P. Brix, G. Backenstoss, K. Goebel and B. Stadler, Nucl. Phys. 51, 609 (1964).

Schec 63 F. Scheck, Z. Physik 172, 239 (1963).

Ste 66 E. Steichele, Dissertation TH Darmstadt (1966), Inst. für Techn. Kernphysik.

TheE 66 H. Theissen, R. Engfer and G.J.C. van Niftrik, Phys. Letters 22, 623 (1966).

Wien 66 K. Wien, Phys. Letters 23, 353 (1966).

Wil 54 L. Wilets, Dan. Mat. Fys. Medd. 29, No. 3 (1954).

WitB 66 S.A. de Wit, G. Backenstoss, C. Damm, J.C. Sens and H.L. Acker, (submitted to Nuclear Physics, 1966).