EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

PH III-70/16
5 May 1970

PHYSICS III COMMITTEE

CERN LIBRARIES, GENEVA

CM-P00044190

REQUEST FOR SC TIME TO CONTINUE EXPERIMENT SC 2a: NUCLEAR EXCITATION AND ISOMER SHIFTS IN MUONIC ATOMS

by

H. Backe, E. Kankeleit, W.U. Schröder, H.K. Walter
Institut für Technische Kernphysik, T.H. Darmstadt

U. Jahnke, K.H. Lindenberger
Hahn-Meitner-Institut für Kernphysik, Berlin

R. Engfer, C. Petitjean
CERN and SIN, Zürich

H. Schneuwly
Institut de Physique de l'Université, Fribourg

1. SUMMARY OF EXPERIMENTS PERFORMED DURING THE LAST 12 MONTHS

Two different types of Ge(Li) detectors are used for the spectroscopy of μ-X rays and nuclear γ rays in μ atoms: small detectors (≤ 5 ccm) with high energy resolution (~ 1.2 keV at 100 keV) for the investigation of the low-energy region (< 1 MeV) and a large coaxial detector (25 ccm) for measurements of high-energy γ rays. The analysis of intensities and energies of these spectra yields correlated as well as uncorrelated information on nuclear and atomic properties. These different results which have been deduced from our data are now shortly summarized. The final analysis of the data is in progress.

1. Muonic isomer shifts were measured for nuclear transitions in 20 isotopes. The results are listed in references (BacK69, Eng 69).
2. Absolute intensities of nuclear γ rays in μ atoms of deformed nuclei were measured in order to get information on the excitation mechanism. They mostly can be explained by an E2 mixing of muonic and nuclear states. In some nuclei an additional excitation of higher states may contribute to the intensity of the lowest nuclear levels. In ^{205}Tl, e.g., some high energy γ transition were already observed.
3. Relative intensities of μ-X rays for transitions from levels up to n = 16 were measured in several heavy atoms. Present calculations of the μ cascade do not explain these experimental data accurately.
4. Energies of some muonic X rays show shifts of up to 1.5 keV compared to calculations from the Dirac equation including vacuum polarization and finite size effects. This deviation could be due to a shielding of the nuclear charge by the electron cloud.
5. High energy prompt γ rays were found in μTl and μBi, which can be ascribed to a nuclear excitation of these nuclei. In ^{209}Bi the nuclear excitation is well explained by an E3 mixing of the two $15/2^+$ and $9/2^+$ septuplet states at 2741 keV and 2564 keV, respectively, with the muonic 3d and 2p states. Large isomer shifts up to 6 keV were observed for transitions from these levels (Fig. 1).
6. In μ-Bi for the first time a 3d-1s E2 transition was found at 8.5 MeV. The intensities of these transitions are sensitive to details of the μ cascade mechanism and yield also information on the excitation of nuclear states.

7. From a fit to the exponential time distribution of delayed γ rays from μ capture one can deduce the capture rate. This method can be applied to different isotopes in natural targets.
   In ^{151,153}Eu an isotope effect of $\Delta\tau = (4.7 \pm 1.2)$ ns was observed (Bac E 69). It is intended to study one or two other elements in order to test present theories on the μ capture process (Pri 59, Luy T 65, Bun 66).

2. THE FUTURE EXPERIMENTAL PROGRAM

Our future research program is directed to answer the following questions:

1. How large is the magnetic hyperfine splitting in μ atoms of deformed nuclei?
2. What is the influence of the chemical environment on the energies and intensities of outer μ transitions?
3. What are the details of the excitation mechanism of high energy nuclear states?
4. What is the energy spectrum of neutrons from μ capture?

To 1. and 2.: The knowledge of the magnetic hf splitting in μ atoms of deformed nuclei is essential for the corrections of the muonic isomer shifts (Baa B 68a). A windowless Ge detector with an energy resolution of ~ 800 eV at 100 keV will be available to our group. We intend to measure the magnetic hf splitting of nuclear transitions in a deformed nucleus (see (Baa B 68 b)). From this splitting, information on the form factor of the g_R factor can be deduced, which is unknown up to now. With this diode it will also be possible to measure the outer low energy μ transitions.

To 3. and 4.: To get an answer for these two questions a combined study of neutron and γ spectra is necessary. Radiationless μ cascade transitions in heavy atoms can lead to excitations of the nucleus above neutron threshold. This effect can be observed by detection of prompt neutrons. For details see Appendix.

3. REQUEST FOR SC TIME IN 1970

55 main user or sharing shifts and about 25 parasitic shifts (intensity less than 40%) were estimated to be sufficient for the period from 1.7.1970 to the end of 1970. The experiments with neutron time of flight and Ge(Li) detectors will be performed simultaneously with the same target.

APPENDIX

SPECTROSCOPY OF NEUTRONS FROM μ ATOMS

As experiments (Mac D 65) have indicated, μ capture is mainly accompanied by emission of one or more neutrons. The neutrons may be emitted either directly or in the decay of intermediate collective states, excited in the μ capture process. Hence the spectrum of these neutrons should depend on the details of the capture process.

It was suggested by several authors (Bar S 64, Bal K 67, Fol W 64, Kel Ü 68) that μ capture in the light elements should lead predominantly to excitation of giant resonances in the intermediate nucleus. Barlow et al. (Bar S 64) and Foldy and Walecka (Fol W 64) have shown that this capture mechanism could account well for the total μ capture rate in ^{12}C, ^{16}O, ^{40}Ca.

There has been a number of detailed calculations on the spectra of neutrons, assuming the giant resonance capture mechanism (Kel Ü 68, Bal K 67, Bal E 69). However, there is still only little experimental information on the shape of the spectra of neutrons, emitted following μ capture. Some groups (Hag 63, Sun S 68, Kri 69, Eus K 69) measured the neutron spectra, using proton-recoil techniques.

These experiments suffer from two main disadvantages: the rejection of the high γ background must be extremely efficient. The necessary unfolding procedure is complicated because of the little known neutron-induced processes in ^{12}C. Thus it seems to be desirable to perform a measurement with another technique in order to get further confirmation on the recent results of Evseev et al. (Evs K 69), who have seen structures in the spectra of neutrons from the μ capture in ^{16}O, ^{32}S, ^{40}Ca, Pb.

We suggest to use a time-of-flight technique. This method is expected to be applicable, since recent experiments of Backenstoss et al. (Bac C 69) have shown, that in several elements μ capture leaves the final nucleus favourably in an excited state. The γ rays from the decay of these states, if not isomeric, can provide a time-zero signal for starting the neutron time-of-flight apparatus.

The disadvantages of this technique are obvious: 1) neutron from μ capture, leading to the ground state of the final nucleus, are not recorded. 2) in order to get a sufficient energy resolution the neutron detector has to be placed in a distance of about 1 m from the target, so the coincidence counting rate is rather small.

On the other hand, the advantages of the time-of-flight method are striking: a time-of-flight spectrum is easily converted into an energy spectrum. The background problem is not severe, because of the different flight times of γ rays and neutrons. Measurements in two different distances from the target allow elimination of most other background. The additional measurement of the energy of the capture-γ rays may provide means to distinguish between neutron groups from the decay of the intermediate states to different excited states in the possible final nuclei.

During the last few months some tests were made to check the feasability of this experiment. In a test run with ^{209}Bi as target a 2" x 2" NaI crystal was used for detection of capture γ rays. The neutrons were detected in an NE213 liquid scintillator. A γ-n-pulse shape discrimination was applied.

Figure 3 shows the time-of-flight spectrum of neutrons from μ capture in ^{209}Bi, as obtained after a 9 hours-measurement. The flight path was 1 m, the time resolution was 3 ns. The strong line on the left is the "prompt peak", caused by γ rays coincident in both detectors. The broad bump, when converted to energy scale, exhibits a Maxwellian shape, which is typical for evaporation spectra. The most striking feature is the line between prompt peak and evaporation bump. The corresponding energy is about 10 MeV, the width about 6 MeV. These neutrons are probably not emitted in an evaporation process. The tests have shown the feasability of this type of experiment. We intend to apply this method later on to light nuclei.

SPECTROSCOPY OF PROMPT NEUTRON EMITTED DURING THE μ CASCADE

Simultaneously to the ($t_\gamma \rightarrow t_n$) time-of-flight measurement discussed in the previous section the time interval between the μ stop and the event in neutron detector is recorded. Essentially this measurement is a repetition of an experiment recently performed by the Ottawa group (Har H 69). A spectrum of this type (μ stop → t_n) for μ-Bi is shown in Fig. 4a. Fig. 4b exhibits the same spectrum subject to the condition that a delayed capture-γ-ray be detected in a 3" x 4" NaI crystal during a gate time of 100 ns after the neutron event. This condition eliminates μ capture-neutrons from the simple spectrum, Fig. 4a, except those which are followed by accidental counts in the NaI detector. From the comparison of both spectra it is obvious that the major part of the simple spectrum is due to capture-neutrons, which are emitted with exponentially decreasing probability after the μ- stop, corresponding to the μ capture half life of 73 ns. A fraction of 5 to 10% of the neutrons, mainly those which form the peak on top of the broad distribution, is followed by delayed capture-γ-rays. These neutrons have been interpreted as "prompt" neutrons emitted from nuclei which have been excited by radiationless muonic transitions (Har H 69). The energy of these neutron groups is consequently $E_n = \Delta E_\mu - E_s - E^*$ (ΔE_μ energy of the muonic transition, E_s neutron separation energy (7,43 MeV), E^* excitation energy of the residual nucleus.

The excistence of this mechanism is supported by the observation of prompt nuclear γ transitions in isotopes of the target element (Har H 69), (Bac E 69). The radiationless muonic transitions proposed may also account for the observed discrepancies between measured and calculated muonic transition intensities (Bac 69). The present "prompt" neutron spectra at most establish the existence of the excitation mechanism, details cannot be deduced. A complete investigation requires simultaneous measurements of cascade X rays, prompt nuclear γ rays and neutron spectra. For the neutron spectra, however, improved energy resolution as well as better statistics are necessary.

REFERENCES

Baa B 68 a	R. Baader et al., Phys. Letters 27B, 425 (1968).
Baa B 68 b	R. Baader et al., Phys. Letters 27B, 428 (1968).
Bac 69	H. Backe, Thesis, Institut für Technische Kernphysik, T.H. Darmstadt, 1969.
Bac C 69	G. Backenstoss et al., Proc. 3rd Int. Conf. on High-Energy Physics and Nucl. Structure, Columbia Univ., 1969.
Bac E 69	H. Backe et al., Proc. 3rd Int. Conf. on High-Energy Physics and Nucl. Structure, Columbia Univ., 1969.
Bac K 69	H. Backe et al., CERN document PH III-69/25.
Bal E 69	V.V. Balashov et al., Proc. 3rd Int. Conf. on High-Energy Physics and Nucl. Structure, Columbia Univ., 1969.
Bal K 67	V.V. Balashov et al., Nucl. Phys. B1, 158 (1967).
Bar S 64	J. Barlow et al., Phys. Letters 9, 84 (1964).
Bun 66	G.G. Bunatyan, Sov. Journ. Nucl. Phys. 2, 619 (1966).
Eng 69	R. Engfer, Lectures at the "Sommerschule über Mittelenergie-Physik", Leysin, Sept. 1969.
Evs K 69	V. Evseev et al., Proc. 3rd Int. Conf. on High-Energy Physics and Nucl. Structure, Columbia Univ. 1969.
Fol W 64	L.L. Foldy et al., Nuovo Cim. 34, 1026 (1964).
Hag 63	D.E. Hagge, UCRL 10516 (1963).
Har H 69	C.K. Hargrove et al., Phys. Rev. Letters 23, 215 (1969).
Kel U 68	F.J. Kelly et al., Nucl. Phys. A118, 302 (1968).
Kri 69	M.H. Krieger, Nevis-172 (1969).
Luy T 65	J.R. Luyten et al., Nucl. Phys. 70, 641 (1965).
Mac D 65	B. MacDonald et al., Phys. Rev. 139, B 1253 (1965).
Pri 59	H. Primakoff, Rev. Mod. Phys. 31, 802 (1959).
Sun S 68	R.M. Sundelin et al., Phys. Rev. Letters 20, 1198 (1968).

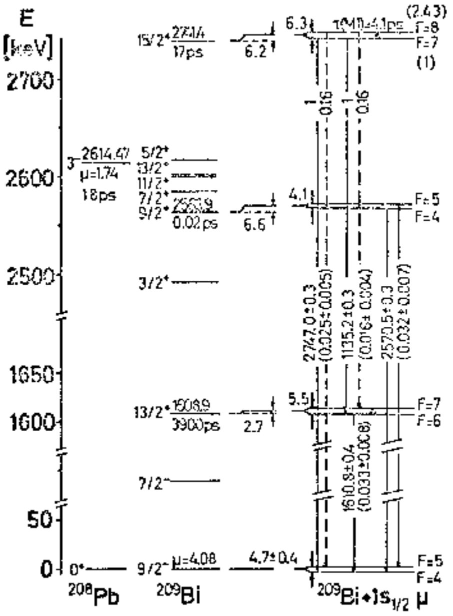

Fig. 1

Level scheme of μ-^{209}Bi. For the isomer shift and the intensities of the γ transitions the experimental values are given. The magnetic hf splitting for the 13/2$^+$ level are calculated from shell model and for the 9/2$^+$ and 15/2$^+$ levels from the coupling of the h 9/2 proton to the 3$^-$ lead core.

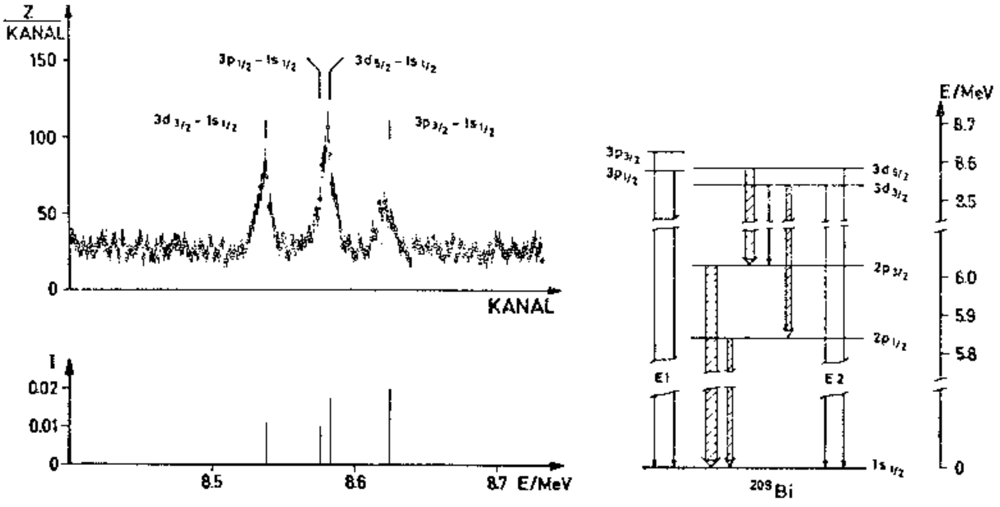

Fig. 2

3p-1s E1 and 3d-1s E2 X rays in μ-Bi

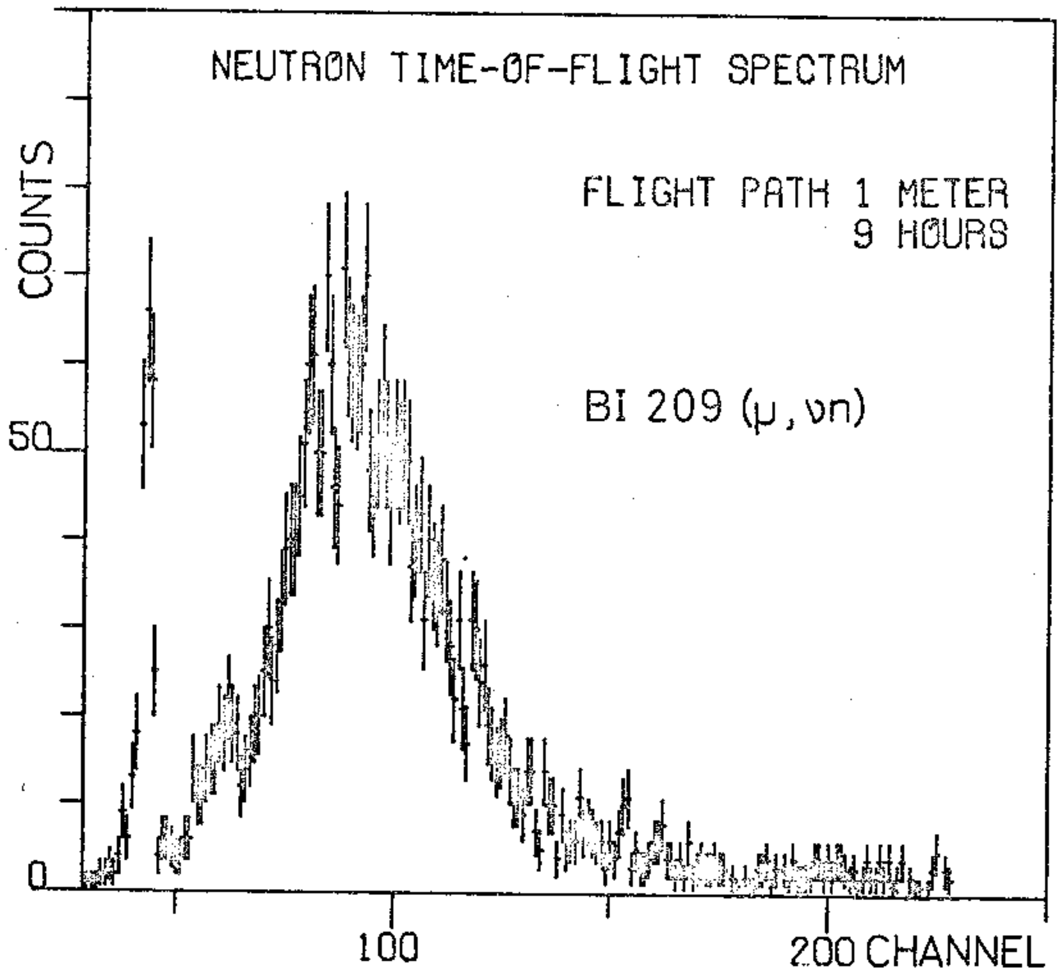

Fig. 3

Neutrons from μ capture in ^{209}Bi

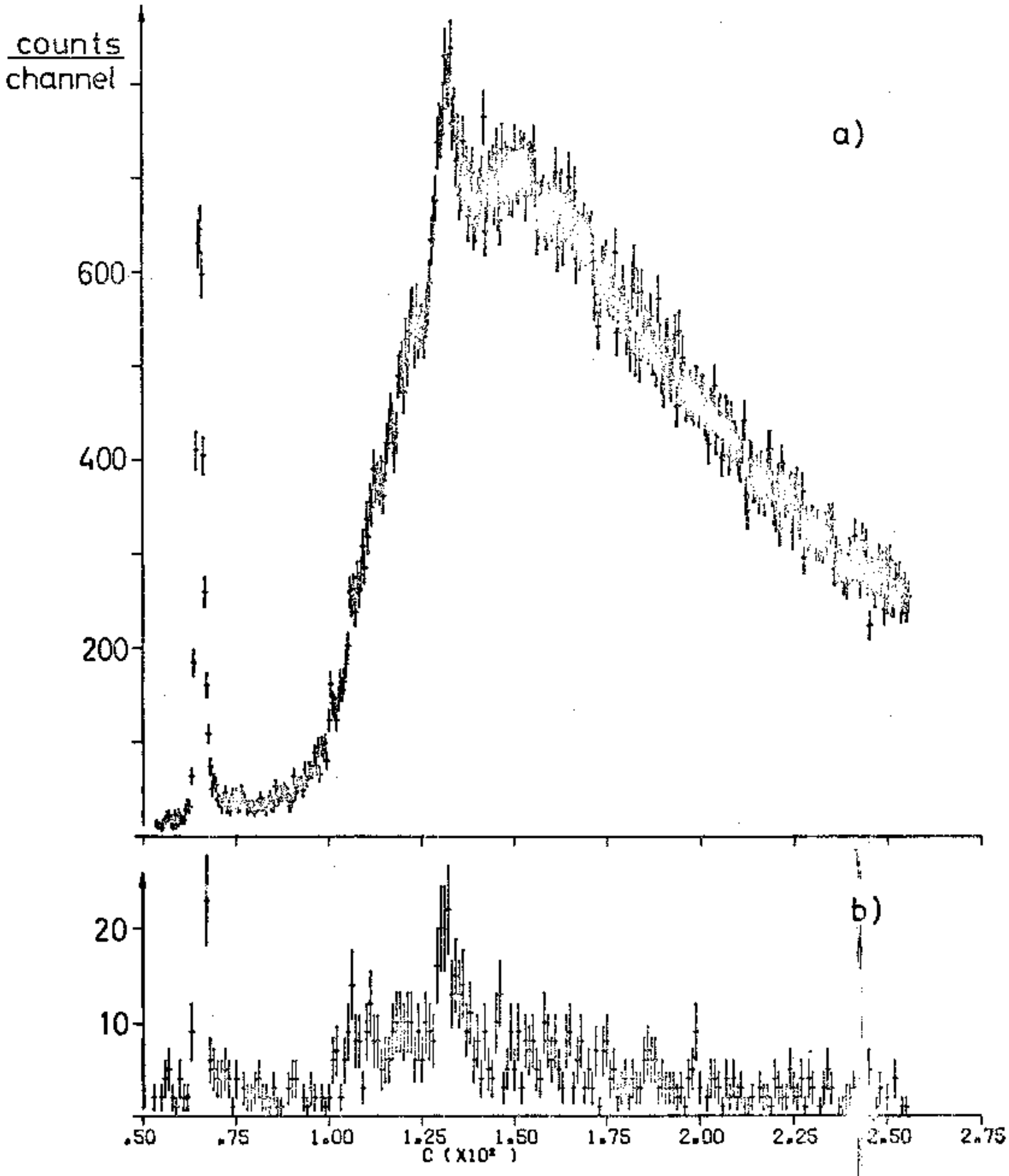

Fig. 4

a) Time distribution of neutrons related to a μ stop in ^{209}Bi

b) Time of flight spectrum of prompt neutrons. Measuring time: 9 hrs. Distance of the neutron counter: 1m.