NEUTRON EMISSION FROM NUCLEAR EXCITATION BY RADIATIONLESS TRANSITIONS IN μ-ATOMIC Bi^{209}†

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Neutron emission by radiationless μ-atomic transitions in Bi^{209} has been observed. The analysis of the neutron time-of-flight spectrum shows that this process takes place in muon transitions from the $n=3$ or higher states to the ground state of the muonic atom while the nucleus is left either in the ground state or in an excited state, possibly one belonging to a particle-hole multiplet of Bi^{208}. The process investigated here occurs in $7\pm2\%$ of all muon stops in bismuth.

Like so many aspects of μ-atomic physics, the possibility of radiationless transitions of the muonic atom leading to nuclear excitation was forseen early by Wheeler.[1] He referred specifically to muon-induced fission, a process which received attention in the late fifties and early sixties, both from the experimental and from the theoretical point of view. Negative-muon-induced fissions were observed by John and Fry[2] in uranium-loaded nuclear emulsions. Counter experiments by Diaz et al.[3,4] showed later that about 7% of muon-induced fissions in uranium are "prompt"; the rest result from the relatively slow nuclear capture of the muon from the 1s state. "Prompt" fission was also observed by Belovitskii et al.[5] A number of theoretical papers by Zaretsky and Novikov[6-11] are devoted to radiationless transitions with special emphasis on fission. Indirect evidence for a large contribution of radiationless transitions came also from the observation[12,13] that the intensity of the 2p-1s line in uranium and thorium is lower than in lead and bismuth by about 20%. Such radiationless transitions could lead not only to fission, but also to disintegration of the nucleus with emission of a single neutron or to a return to the ground state with emission of γ rays. In the present paper we will describe an experiment in which the "prompt" neutrons emitted in radiationless μ-atomic transitions were observed and their energy spectrum measured. The target chosen was Bi^{209}, where a radiationless (γ, n) reaction leading to Bi^{208} is energetically permitted but fission is not.[14]

In the course of an experiment[15] on muonic transitions in Pb^{206}, Pb^{207}, and Pb^{208}, γ-ray lines were found corresponding to known nuclear transitions in the lead isotopes with intensities of the order of 10% of the main lines of the μ-atomic spectra. As reported earlier by one of us,[16] the Pb^{206} 803-keV first-excited-state γ ray was observed in the spectra from both the Pb^{206} and Pb^{207} targets. Similarly, the first two excited states in Pb^{207} (570 and 897 keV) were observed from the Pb^{207} and Pb^{208} targets. These lines appeared in the "prompt" spectra and were therefore interpreted tentatively as produced by radiationless transitions of the muon, leading to nuclear excitation with or without emission of a neutron. However, since the experiment was not designed specifically to observe this effect, the need for further experimentation was indicated.

The present experiment was designed to detect neutrons emitted from nuclei excited by radiationless μ-atomic transitions to the ground state. That in the lead experiment mentioned above the "prompt" γ rays observed were characteristic not only of the particular isotope used as target material, but also of the isotope with one mass number less, suggested the possibility of studying the radiationless transitions by observing the neutrons emitted. From the intensity of the "prompt" γ rays, we expected that "prompt" neutrons should be produced in 5 to 15% of muon stops. Also, we expected the neutrons to have a characteristic energy spectrum according to

$$E_n = \Delta E_\mu - E_s - E_N, \tag{1}$$

where E_n is the neutron energy, ΔE_μ is the energy difference of the μ-atomic levels, E_s is the neutron separation energy of the target material (7.43 MeV for Bi^{209}), and E_N is the excitation energy of the daughter nucleus.

The cascade process is essentially instantaneous with respect to a muon stop, occurring in a time of the order of 10^{-12} sec, whereas the capture process, which takes place when the muon has reached the 1*s* state, has a half-life of the order of 50 nsec.[17,18] The "prompt" neutrons must be measured in the presence of the much higher yield of μ-capture neutrons. The method we have chosen is as follows: The time of flight of the neutron between the target and the neutron counter is measured subject to the condition that it be followed by a capture event. By requiring the detection of such a "capture" event after the detection of the "prompt" neutron, one is assured that the latter is, in fact, a cascade particle.

The experiment was performed at the 450-MeV synchrocyclotron of the Enrico Fermi Institute at the University of Chicago. Magnet settings for the muon channel were adjusted so that the "backward" muon was directed into the target in order to obtain a muon beam essentially free from pion contamination at some sacrifice in intensity. A rate of about 6000 muons/sec stopping in a 4-g/cm^2 target was usually obtained.

The experimental setup is shown in Fig. 1(a). A muon stop is signaled by a coincidence of the scintillation counters A and B, with C in anticoincidence. E is a Lucite Čerenkov counter used to veto electrons present in the beam. The large DC, or delayed coincidence, counters surrounding the target are used for efficient detection of the capture γ rays and neutrons. The N, or neutron, counter is a $4\frac{1}{2}$-in.-diam × $\frac{1}{2}$-in.-thick disk of NE213 scintillator viewed by an RCA 4522 phototube. Use of the comparatively slow NE213 scintillator (3.7-nsec decay time), together with a detector size which is extensive for the short (18-in.) flight path used, results in a time resolution of only 2.5 nsec. However, the NE213 permits a pulse-shape discriminator[19] to reduce a considerable background of x and γ rays. The discrimination is enhanced by the addition of 24 g/cm^2 of lead absorber in front of the neutron detector. The F counter is used to veto charged particles entering the neutron detector.

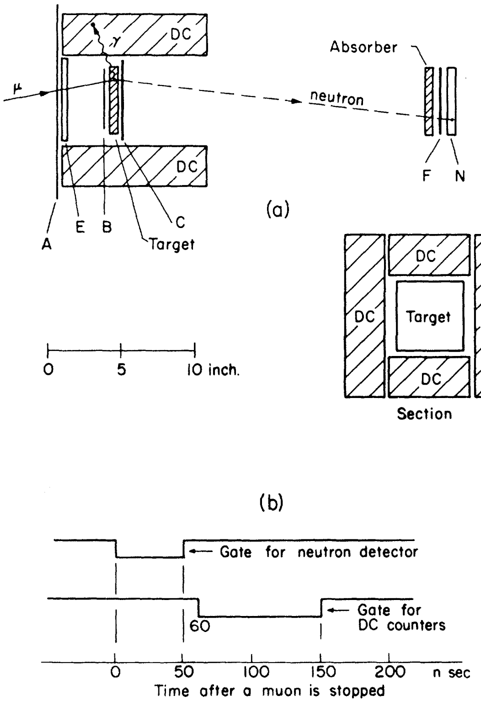

FIG. 1. (a) Experimental setup. A, B, C, DC, and F are plastic scintillation counters. E is a Lucite Čerenkov counter, and N is the neutron detector. (b) Basic timing sequence.

Counter B, just in front of the target, gives the start signal for the time-of-flight measurement, while the actual time of flight is determined from the time overlap between the stretched B and N pulses. The resulting pulse is fed through suitable gating circuits to a time-to-amplitude converter, the output of which is analyzed and stored in a 200-channel pulse-height analyzer. The basic timing sequence is shown in Fig. 1(b).

Figure 2(a) shows a summed, but otherwise untreated, spectrum from the pulse-height analyzer using a bismuth target. (The data were summed over a number of runs and also over two adjacent channels, as indicated.) Although the energy dependence of the neutron detection efficiency has not been applied, its inclusion leaves the main features of the spectrum unchanged. For comparison, we show in Fig. 2(b) a spectrum obtained with a silver target for roughly the same number of muon stops as in Fig. 2(a). It is energetically impossible for cascade neutrons to be emitted from silver, but otherwise the conditions for silver are very similar to those in bismuth; in particular, the muon-capture half-life of silver is close to that of bismuth, an important consideration in this experiment which requires detection of a capture γ ray or neutron within a given time window.

The silver spectrum in Fig. 2(b) shows no apparent structure except for the sharp peak at channel 19 which is due to "prompt" x and γ rays recorded by the neutron detector. The rest of the silver spectrum is interpreted as being produced entirely by accidental coincidences of various kinds, due to the relatively long time windows required by the time-of-flight measurement, as well as the high singles rates in the thick DC counters. The neutron spectrum from

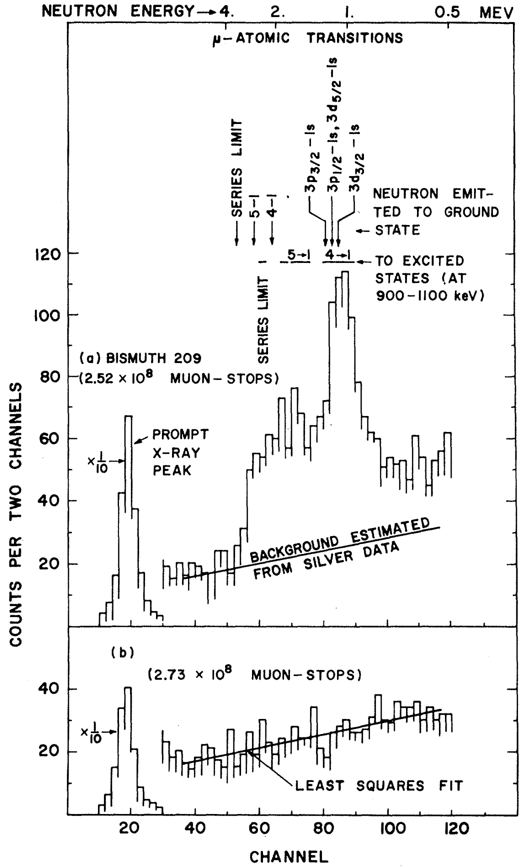

FIG. 2. (a) Neutron time-of-flight spectrum obtained with a bismuth target. Transitions likely to contribute to this spectrum are indicated at the top of the figure. (b) Neutron time-of-flight spectrum for silver target.

silver can be fitted with a straight line, and the total number of counts in this spectrum is close to the accidental rate which we estimate from the known rate of muon stops. These estimates also show that the main contribution to the background comes from detecting either random neutrons or capture γ rays which are not rejected by the γ-n discriminator.

When the background derived from the silver data is subtracted from the bismuth spectrum in Fig. 2(a), the spectrum shows the following interesting features:

(1) The most prominent feature is the large peak around channel 85 (about 1100-keV neutron energy). This corresponds to a 3 → 1 radiationless transition of the muon accompanied by neutron emission leaving the daughter nucleus Bi^{208} in its ground state. From the location of the peak it appears that if transitions from $n = 3$ states are responsible, the main contribution comes from $3d \rightarrow 1s$ rather than $3p \rightarrow 1s$. The 2 → 1 transition of the muon has not enough energy for neutron emission, and cascade calculations[20] show that $3d \rightarrow 1s$ is indeed the best candidate for this process.

(2) The sharp rise of the spectrum occurring at an energy corresponding to the muon series limit is very significant. It shows that transitions of higher μ-atomic states to the ground state also contribute to neutron emission, although the neutron lines are not resolved in this region.

(3) The large peak around channel 85 cannot be entirely due to the 3 → 1 transition mentioned above because it is wider than expected from the resolution of our apparatus. In addition, other processes must be present to fill the wide energy gap between the energies corresponding to the transitions 3 → 1 and 4 → 1. It is very likely that the two overlapping particle-hole multiplets of Bi^{208} in the energy interval 930-1150 keV described by Alford, Schiffer, and Schwartz[21] play an important role here. The neutron energy in a muon transition 3 → 1, leaving Bi^{208} in one of the multiplet states, would be very low, well outside the range of this experiment. The transition 4 → 1, however, would lead to a broad band covering almost exactly the large peak of the experimental spectrum, as indicated in Fig. 2. It also suggests that higher muon transitions, leaving the nucleus in such an excited state, are responsible for the bump in the experimental spectrum around channel 70 (neutron energy 1800 keV). It is possible that another particle-hole multiplet around 635 keV[21] also contributes to this bump.

(4) From the knowledge of the total number of events in the spectrum above background and a detailed analysis of the detection efficiency of the system, we have deduced the probability of radiationless transition in bismuth, leading to neutron emission above 0.5-MeV kinetic energy. This probability is $7 \pm 2\,\%$ per stopped muon.

Preliminary work on lead isotopes shows features similar to those of bismuth, while the "prompt" neutron spectrum from U^{238} appears to be dominated by fission neutrons produced in radiationless transitions. The results presented here show that it would be very desirable to improve the energy resolution. This is, however, by no means a trivial problem because the necessity of discriminating between prompt and capture events imposes a limit on the width of the time-of-flight window which is of the order of the muon-capture half-life, so the flight path for neutrons cannot be increased much beyond the value used in the present experiment.

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SOME OBSERVATIONS ON THE THERMOMAGNETIC GAS-TORQUE ANOMALY

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The magnetic gas-torque effect in polyatomic gases (the Scott effect) has been examined experimentally by means of a torsion pendulum with both linear and cylindrical torque-sensing elements. The addition of barriers installed to impede possible bulk rotation of the gas (oxygen in these experiments) reduced the torque appreciably. These observations suggest that rotation of the gas contributes to the torque.

This note presents the results of an experimental study of the anomalous thermomagnetic torque in rarified polyatomic gases (the Scott effect).[1] In these particular experiments oxygen was used. To detect the small torques we employed a torsion pendulum similar to those described elsewhere,[1,2] except that we have replaced the cylindrical torque-sensing elements with elements of different forms. These were suspended about the heat source, a small cylindrical lamp ($\frac{3}{4}$ in. diam)