SUBNANOSECOND LIFETIME MEASUREMENTS OF EXCITED STATES IN NUCLEI FAR FROM STABILITY

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A system has been developed to measure the lifetimes of nuclear states in the range of 0.05 to 1 nanosecond in nuclei far from stability. A Gerholm magnetic lens was placed on-line with the UNISOR mass separator to observe conversion electrons in coincidence with γ rays detected in a plastic scintillator. With this system, the half-life of the 522 keV, 0^+ level in ^{186}Hg was measured to be 155±70 picoseconds. Improvements in this system should make possible on-line measurements of half-lives as short as ≈50 picoseconds.

INTRODUCTION

Several recent experimental studies on the isotopes ^{184,186,188}Hg have indicated that these nuclei exhibit a coexistance of a near spherical oblate and strongly deformed prolate shapes. This shape coexistance theoretically manifests itself in the presence of two minima in the nuclear potential energy surface. A variety of theoretical approaches [1,7] have been taken for the mixing of single-particle states in Hg isotopes and all have resulted in two minima in the potential energy surfaces. Dickmann and Dietrick [1] have made approximate predictions of the mean life of the excited 0^+ levels assuming pure E2 decay to the first 2^+ levels in ^{184}Hg and ^{186}Hg. Their model assumes an energy surface with a lower minimum corresponding to a small oblate minimum and an upper minimum corresponding to a significant prolate deformation. The small oblate deformation was neglected, and it was assumed that the states associated with it are harmonic vibrations built on a quasi-spherical ground state with rotational states built on the prolate minimum. The mean lives of 20 nanoseconds and 12 nanoseconds were predicted for the excited 0^+ states for ^{184}Hg and ^{186}Hg, respectively [1]. Measurements of these lifetimes offer important tests of the structures of these nuclei.

The experimental studies at UNISOR [8,10] have clearly demonstrated that the E2 transitions from the excited 0^+ levels in these isotopes are too weak to be observed. Their dominant decay is via an E0 transition to the ground state. Careful timing experiments with a Si(Li)-Ge(Li) system gave a lifetime of the excited 0^+ state in ^{184}Hg of 0.9±0.3 nanoseconds [9]. A similar trial for ^{186}Hg only revealed that $T_{1/2}$ was << 1 nanosecond. One nanosecond is about the limit of a Si(Li)-Ge(Li) system and even then the error is large. A new on-line system was developed to measure lifetimes of nuclear states with $T_{1/2}$ < 1 nanosecond. The half-life of the first excited 0^+ level in ^{186}Hg was measured with this system to be (155±70) picoseconds. Thus, we have shown the usefulness of on-line measurements of subnanosecond lifetimes with a magnetic lens for high resolution, coupled with plastic detectors for fast timing.

INSTRUMENTATION

In nuclei far from stability, it is typically the case that hundreds of transitions are seen in the decays of each mass chain. Thus high resolution is required to separate the individual transitions. By careful setting of the timing over limited energy regions, it is possible to achieve revolving times of the order of 6 to 10 nanoseconds with a Si(Li)-Ge(Li) system. One can use such a system to measure half-lives of nuclear states as short as about 1 nanosecond, but the errors are of the order of 0.3 to 0.5 nanoseconds. Two fast plastic scintillators can be used to measure half-lives on the order of 50 picoseconds, but there is no energy selection.

The experimental technique used in this investigation is based on the high transmission magnetic lens designed by Gerholm [11] to detect the internal conversion electrons. The lens is equipped with a set of helical baffles which affords excellent discrimination against positrons from the expected positron decays of protron rich nuclei far from stability. The coincident γ rays were detected in a large plastic scintillator. The two-detector configuration is coupled to the tape transport system of the UNISOR isotope separator which in turn is coupled to the Oak Ridge Isochronous Cyclotron (ORIC). The detector configuration is shown in Figure 1. The Mylar tape on the tape drive is threaded through special rollers so that the radioactive deposit from the separator collection point can be rapidly transported to the spectrometer entrance which is opposite the plastic scintillator used for γ ray detection. In this system one channel has good energy resolution while both have excellent timing characteristics derived from the fast rise-time of the light pulses from the plastic scintillators.

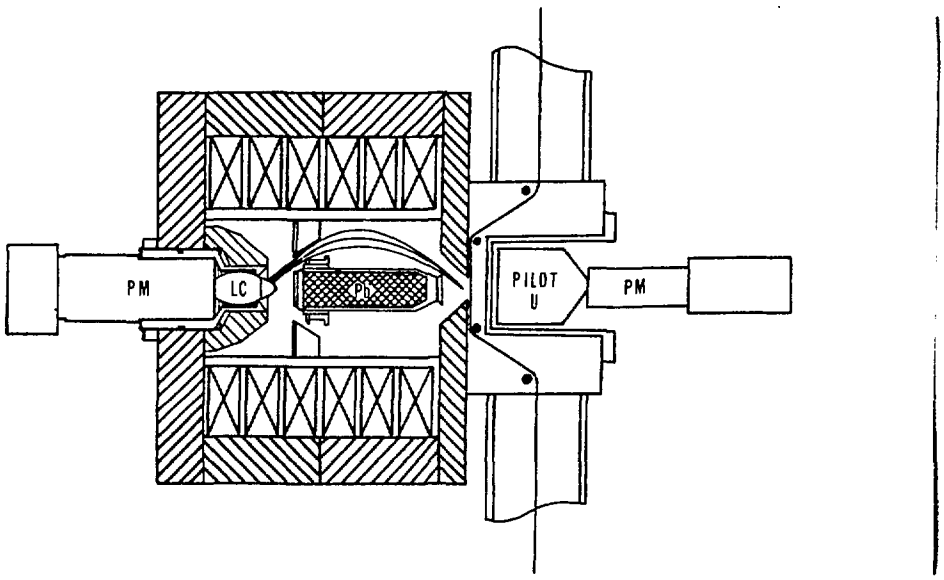

Figure 1
Diagram of the Gerholm lens and plastic scintillator coupled to the UNISOR tape drive.

The electrons are momentum-selected by the spectrometer baffles and are detected with a small conical Pilot-B scintillator coupled to a fast RCA C31024 photomultiplier tube. A large 7.62 cm in diameter by 7.62 cm long cylindrical NE-102 scintillator was coupled to the same type tube in the γ-ray detector for the measurements presented in this paper. Since those measurements, the γ-ray detector has been modified by tapering a Pilot-U scintillator so that only the central half

of the face of the photo-cathode views the scintillator. Diffuse reflectant paint is used and the light collection is not noticeably affected while the timing characteristics are improved by the reduction in the transit time spread of the photo-electrons from the photo-cathode. The fast negative pulses from the photo-cathodes of both tubes were fed through two stages of an ORTEC model AN-302 quadamplifier and then to ORTEC model 473, constant fraction discriminators. The fast logic pulses from the discriminators were then used as "START" and "STOP" pulses of the time-to-amplitude converter (TAC). The TAC spectra from the calibration and life-time measurement of the 522 keV, 0^+ level in ^{186}Hg, are shown in Figure 2.

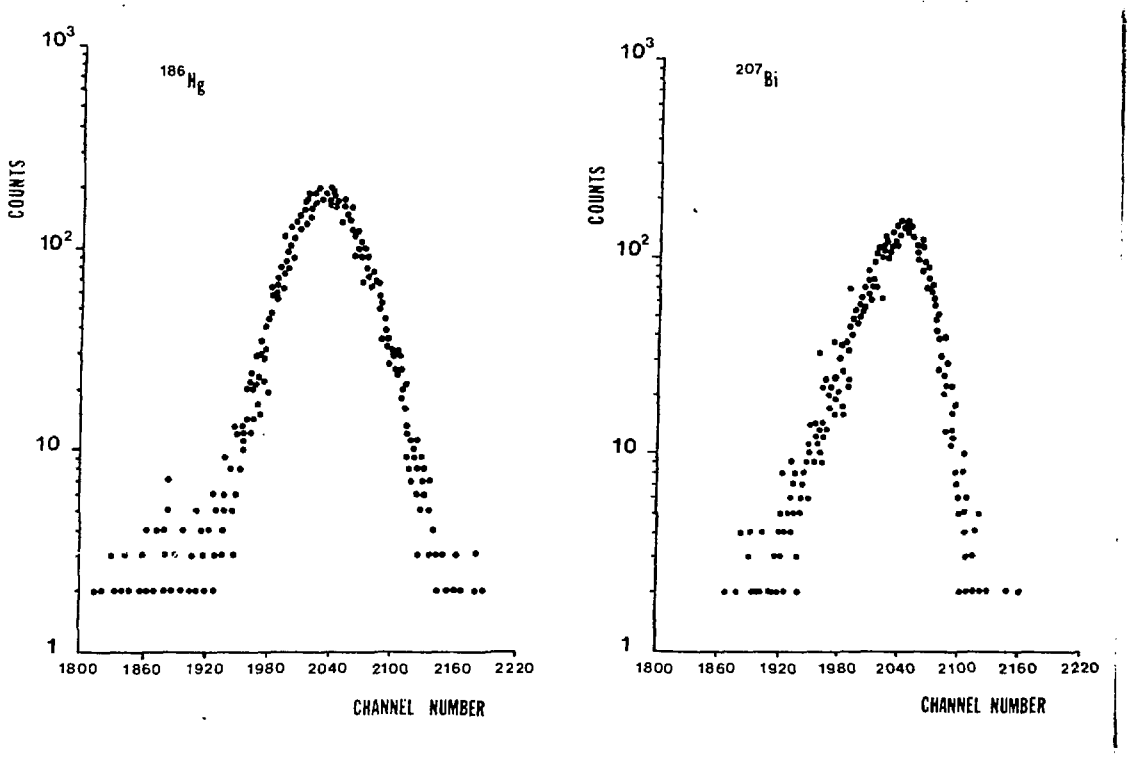

Figure 2
Time-to-Amplitude Converter spectra for the delayed coincidence functions G(C). The time-to-channel conversions do not have the same scale.

EXPERIMENTAL PROCEDURE

The mass chain A = 186 was entered at ^{186}Tl and ^{186}Hg via the reactions ^{180}W(^{14}N, 8n+p)^{186}Hg and ^{180}W(^{14}N, 8n)^{186}Tl. The target was mounted in a special high temperature target ion source developed at UNISOR. The ionized reaction products were then mass separated and deposited on aluminized Mylar tape at the separator collection point. Collection and counting times of 56 seconds were used. The energy calibration of the lens was accomplished by using the conversion electrons from radioactive sources of ^{207}Bi and ^{137}Cs. Coincidences between the conversion electrons from the 1064 keV transition and the γ rays from the 570 keV transition in the decay of ^{207}Bi were used to obtain a TAC spectrum for a known half-life, namely the 129 picosecond half-life of the 1078 keV level in ^{207}Pb. This spectrum was used to aid in the analysis by using the method of higher moments of the two TAC spectra shown in Figure 2. The full width at half maximum of the spectrum from the ^{207}Bi decay was 900 picoseconds. Since the time of these measurements,

we have found that an excellent prompt curve can be obtained by using the 2317 keV β^- branch in the decay of ^{124}Sb in coincidence with the 603 keV γ ray in ^{124}Te. Resolving times of $\simeq$ 800 picoseconds were later obtained. Efforts to further reduce the resolving time of the system are presently in progress.

ANALYSIS OF THE DATA

When an actual prompt or no-delay curve can be obtained, the simplest method of extracting the half-life from this type of data is the centroid shift method. The prompt curve in the present experiment was not actually a prompt curve; hence, we were forced to use methods involving higher moments about the centroid. The observed delayed coincidence spectrum is actually a convolution of the detector timing response function P(t) and the exponential decay function $\lambda e^{-\lambda t}$. The moment of order k of the function f(t) about the centroid is defined as follows:

$$M_k(f) \equiv \int_{-\infty}^{\infty} f(u)\, u^k\, du \,/\, \int_{-\infty}^{\infty} f(u)\, du, \tag{1}$$

where $u \equiv t - t_o$ and t_o corresponds to the centroid.

The convolution or delayed function G(t) is defined as,

$$G(t) = \lambda \int_0^t P(t')\, e^{-\lambda(t-t')}\, dt'. \tag{2}$$

In the present case, the function P(t) was not available since the lifetime of the 1078 keV level of ^{207}Pb has a finite half-life $T_{1/2} \simeq 129$ picoseconds [12]. The advantage of using ^{207}Bi to obtain a calibration is that it has the strongly converted 1064 keV transition, while the main disadvantage of using any cascade with a lifetime approximately equal to the one being measured experimentally, is that it results in the subtraction of two almost equal numbers which can lead to a large fractional error. In this analysis, the second moments of the two delayed functions $G_1 \equiv G_1(u, {}^{207}\text{Bi})$ and $G_2 \equiv G_2(u, {}^{186}\text{Hg})$ were used. It can be shown that their second moments are simply related by .

$$M_2(G_1) - M_2(G_2) = \tau_1^2 - \tau_2^2. \tag{3}$$

The numerical values for the second moments of G_1 and G_2 are given in Table 1 along with the resulting mean lives τ_1 of the delayed function G_1, which is known, and τ_2 of the delayed function which is to be determined. The continuous variable u was converted into the discrete variable c, which represents the channel number, and Δc is the number of channels used in the analysis. It is not possible to determine exactly how many channels should be included and it can be seen from the table that this adds to the statistical uncertainty in τ and $T_{1/2}$.

Table 1
Calculated Second Moments, Mean-lives, and Half-lives

Δc	$M_2(G_2)$	$M_2(G_1)$	τ_2(PS)	$T_{1/2}$(PS)
245	1069(122)	1007(109)	215(139)	149(96)
225	1066(103)	992(90)	222(112)	154(78)
205	1059(86)	979(72)	226(91)	157(63)
185	1029(70)	955(57)	222(74)	154(51)
165	983(56)	896(44)	230(57)	159(40)

RESULTS AND CONCLUSIONS

The half-life of the 522 keV, first excited 0^+ state of ^{186}Hg, was determined from the second moments given in Table 1 to be (155±70) picoseconds. The γ-ray and conversion electron spectra collected during our earlier work indicates that this level decays almost entirely by E0, internal conversion to the 0^+ ground state. The short half-life measured here is about two orders of magnitude less than the estimate of Dickmann and Dietrick [1] for the decay by electric quadrupole transition. If one considers the simplicity of the electromagnetic monopole operator, one might expect a short lifetime in the case that there is excellent overlap of the wave functions of the first excited 0^+ states and the 0^+ ground states. This view seems somewhat inconsistant with the hypothesis of any model based on the assumption that these states correspond to two very different nuclear shapes. This conclusion can be stated more securely only after calculations of the half-life based on E0 decay are made.

The emphasis of this paper, however, is that the present technique has efficiency and timing characteristics which are sufficient to make lifetime measurements at UNISOR with the present state of ORIC beam intensities and separator, ion-source efficiencies. With an upgrading of the electronics, we anticipate that measurements of half-lives down to the order of 50 picoseconds should become routine for states which have observable conversion electron decays.

REFERENCES

[1] Dickmann F. and Dietrick, K., Z. Phys. 271 (1974) 417.

[2] Cailliau, M., Letessier, J., Flocard, H., and Quentin, P., Phys. Lett. 46B (1973) 11.

[3] Kolb, D. and Wong, C. Y., Nucl. Phys. A245 (1974) 205.

[4] Kumar, K., Remaud, B., Auger, P., Vaagen, J. S., Rester, A. C., Foucher, R., and Hamilton, J. H., Phys. Rev. C16 (1977) 1235.

[5] May, F. R., Pashkevich, V. V., and Frauendorf, S., Phys. Lett. 68B (1977) 113.

[6] Nilsson, S. S., Nix, J. R., and Moller, P., Nucl. Phys. A222 (1974) 221.

[7] Frauendorf, S. and Pashkevich, V. V., Phys. Lett. 55B (1975) 365.

[8] Hamilton, J. H., et. al., Proceedings of the International Conference on Reactions Between Complex Nuclei (Nashville, Tennessee, 1974), Robinson, R.S., McGowan, F. K., Ball, J. B., and Hamilton, J. H. (eds) (North Holland, Amsterdam, 1974).

[9] Cole, J. D., et. al., Phys. Rev. Lett. 37 (1976) 1185.

[10] Cole, J. D., et. al., Phys. Rev. C16 (1977) 2010.

[11] Gerholm, T. R. and Lindskog, J., Arkiv Fysik 24 (1963) 171.

[12] De Lima, E., Kawakami, H., De Lima, A., Hichwa, R., Ramayya, A. V., Hamilton, J. H., Dunn, W., and Kim, H. J., Nucl. Inst. and Meth. 191 (1978) 221.

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