Lower Limit for the Lifetime of the 0.8-Mev Excited Level of Mo^{96}

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(Received July 5, 1951)

THE method of delayed coincidences yields upper limits for the lifetimes of nuclear levels which are shorter than $\sim 10^{-10}$ sec. Resonant nuclear scattering of gamma-rays,[1,2] on the other hand, is more easily observed the shorter the lifetime and will therefore enable one to determine very short lifetimes or set lower limits to them. The two methods thus complement each other.

The cross section for nuclear resonant scattering is large at resonance ($\sim 2\times 10^{-21}$ cm^2 at one Mev); but in general the gamma-rays are off resonance owing to the energy transferred to the recoiling nuclei in the emission process as well as in the absorption process. In optics, where resonance fluorescence is a well-known phenomenon, this energy transfer is small compared with the energies of thermal motion; for gamma-rays the recoil energies are orders of magnitude larger than the line widths. For a given off-resonance energy the reduction in the scattering cross section is smaller the larger the gamma-ray width, i.e., the faster the transition. Observation of nuclear resonance scattering will therefore be most probable for fast transitions, i.e., transitions of low multipole order.

According to Medicus, Preiswerk, and Scherrer,[3] the last gamma-ray emitted in the decay of Tc^{96} is an electric dipole. For this reason we investigated the resonant scattering in Mo^{96} into which Tc^{96} decays. Mo^{96} seemed to be a favorable choice for another reason: the 0.8-Mev gamma-ray transition to the ground state of Mo^{96} is preceded by a cascade of two other gamma-rays. After the emission of these two gamma-rays the nucleus will have a certain momentum which depends on the angle between the two gamma-rays. If the third gamma-ray is emitted before the recoiling nucleus comes to rest, its energy (0.8 Mev) will be changed because of the Doppler effect. Thus, in a small percentage of the disintegrations of Tc^{96}, the resonance condition for the transition to the ground state is fulfilled owing to the preceding radiation; therefore, the observation of resonant scattering is greatly facilitated.

Using a 0.1 m-C Tc^{96} source we observed the radiation scattered by about 100 degrees from a sheet of molybdenum. Sodium iodide scintillation counters were used as detectors. At low discriminator settings the counting rate was primarily due to the soft Compton scattered quanta. At high discriminator settings the main contribution was due to the unmodified radiation arising from coherent scattering and resonant scattering. The amount of coherent scattering was estimated in a separate experiment using a cadmium scatterer in place of the molybdenum.

With a molybdenum sheet of 0.57 g/cm^2 the contribution of the resonant scattering was found to be less than 20 counts per minute, whereas the counting rate due to Compton scattering was 20,000 counts per minute. This result indicates that the width of the 0.8-Mev gamma-ray is several orders of magnitude smaller than the width of the recoil distribution.

In order to insure that our equipment had the expected sensitivity, we investigated the coherent scattering of Co^{60} gamma-rays from lead and zinc radiators. The amount of coherent scattering observed agreed reasonably well with the values calculated from Franz's[4] formula (7×10^{-4} and 9×10^{-5} times the Compton cross section, respectively). This formula had been checked at lower energies by Moon[5] and Storruste.[6] We therefore feel confident that our failure to detect resonant nuclear scattering from Mo^{96} is due to the small width of the gamma-line.

After applying all the necessary corrections to our experimental data, we find that the gamma-ray width Γ of the 0.8-Mev transition to the ground state of Mo^{96} is $\leqslant 10^{-2}$ ev. From Weisskopf's[7] formula for the transition probability one calculates a maximum width of one ev for an electric dipole transition, and a width of 1.1×10^{-2} ev for a magnetic dipole transition.

From our experiment we conclude that either the matrix element for the electric dipole transition is strongly reduced or that the transition to the ground state of Mo^{96} is of a higher multipole order.

From $\Gamma \leqslant 10^{-2}$ ev one finds for the half-life of the 0.8-Mev excited state in Mo^{96} $T_{\frac{1}{2}} \geqslant 0.5\times 10^{-13}$ sec.

* This work was supported in part by the joint program of the ONR and AEC.

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[7] Privately circulated notes, to appear as part of a book on nuclear physics.

The Differential Cross Section for High Energy Nucleon-Nucleon Collisions

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(Received July 2, 1951)

IN an attempt to account theoretically for the lateral and angular spread of the penetrating particles in high energy cosmic-ray showers, we have developed a method for deriving the differential from a given total cross section for inelastic nucleon-nucleon collisions in the laboratory frame of reference. An integral equation was set up for the differential cross section and solved assuming that in the c.m. frame of reference it was of the form $R+S\cos^2\bar{\Theta}$, where R and S are functions of the incident and scattered energies only, and $\bar{\Theta}$ is the scattering angle.

We define $W(U, c)dUdc$ as the probability in the laboratory frame of reference of finding a nucleon with total energy in the interval U, $U+dU$ and scattered at an angle whose cosine lies in the interval c, $c+dc$. Similarly $F(U)dU$ gives the total probability of finding a nucleon with energy in the interval U, $U+dU$. These two functions are related by the integral equation

$$\int W(U, c)dc = F(U). \tag{1}$$

The differential probability $W(U, c)dUdc$ is invariant under Lorentz transformation and we may therefore write

$$W(U, c)dUdc = (R+S\bar{c}^2)d\bar{U}d\bar{c}, \tag{2}$$

where the barred symbols refer to c.m. coordinates. Writing $\bar{U}=\cosh\bar{u}$, and $U_0=\cosh 2v$ for the energy of the incident nucleon we have found from (1)

$$R(\cosh\bar{u}) = (d/d\bar{u})\{\sinh^{-1}\bar{u}\, g'(v-\bar{u})\}, \tag{3}$$

$$\begin{aligned} S(\cosh\bar{u}) = {} & -\sinh^{-2}\bar{u}(d/d\bar{u})\{\sinh\bar{u}\, g'(v-\bar{u})\} \\ & -\tfrac{1}{2}(\sinh\bar{u}\sinh v)^{-2}[\sinh v\{f'(v+\bar{u})-f'(v-\bar{u})\} \\ & -\cosh v\{f(v+\bar{u})-f(v-\bar{u})\}], \end{aligned} \tag{4}$$

where the primes indicate derivatives, and

$$f(u) = F(\cosh u), \tag{5}$$

$$g(u) = \{4\cosh v \sinh(u-v)\}^{-1}\{f(u)-f(2v-u)\}. \tag{6}$$

Thus starting from the general total probability function $F(U)dU$ we have without specializing it found the differential probability function $W(U, c)dUdc$.

To obtain explicit results we adopted the form of $f(u)$ found by Messel[1] to account best for the vertical development of the high energy nucleon component of the cosmic radiation:

$$f(u) = 20(U_0-1)^{-5}(\cosh u-1)(U_0-\cosh u)^3. \tag{7}$$

In the ultra-relativistic approximation (7) leads to

$$R = -S = 30e^{-5v}(\exp v-\exp\bar{u})\exp(3\bar{u}). \tag{8}$$

We have calculated the mean square angle of scatter for a single nucleon-nucleon collision using (8) and found

$$\langle\Theta^2\rangle_{\text{Av}} = 4U_0^{-1}\ (\text{radians})^2. \tag{9}$$

The primary energy U_0 is measured in proton mass units.

Consideration of this result leads us to the conclusion that the lateral spread of the high energy nucleon component of the cosmic radiation in extensive air showers must be considerably greater than that for the majority of electrons whose mean square angular deflection is proportional only to U_0^{-2}.

The details and full discussion of the above work will be given in a subsequent publication. We are indebted to Professor E. Schrödinger for valuable suggestions in the course of the above work.

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Two-Step Isomeric Transition in Hf^{179m}*

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(Received July 5, 1951)

A 19-sec activity was reported in Hf by Flammersfeld,[1] and was assigned to Hf^{179m} by Muehlhause.[2] Hole[3] measured the energy of the conversion electrons in a β-ray spectrometer and obtained a value of 150 kev for the transition energy. The authors,[4] who investigated the unconverted gamma-rays in a scintillation spectrometer, found an intense gamma-ray line of 215-kev energy and suggested the possibility of a two-step isomeric transition. The measurements of Hole were repeated and confirmed by Burson *et al.*,[5] who found 160 kev for the internally converted transition. Thus it was apparent that two gamma-rays were involved in these measurements, a highly internally converted transition of 160 kev and a weakly converted transition of 215 kev.

To test the possibility of a two-step isomeric transition a number of experiments were carried out. Since previous investigations of the lifetime and the assignment of the 19-sec activity to Hf^{179m} had been based on observations of conversion electrons, it was necessary to determine whether the 215-kev gamma-rays were also associated with Hf^{179m}. Enriched isotopes of Hf (Hf^{176}, Hf^{177}, Hf^{178}, and Hf^{179}) were irradiated in the Brookhaven reactor and the 215-kev line was observed with a scintillation spectrometer. It appeared most intense in $Hf^{178}+n$. The γ-rays were found to decay with a half-life of 19 sec.

To record the expected coincidences in such a short-lived activity we made use of the following scheme. The Hf^{179m} sample was placed between two scintillation crystals mounted on RCA 5819 tubes. The pulse from one photomultiplier was used to start the sweep of an oscilloscope, while the pulse from the other photomultiplier was impressed upon the screen (y axis) of a cathode-ray tube. Under these conditions, the distribution seen is due to pulses in coincidence with the triggering pulses. By using either NaI-Tl or anthracene crystals, the detectors were made sensitive to gamma-rays or electrons, respectively. By triggering the sweep with electron pulses from an anthracene crystal and impressing the gamma-ray pulses from a NaI-Tl crystal upon the screen, the pulse distribution due to the 215-kev gamma-ray was seen (Fig. 1), indicating the existence of coincidences with a time delay <0.5 μsec. In coincidence with gamma-rays >160 kev an electron distribution with an upper limit of $\sim$95 kev was obtained. Adding the K-work function of Hf we find $\sim$150 kev for the energy of the highly converted transition, in good agreement with the beta-spectrographic investigations. The photon pulses obtained in coincidence with gamma-rays >160 kev showed only the Hf K-x-rays. The 160-kev transition is evidently highly converted, as already noticed by Hole,[3] who found a conversion coefficient $\epsilon > 19$. A search was made for L conversion electrons from the 215-kev transition with the help of an anthracene crystal. An upper limit of 10 percent of the intensity of the K electrons of the 160-kev transition was established. (The K conversion electrons would approximately coincide with L conversion electrons from the 160-kev transition.) No cross-over transition of (160+215) kev=375 kev was detected. If present, it takes place in <1 percent of the transitions. With the help of the K conversion coefficients calculated by Rose *et al.*[6] (see Table I) and the empirical lifetime energy relations and K/L ratios given by Goldhaber and Sunyar[7] the results given above allow us to conclude that the 160-kev transition is an $M3$ transition and that the 215-kev transition corresponds to a spin change $\Delta I \leq 2$, with an $M2$ transition excluded.

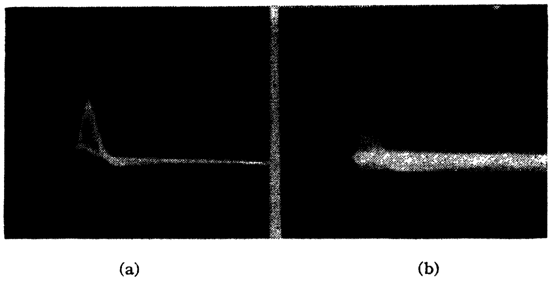
(a) (b)

FIG. 1. (a) Te^{123m} γ-rays (159 kev) for calibration; (b) Hf^{179m} γ-rays (215 kev) and Hf K x-rays which coincide with conversion electrons preceding them.

TABLE I. K conversion coefficients.[a]

E(kev)	α_1	α_2	α_3	β_1	β_2	β_3
160	0.088	0.31	0.93	1.05	5.4	20.0
215	0.043	0.14	0.43	0.47	2.1	7.0

[a] See reference 6.

A final level assignment must await a measurement of the ground-state spin of Hf^{179} (known to be $\leq\frac{3}{2}$)[8] and the determination of the character of the 215-kev transition. The following tentative decay scheme is compatible with existing knowledge and shell theory, but is not unique:

$$h_{9/2} \xrightarrow{\text{160 kev}} p_{3/2} \xrightarrow{\text{215 kev}} p_{1/2}.$$

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* Research carried out under contract with the AEC.

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On the Decay of Neutral *V*-Particles*

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(Received July 5, 1951)

SEVERAL new examples of the decay of neutral V-particles[1-4] have been obtained recently at Pasadena, using two new magnet cloud chambers arranged to respond to cosmic-ray penetrating showers. Nine of these are of special interest in that it is possible to draw some conclusions as to the identity of the charged secondaries in each case. The momentum and estimated specific ionization (relative to the minimum for fast, singly charged particles) and the mass-value computed from these quantities are tabulated for each charged decay-particle in Table I.

It is apparent from this table that all of the negative particles are mesons; one of these underwent a sudden deflection in flight, the angular deviation of 6° being within the allowable range for a $\pi-\mu$-decay, so that the negative particles are indeed probably π-mesons.

On the other hand, it is also apparent that most of the positive particles are surely much heavier than mesons, and while the

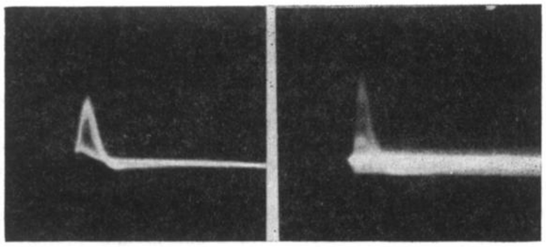
(a) (b)

FIG. 1. (a) Te^{123m} γ-rays (159 kev) for calibration; (b) Hf^{179m} γ-rays (215 kev) and Hf K x-rays which coincide with conversion electrons preceding them.