LIFETIME OF THE 4^+ (2310 keV) LEVEL IN Ti^{48}

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The lifetime of the 4^+(2310 keV) level of Ti^{48} has been determined by investigating the dependence of the resonance scattering cross section on the source density. The lifetime derived is $(2^{+0.9}_{-0.7}) \times 10^{-12}$ sec, which is about 2.5 times greater than the lifetime expected on the basis of the vibrational model. The results are discussed in light of conclusions drawn on the basis of a model in which pair correlation of nucleons is taken into account.

INTRODUCTION

KNOWLEDGE of the lifetime of the second and higher excited states of nuclei is of great importance for an estimate of the correctness of different nuclear models. One of the methods which permits determination of these times (reduced transition probabilities) is the cascade Coulomb excitation method. In spite of the considerable experimental difficulties, this method was used to determine the ratio of reduced probabilities $b_4 = B(E2, 4 \rightarrow 2)/B(E2, 2 \rightarrow 0)$ of many spherical even-even nuclei [1-3].

It was shown earlier [4,5] that the second-level lifetime τ_2 can be determined by comparing the experimentally obtained dependence of the cross section of the resonant scattering of γ quanta on the density of the gaseous source, with the theoretical value for different values of τ_2. The region of applicability of this method is discussed in detail in [6].

In the present paper we determined by this method the lifetime of the level 4^+(2310 keV) of Ti^{48}. The choice of Ti^{48} as the object of investigation is due to the fact that the resonant scattering of γ quanta with energy 990 keV by Ti^{48} nuclei can be readily observed by using the γ-line Doppler broadening resulting from the preceding decays (β^+ and K capture with energies $(E^{kin}_{\beta^+})_{max} = 690$ keV, $E_k = 1710$ keV and γ transition with energy $E_\gamma = 1320$ keV) in a gaseous $V^{48}Cl_4$ source.[7] The high velocity of the recoil nuclei and the possibility of obtaining the necessary density of the gaseous source at low temperatures makes it possible, in addition, to observe distinctly the influence of the collisions on the magnitude of the resonance effect.

PREPARATION OF SOURCE

Radioactive V^{48} was obtained from the reactions $Ti^{48}(d, 2n)V^{48}$ and $Ti^{47}(d, n)V^{48}$ by bombarding a target of natural titanium with 13-MeV deuterons in the internal beam of the cyclotron of the Ural Polytechnic Institute.

The average current of accelerated deuterons was 300 μA, and the bombardment time was 10 hours. After storage for ~ 12 hours, the active surface layer of the target was dissolved in hot concentrated hydrochloric acid; the solution was evaporated and the precipitate roasted. The oxides of V, T, and Sc produced as a result of the roasting were mixed with finely ground carbon and the mixture was placed in an oven joined hermetically with an apparatus used to obtain thoroughly dehydrated chlorine.

To remove the air prior to the start of chlorination, a stream of helium was passed through the entire system. The chlorination of the mixture was at a temperature ~ 400°, thus preventing the radioactive isotope Sc^{46} from being carried away from the oven in the form $ScCl_3$. The mixture of $V^{48}Cl_4 + TiCl_4$ vapor was doubly distilled and condensed in a dry-ice cooled pyrex ampoule approximately 16 milliliters in volume. The pumped and sealed ampoule contained 0.786 grams of $VCl_4 + TiCl_4$. Precise measurements of the spectrum[1)] and of the half life have shown that the source we obtained contained in practice only V^{48}.

DESCRIPTION OF THE EXPERIMENT

The ampoule with the source was contained in a thin-wall steel container, which was placed in a furnace with a highly homogeneous temperature field. A series of measurements of the resonance effect was made with the above-described source at different source temperatures. The measurements were made with a semi-automatic two-channel installation described in [8], using flat

[1)]We are grateful to V. R. Burmistrov and his co-workers for careful measurements of the V^{48} spectrum.

titanium and iron scatterers 30 × 30 cm in size. One channel of the installation is shown schematically in Fig. 1. The thickness of the titanium scatterer is 1.2 cm, while that of the iron scatterer was chosen such as to make the background of the scattered radiation with the source at room temperature the same for both scatterers. The detectors were 40 × 40 mm NaI(Tl) crystals and an FÉU-11 photomultiplier. Both analyzers were tuned to 990 keV with a 10 V window. The number of pair measurements with scatterers of Ti and Fe depended on the density of the gaseous source and was such as to ensure an accuracy of 7—12% in the measurement of the resonance effect.

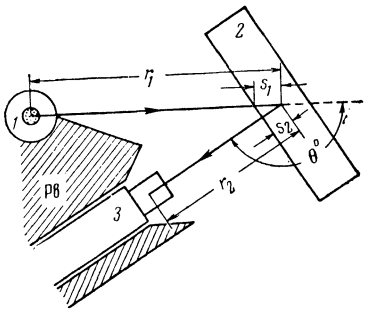

FIG. 1. Experimental set-up (for one channel): 1 – furnace, 2 – scatterer, 3 – detector.

It is known that a $VCl_4 + TiCl_4$ mixture has a low boiling temperature (~ 140°) and consequently the density of the vapor filling the ampoule varies appreciably in a small temperature interval (in our case ρ_{max}/ρ = 3.3 for t = 155—205°). It is clear that in this case it becomes necessary to maintain the source temperature constant and with high accuracy. To this end, the furnace was fed from a stabilized voltage source, thus keeping the temperature constant to ~1%. The dependence of the density of the gaseous source on the temperature was determined experimentally by measuring the counting rate of a γ beam confined by a narrow collimator from the upper part of the ampoule. This dependence is shown in Fig. 2, which shows also the results of the measurements of the resonance effect[2)] N_p (the difference of readings with scatterers of titanium and iron, averaged over both channels), with allowance for the decay of the source during the course of the measurements. Extrapolation of the curve drawn through these points to the region of lower temperatures shows that the dependence of the resonance effect and of the vapor density on the temperature becomes the same at approximately 110°. Consequently the resonance scattering cross section can be regarded

[2)]Owing to the small specific activity of the source employed, we were unable to carry out measurements at temperatures <155°.

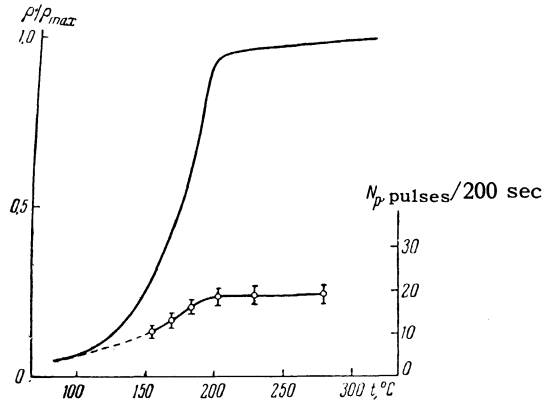

FIG. 2. Density dependence of gaseous source (ρ_{max} = 49 mg/cm³) and experimental value of the resonance effect (points).

free of the influence of collisions of the recoil nuclei with the source molecules only for these temperatures. The use of the measurements of the resonance effect at temperatures greater than 110° to determine the lifetime of the 2^+(990 keV) level, without a correct account of the collisions, as was done in [6], is not strictly justified. Therefore, to determine the lifetime of this level we have carried out an experiment with self-absorption of the resonance radiation [9] and obtained τ_1 = (7.1 ± 2.2) × 10^{-12} sec.

The resonance scattering cross section $\bar{\sigma}$ was obtained from the formula

$$N_p = n\bar{\sigma}\varkappa\varepsilon N_0 D^2 \int_V \frac{f(\vartheta)\,k(s_1)\,e^{-\mu(s_1+s_2)}\,\psi(\vartheta)}{4\pi r_1^2 r_2^2}\,dV, \qquad (1)$$

where n—number of Ti^{48} atoms in 1 cm³, κ—fraction of the entire activity in the gaseous phase, N_0—number of γ quanta registered by the detector in the direct beam at a distance D from the source during the same time as N_p, and ϵ—efficiency of registration of the γ quanta with energy 990 keV. The integral in (1) was evaluated numerically. It takes into account (see [10]) the geometry of the scatterer, the angular distribution $f(\vartheta)$ of the resonantly scattered quanta, self-absorption $k(s_1)$ in the scatterer, and the dependence of the registration efficiency $\psi(\vartheta)$ on the angle of incidence of the γ quanta on the crystal; μ is the total linear absorption coefficient of the γ quanta; the values of r_1, r_2, s_1, s_2, and ϑ are shown in Fig. 1. The resonant scattering cross section calculated by formula (1) for different source densities is shown below:

ρ, mg/cm³	15,2	21,07	30,9	45,6	49
$\bar{\sigma}$, mb	15.0±1.5	12.5±1.2	11±1	8.5±0.7	7.7±0.6

The theoretical dependence of the cross section on the density for different lifetimes τ_2 of the sec-

ond level of Ti^{48} was determined from the formula

$$\sigma_r = 1.82 \cdot 10^3 P\,(E_p,\ i,\ \tau_1\tau_2 d), \qquad (2)$$

where $P(E_p, \rho, \tau_1\tau_2 d)$ is the fraction of the γ quanta whose energy lies in the interval one eV about the resonant E_p, and τ_1 is the lifetime of the first level and d is the collision diameter.

The function $P(E_p, \rho, \tau_1, \tau_2 d)$ was calculated on the basis of the elastic collision model by the method described in [6], it being assumed that the collisions occur between the free atom of Ti^{48}* (there is no influence of the chemical bond) and one of the atoms of the $TiCl_4$ molecule. Indeed, the values of $P(E_p)$ obtained from a calculation of the microspectra with and without allowance for the chemical bond (the binding energy of the atom V in the molecule VCl_4 is approximately 5 eV) coincide and are equal to $P(E_p) = 1.2 \times 10^{-2}$ eV^{-1}. It is known further that at greater velocities of the atom incident on a polyatomic molecule, the effective interaction occurs only with one of the atoms in the latter [11]. We have also carried out calculations for the case when a Ti^{48}* atom collides with a $TiCl_4$ molecule. However, to reconcile the calculation with the experiment in this case it would be necessary to assume a perfectly unrealistic collision diameter ~ 9 Å.

Figure 3 shows part of the calculated curves for different values of the lifetime of the 4^+ level together with the experimental points. As can be seen from the figure, the curves for $\tau_2 = \tau_1 = 7.1 \times 10^{-12}$ sec and $\tau_2 = \tau_1/2 = 3.55 \times 10^{-12}$ sec are located above the curve for $\tau_2 = \tau_1/3 = 2.36 \times 10^{-12}$ sec, while the curves $\tau_2 = \tau_1/4 = 1.78$ and $\tau_2 = 0$ cross it. Such an arrangement

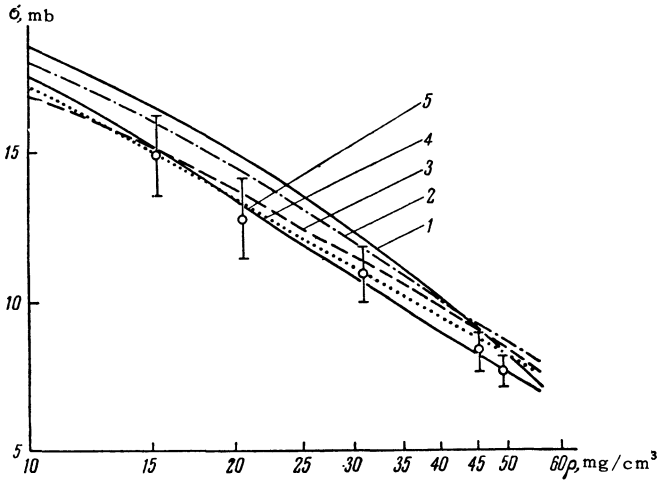

FIG. 3. Calculated resonant scattering cross section vs. density: $1 - \tau_2 = 7.1 \times 10^{-12}$ sec, $2 - \tau_2 = 3.55 \times 10^{-12}$ sec, $3 - \tau_2 = 2.37 \times 10^{-12}$ sec, $4 - \tau_2 = 1.78 \times 10^{-12}$ sec, $5 - \tau_2 = 0$. Points – experimental data.

of the curves is due to the peculiarities in the variation of the velocity distribution function during the deceleration process. Such a peculiarity is observed, as shown by Metzger [12], when the velocity of the recoil nucleus exceeds the velocity necessary to restore the resonant conditions by a factor 2–3 times. In our case $v_{max}/v_p \approx 3$.

For a more accurate determination of the curve with which the experiment is reconciled we have compared the slopes of the curves and of the line drawn through the experimental points by the "least squares" method. The curves which fall into the region of the experimental errors were selected additionally by the χ^2 method. As a result of such a comparison we find that the best agreement between experiment and calculation is observed when $\tau_2 = 2 \times 10^{-12}$ sec. The corresponding value of the collision diameter d is found to be 3.2×10^{-8} cm.

Taking into account the measurement error, and also the error in the determination of τ_1, we obtained for the lifetime of the 4^+ level (2,310 keV) of Ti^{48} a value $\tau_2 = (2^{+0.9}_{-0.7}) \times 10^{-12}$ sec.

DISCUSSION OF RESULTS

Actually there are two models which give numerical values for the ratio of the reduced probabilities $b_4 = B(E2, 4 \to 2)/B(E2, 2 \to 0)$: for the Goldhaber-Weneser pure vibrational model [13] $b_4 = 2$, while for the Davydov model [14], $b_4 = 1.37$ ($\gamma = 25°$). We note that these models start from a description of the higher excited states as collective.

Recently new notions have been successfully developed concerning the properties of excited nuclei on the basis of the pair-correlation model [15,16]. According to these notions, the pair correlations of the nucleons play an essential role particularly in nuclei with almost filled shells. With the aid of a sensible choice of the main constants of the model, it was possible to obtain for the first time the correct dependence of $B(E2, 0 \to 2^+)$ on the degree of filling of the shell [17]. A qualitative agreement is obtained, as can be seen from Fig. 4, also for the energy dependence of $B(E2, 0 \to 2^+)$ for Ti isotopes.

Guman, Sliv, and Sogomonova [19] succeeded in obtaining on the basis of this model for the Pb^{206} nucleus the scheme of levels, their quantum characteristics and the reduced probabilities, all in agreement with experiment. For the ratio b_4, the pair correlation model gives a value which is appreciably smaller than 2. Thus, Raz always obtains $b_4 < 1$. [2]

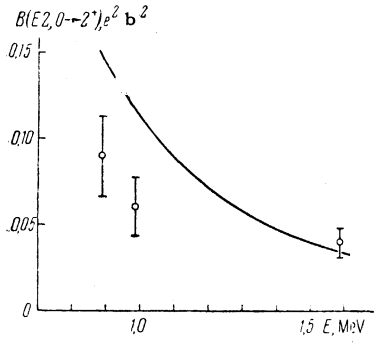

FIG. 4. Energy dependence of B(E2, $0 \to 2^+$) for the isotopes of Ti (Ti^{46} [8], Ti^{48} [9], Ti^{50} [22]). Solid curve – calculation by the pair-correlation model,[17] points – experimental data.

For the configuration $(f^{7/2})^4$, Drozdov[21] gives $b_4 = 1.1$. The value $b_4 = (0.83\ ^{+0.29}_{-0.37})$ which we obtained for Ti^{48}, which has two protons on top of the filled shell and two holes in the neutron shell, agrees with the predictions of the pair correlation model, but disagrees with the value $b_4 = 2$ for the purely vibrational model.

Yet the majority of the results obtained with the aid of double Coulomb excitation[1,2] appears to agree with precisely this model. The latest measurements[18], however, carried out with Pd isotopes, give for b_4 values which are approximately 1.5 times as small as those obtained in[1]. On the other hand, for the Te isotopes (Z = 50 + 2), assuming that the observed cascades go from the 4^+ state, Gangrskiĭ and Lemberg[3] have obtained an average value $b_4 = 1.0$.

In addition, in experiments with double Coulomb excitation of the 4^+ level, the possibility is not excluded of simultaneously exciting the 0^+ level, which is located in close proximity to 4^+, as for example for Cd^{112} and Cd^{114}. This circumstance should also decrease the value of $b_4 = 1.61$ obtained for these nuclei. Further experiments and detailed calculations by the pair correlation model for specific nuclei make it possible to estimate its correctness more accurately.

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