Measurement of the lifetimes of excited nuclear states by the Doppler-shift attenuation method using the reaction $(n,n'\gamma)$ with two targets[1)]

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An experimental technique for measuring the lifetimes of excited nuclear levels using the Doppler-shift attenuation method is reviewed. The original feature of this technique is the simultaneous use of two targets for the inelastic scattering of fast neutrons [the reaction $(n,n'\gamma)$] responsible for the excitation of the measured levels. An empirical solution is proposed for the problem of finding the effective energy of the incident neutron. An expression for the exact calculation of the attenuation factor for an inhomogeneous medium is obtained using the LSS theory describing the stopping of ions in a given medium and the Blaugrund formalism. The advantages of using this two-target technique are described in detail. The measured lifetimes of excited states of 20 light nuclei are given. The probabilities of γ transitions for which the multipole mixing ratios are known are calculated using the experimental lifetimes.

INTRODUCTION

The construction of a unified theory of nuclear structure and nuclear dynamics is the fundamental goal of contemporary nuclear physics. The existence of such a theory would make it possible to obtain, at each instant of time, accurate information on the structure of a particular nucleus of interest and on the processes occurring in it. Moreover, such a theory would allow us to follow the dynamics of nuclear processes and not only describe the instantaneous nuclear structure, but also predict future structural variations and attendant phenomena, such as nuclear emission. In other words, the nuclear structure, nuclear forces, and internucleon interactions would be known at each instant of the past, present, and future. Unfortunately, the construction of a universal, unified nuclear theory of this type is impossible from the viewpoint of present-day physics, mathematics, and computational techniques, since it would require the exact solution of the many-body problem for the nucleus. Therefore, current research in nuclear physics focuses on the search for model approximations which, on the one hand, can be solved by currently available physicomathematical methods and, on the other hand, describe the nucleus as realistically as possible, i.e., with the minimum error.

Of course, any model must be consistent with the fundamental physical laws and principles. In constructing a model, the question arises of how accurate the model is in its region of applicability. This question is answered by the experimental values of the parameters, which are eigenvalues of the operators in the model. Agreement between the experimental and calculated values of the parameters is the first and most important criterion for the accuracy of a model.

An important role in the development of models of nuclear structure is played by nuclear spectroscopy, which provides the experimental determination of a number of important structural parameters—the nuclear energy of excited levels, their spin and parity, lifetime, radiative width, electromagnetic multipole moments, radiative transition probabilities, deformation parameters, and so on.

The transition probabilities carry the largest amount of information on these parameters. This is the case because the transition probability depends on a large number of nuclear-structure parameters: it involves the spins of the levels between which the transition occurs, the parities, the multipole order of the transitions and their mixing ratios, the branching coefficients, the transition energy, and the mean lifetime of the level from which the transition starts. However, this implies that the measurement of the mean lifetime allows the transition probability for a given nucleus to be determined, while, in turn, this probability can be used to obtain all the further information on the structural parameters. By comparing these results with the calculated values for a particular model, we can judge the accuracy of that model, i.e., the structure of the nucleus as a whole. Experiments to measure the average lifetimes of excited nuclear levels over the entire time scale are therefore of primary importance.

Many methods have been developed for measuring the average lifetime as a function of the time range, but a review of these lies outside the scope of this study. Here we describe a variant of the Doppler-shift attenuation (DSA) method, used in the $(n,n'\gamma)$ reaction of inelastic scattering of fast reactor neutrons on two targets simultaneously.

An experiment was carried out with the research accelerator of the Institute for Nuclear Research and Nuclear Power of the Bulgarian Academy of Sciences. This review has two aims: firstly, to demonstrate the method for obtaining physical results on the nuclear-structure parameters by means of specific examples and, secondly, to generalize and draw attention to the experience gained in this field by the Bulgarian group over the course of six years of investigation.

1. THE DSA METHOD FOR MEASURING THE LIFETIMES OF EXCITED NUCLEAR LEVELS

The physical principle of the method

The first attempts to measure a lifetime using the Doppler shift of the γ energy were made 40 years ago by Elliott and Bell.[1,2] In spite of the lack of success of these attempts, the idea persisted and subsequent experiments[3-5] demonstrated its viability.

In the DSA method the lifetime of the measured excited state is compared with the stopping time a of the recoil nucleus in a moderating medium. The physical idea on which the DSA method is based is contained in the Doppler-shift equation

$$h\nu' = h\nu\,[1 + (v/c)\cos\theta] \qquad (1)$$

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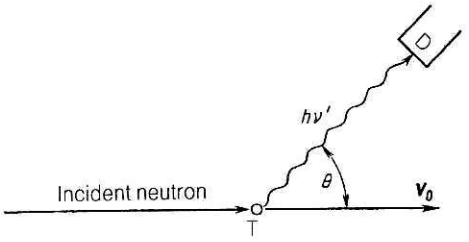

FIG. 1. Definition of the angle θ in expression (2): T–target; v_0–recoil direction; D–γ-ray detector.

where ν is the emission frequency of a source at rest, ν' is the emission frequency of a source moving with speed v, and θ is the angle between the direction of motion of the source and the vector to the detector of the radiation ν'.

For a nucleus this process occurs as follows. An excited nucleus at rest emits a photon of energy E_γ. If the same photon is emitted by a nucleus moving with speed v, the energy of the emitted γ is given by

$$E_\gamma = E_\gamma^0 [1 + (v/c) \cos \theta], \tag{2}$$

where θ is the angle between the direction of motion of the recoil nucleus ${}^A_Z X$ and the vector pointing to the γ detector (Fig. 1).

In expression (2), v is the speed of the recoil nucleus at the instant of emission of the photon of energy E_γ. It we take into account the fact that the nucleus moves in the medium of ions surrounding it, i.e., that the velocity decreases with time, we can write

$$v(t) = F(t)\, v_0, \tag{3}$$

where $F(t)$ is the velocity attenuation factor and v_0 is the speed of the recoil nucleus at the instant of excitation of the nucleus, $t = 0$. These speeds are usually expressed as fractions of the speed of light ($v = \beta c$), so that the expression (2) takes the final form

$$E_\gamma = E_\gamma^0 [1 + F(t) \beta_0 \cos \theta]. \tag{4}$$

If E_γ^1 and E_γ^2 are the γ-transition energies measured at two angles θ_1 and θ_2, then after subtracting the two expressions we obtain

$$F(t = \langle t_n \rangle) = \frac{\Delta E}{E_\gamma^0 \beta_0 (\cos \theta_1 - \cos \theta_2)}, \tag{5}$$

where $\langle t_n \rangle$ is the average time of emission of $E_\gamma^{1,2}$, i.e., the average lifetime of the level emitting the energy $E_\gamma^{1,2}$.

In an experiment, one measures the difference $\Delta E = E_\gamma^1 - E_\gamma^2$, thereby determining the value of $F(t = \langle t_n \rangle)$ and, from (3), the value of the speed $v(t = \langle t_n \rangle)$ at the emission time. However, the velocity attenuation law is known *a priori* (see below), so in this manner we obtain the time for the speed to change from v_0 (the time of excitation of the level) to $v(t = \langle t_n \rangle)$ (the emission time), and this is the mean lifetime of the excited level, $\tau = \langle t_n \rangle$.

The stopping time a of the recoil nucleus is about 5×10^{-13}–10^{-10}, depending on the density of the moderator (gas, liquid, or solid). This determines the time range of the applicability of the DSA method to the lifetime of excited levels: about 10^{-14}–10^{-8} sec, with the DSA method as yet being the only one possible in the range 10^{-14}–10^{-12} sec.

The following important advantage of the DSA method should be noted: it is independent of the properties of the measured excited state (energy, spin, parity) and the energy and multipole order of the transitions from this level.

Elements of the theory of the DSA method

The theory of the DSA method has by now been worked out in great detail. The first theoretical studies appeared in the 1960s and reflected two basic approaches to the problem. The first, the analytic approach, is based on the work of Blaugrund and Winterborn,[6–8] and the second uses the Monte Carlo method.[9,10] It can be stated with certainty that the analytic method of Blaugrund has become the most popular. Exhaustive reviews of the theory of the DSA method can be found in Refs. 1–13.

The Blaugrund theory gives an algorithm for the practical calculation of the attenuation factor $F(t)$ as a function of the level lifetime. The resulting $F^{\text{th}}(t)$ is then compared with F^{exp} from expression (5), and the lifetime τ of the level is taken to be the value of t for which $F^{\text{th}}(t) = F^{\text{exp}}$. Therefore, the main problem is to calculate $F^{\text{th}}(t)$. It should be noted that various equations are obtained for the attenuation factor, depending on the chemical composition of the moderating medium. Henceforth we shall use the term "homogeneous" to refer to a medium consisting of atoms of a single type. An "inhomogeneous" medium will be one consisting of several different types of atoms.

The most convenient expressions for the practical tabulation of $F^{\text{th}}(t)$ are given in Ref. 14 for homogeneous moderating media and in Refs. 15 and 16 for inhomogeneous media. We shall adhere to these studies in our treatment.

Calculation of F(t) for a homogeneous moderating medium

The general form of the attenuation factor $F(t)$ is given by the expression (using $\langle t \rangle = \tau$)

$$F(\tau) = (\tau \beta_0)^{-1} \int_0^\infty \beta(t)\, e^{-t/\tau} \langle \cos \Phi \rangle\, dt, \tag{6}$$

where Φ is the scattering angle of the recoil nucleus relative to the beam direction.

Expression (6) is useless for practical applications, since the velocity attenuation law $\beta(t)$ in a given medium is unknown. It can be found using the Lindhard–Scharff–Schiott (LSS) theory.[17] The velocity law $\beta(t)$ is determined by the energy losses of the recoil nucleus (atom) due to the Coulomb interaction with the ions of the moderator. The energy loss per unit of path length traversed, dE/dR, is the sum of electron (e) and nuclear (n) pieces, i.e.,

$$\frac{dE}{dR} = \left[\frac{dE}{dR}\right]_e + \left[\frac{dE}{dR}\right]_n, \tag{7}$$

where R is the mean free path of the recoil atom in the moderator.

The quantities E and R are associated with the dimensionless quantities ε and ρ via the relations

$$\varepsilon = E/\varepsilon_0, \quad \rho = R/\rho_0, \tag{8}$$

where

$$\varepsilon_0 = \frac{Z_1 Z_2 e^2 (M_1+M_2)}{aM_2};$$
$$\rho_0 = \frac{(M_1+M_2)^2}{4\pi a^2 n M_1 M_2}. \quad (9)$$

Here and below the index 1 refers to the moving atom and the index 2 refers to an atom of the moderator. In the expressions (9), Z is the charge, M is the atomic mass, n is the number of scattered atoms in 1 cm^3, $a = 0.88553 a_0/[Z_1^{2/3} + Z_2^{2/3}]^{1/2}$, and a_0 is the radius of the first Bohr orbit.

In this notation expression (7) becomes

$$\frac{d\varepsilon}{d\rho} = \left[\frac{d\varepsilon}{d\rho}\right]_e + \left[\frac{d\varepsilon}{d\rho}\right]_n. \quad (10)$$

The LSS theory based on the Thomas–Fermi potential gives

$$\left[\frac{d\varepsilon}{d\rho}\right]_e = k\varepsilon^{1/2} \quad (11)$$

and

$$\left[\frac{d\varepsilon}{d\rho}\right]_n = \begin{cases} 0{,}67\varepsilon^{1/4} & \text{for } \varepsilon^{1/2} < 0{,}3; \\ 0{,}45\varepsilon^{1/2}(0{,}29+\varepsilon)^{-1} & \text{for } \varepsilon^{1/2} \geqslant 0{,}3. \end{cases} \quad (12)$$

In expression (11),

$$k = Z_1^{1/6} \frac{0{,}0793 Z_1^{1/2} Z_2^{1/2} [A_1+A_2]^{3/2}}{[Z_1^{2/3}+Z_2^{2/3}]^{3/4} A_1^{3/2} A_2^{1/2}}. \quad (13)$$

For the case of a homogeneous medium under consideration here, $Z_1 = Z_2 = Z$ and $M_1 = M_2 = M$.

We transform to the new integration variable ε using the relation

$$t = t_0 \int_{\varepsilon_0}^{0} (d\rho/d\varepsilon)\, \varepsilon^{-1/2}\, d\varepsilon, \quad (14)$$

where $t_0 = \rho_0 (M/2\varepsilon_0)^{1/2} = 3.75 \times 10^{-15} A^{3/2}/(Z^{1/2} d)$, d is the moderator density, $k = 0.133 Z^{2/3} A^{-1/2}$ for a homogeneous medium, and A is the atomic mass.

Substituting (11), (12), and (14) into (6), we find a convenient equation for computing the attenuation factor $F(\tau)$:

$$F(\tau) = \frac{1{,}62 \cdot 10^{-18} A Z^{2/3}}{\tau \beta_0 d} \int_{\varepsilon_0}^{0} \frac{0{,}29+\varepsilon}{\varepsilon^{1/2}+(k\varepsilon+B)} \langle \cos\Phi \rangle\, e^{-u}\, d\varepsilon, \quad (15)$$

where $B = 0.29k + 0.45$ and

$$u = 3{,}725 \cdot 10^{-15} \frac{A^{3/2}}{\tau d \sqrt{Z}} \left[\frac{0{,}29}{B} \ln \frac{\varepsilon_0 (k\varepsilon+B)}{\varepsilon (k\varepsilon_0+B)} + \frac{1}{k} \ln \frac{k\varepsilon_0+B}{k\varepsilon+B}\right],$$

$$\langle \cos\Phi \rangle = [\varepsilon/\varepsilon_0]^{1/2} \left[\frac{\frac{0{,}483}{k}(1+0{,}67k)+\varepsilon_0}{\frac{0{,}483}{k}(1+0{,}67k)+\varepsilon}\right]^{1/2}.$$

$$G(r) = \begin{cases} 1 + \frac{2}{3} r - \frac{7}{15} r^2 + 8 \sum_{n=3}^{\infty} \frac{(-r)^n}{(2n+1)(2n-1)(2n-3)}, & r < 1; \\ \frac{2}{3} + \frac{8}{15} \frac{1}{r} - 8 \sum_{n=3}^{\infty} \frac{(-1/r)^{n-1}}{(2n+1)(2n-1)(2n-3)}, & r > 1, \end{cases}$$

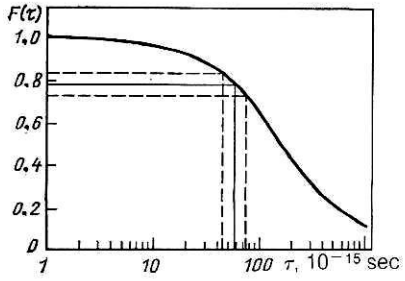

FIG. 2. Typical behavior of the curve and method of finding τ from the measured $F^{\exp}$.

The integral (15) is solved numerically. We use Simpson's method in the time interval 10^{-15}–10^{-11} sec, dividing it into 400 subintervals. The typical behavior of the curve $F(\tau)$ is shown in Fig. 2. In the same figure we show the algorithm for determining the lifetime τ from the factor $F^{\exp}$ using expression (5).

Calculation of F(τ) for an inhomogeneous moderator

For computing the attenuation factor $F(\tau)$ in an inhomogeneous moderator, in addition to ε and ρ we introduce the three characteristic dimensionless variables v, M, and θ, corresponding to the velocity of the recoil atom, the reduced mass of the colliding atoms, and the time:

$$v = hc\beta/e^2, \quad (16)$$

where e is the electron charge, c is the speed of light, and

$$M = \frac{2\varepsilon}{v^2} - \frac{1{,}63 \cdot 10^3 A_1 A_2}{Z_1 Z_2 [Z_1^{2/3}+Z_2^{2/3}]^{1/2} (A_1+A_2)}, \quad (17)$$
$$\theta = t/T; \quad (18)$$
$$T = \frac{h}{e^2} \frac{(A_1+A_2)^2}{4\pi a^2 n A_1 A_2}. \quad (19)$$

In this notation the energy and velocity of the recoil ion are given by an implicit function of time in the form[6]

$$\theta = \left(\frac{1}{2} M\right)^{1/2} \int_{\varepsilon}^{\varepsilon_0} \frac{d\varepsilon}{\varepsilon^{1/2} (d\varepsilon/d\rho)}, \quad (20)$$

where ε_0 is the ion energy for $\theta = 0$.

Let the moderator consist of various types of atoms. As before, the index 1 refers to the moving ion, the index 2 refers to the heaviest ion, and the index $2i$ refers to the ith type of light atom in the order of increasing i. Then expression (20) becomes

$$\theta = \left(\frac{1}{2} M\right)^{1/2} \int_{\varepsilon}^{\varepsilon_0} \frac{d\varepsilon}{\varepsilon^{1/2} \left[d\varepsilon/d\rho + \sum_i C_i (d\varepsilon/d\rho)_i\right]}, \quad (21)$$

where θ and ε refer to the heaviest atom of the moderator, $(d\varepsilon/d\rho)_i$ is the total loss for the energy $(M_i/M)\varepsilon$, and

$$C_i = \frac{n_i}{n} \frac{Z_{2i}}{Z_2} \frac{a_i}{a} \frac{A_1+A_2}{A_1+A_{2i}}.$$

Setting $\tau = A_1/A_2$ and introducing the function

the final expression for $\langle\cos\Phi\rangle$ takes the form

$$\langle\cos\Phi\rangle=\left[\frac{1+d_n/(d_e\varepsilon)}{1+d_n/(d_e\varepsilon_0)}\right]^{-\frac{G}{2r}\frac{d_n'}{d_n}}, \tag{22}$$

where

$$d_e=k+\sum_i C_i k_i (M_i/M)^{1/2};$$
$$d_n=0{,}4\,[1+\sum_j C_i k_i (M/M_i)^{1/2}];$$
$$d_n'=0{,}4\left[1+\sum_i C_i \frac{A_{2i}}{A_2}\frac{G_i}{G}(M/M_i)^{1/2}\right].$$

Expression (22) is valid in the approximation

$$(d\varepsilon/d\rho)=k\varepsilon^{1/2}+0{,}4\,\varepsilon^{-1/2}$$

and for $1.2<\varepsilon<20$.

In this notation the attenuation factor becomes

$$F(\tau)=\frac{e^2}{\hbar c}\frac{T}{\tau}\int_0^\infty e^{-\theta T/\tau\nu}\langle\cos\Phi\rangle\,d\theta, \tag{23}$$

where $\langle\cos\Phi\rangle$ is given by (22).

In practice, one usually deals with a lifetime τ satisfying the condition $\tau/a\leqslant 0.5$, where a is the time for the recoil-ion speed to decrease by a factor of e.

In the case $\tau/a<0.3$–0.5, after some simplifying assumptions[6] expression (23) takes the form

$$E(\tau)=\frac{1}{1+\tau/a}-\frac{d_n}{d_e\varepsilon_0}\left[1+\frac{A_2}{A_1}G\frac{d_n'}{d_n}\right]\frac{\tau/a}{1-(\tau/a)^{1/2}}. \tag{24}$$

For $\tau/a\ll 1$ a similar procedure leads to (23), rewritten as

$$F(\tau)=1-\frac{\tau}{a}-\frac{d_n}{d_e\varepsilon_0}\left[1+\frac{A_2}{A_1}G\frac{d_n'}{d_n}\right]\frac{\tau}{a}. \tag{25}$$

Expressions (24) and (25) are valid only for $\tau/a\leqslant 0.5$. When this requirement is violated ($\tau>a/2$), $F(\tau)$ takes unphysical (negative) values. However, it should be noted that in their region of applicability, expressions (24) and (25) can be computed numerically quite easily and accurately.

In order to circumvent the restrictive requirement $\tau/a<0.5$, in an earlier study[16] we proposed a more general expression for $F(\tau)$ for an inhomogeneous medium. Using the same notation as above, this expression is

$$F(\tau)=\frac{T}{\tau}\left(\frac{M}{2}\right)^{1/2}\int_{\varepsilon_0}^0\left[\frac{d_e\varepsilon+d_n}{d_e\varepsilon_0+d_n}\right]^{\lambda}\times\left[\frac{d_e\varepsilon_0\varepsilon+d_n\varepsilon}{d_e\varepsilon_0\varepsilon+d_n\varepsilon_0}\right]^{\mu}\left(\frac{\varepsilon}{\varepsilon_0}\right)^{1/2}\frac{d\varepsilon}{d_e\varepsilon+d_n}, \tag{26}$$

where $\lambda=(T/\tau d_e)/(M/2)^{1/2}$ and $\mu=Gd_n/2rd_n$.

Expression (26) must be solved numerically by computer using, for example, Simpson's method. In this sense it is not as convenient for practical purposes as expressions (24) and (25); however, it is more accurate, it does not involve simplifying assumptions, and it is physically meaningful [$0<F(\tau)<1$] in the entire time interval. It is also superior from the viewpoint of the accuracy of the results.

Corrections to $F^{\text{th}}(\tau)$

When processing experimental data, one is sometimes forced to introduce corrections to $F^{\text{th}}(\tau)$ calculated from expression (15) or (26). The two most important corrections are the following: 1) the correction to the electron and nuclear terms of expression (7) for the energy losses of the recoil ion; 2) the correction to $F^{\text{th}}(\tau)$ due to the cascade population of the measured excited level.

Correction to the stopping terms. This correction takes into account certain discrepancies between the LSS theory[17] and the experiments for verifying it. An extensive review of this problem was given in Ref. 12. These investigations pertain to a region different from that of the experiment described here, so we shall not discuss them in detail. We present only the final results useful for for the practical determination of the lifetime by the DSA method.

To introduce these corrections, we rewrite expression (7) as

$$\frac{d\varepsilon}{d\rho}=f_e\left[\frac{d\varepsilon}{d\rho}\right]_e+f_n\left[\frac{d\varepsilon}{d\rho}\right]_n, \tag{27}$$

where f_e and f_n are correction factors taking into account the difference between the actual losses and those calculated using the LSS theory. It should be noted that f_e and f_n are introduced only empirically, on the basis of a large amount of experimental data which are inconsistent with the LSS theory.

At speeds above 0.02c electronic stopping dominates and the stopping process is described well by expression (7), i.e., $f_e=f_n=1$. For $\beta<0.005$ nuclear stopping becomes more important, and f_n differs from unity.

Using expression (27) instead of (7) and following the procedure described above for a homogeneous medium, we obtain the following expression for the attenuation factor[16]:

$$F(\tau)=\frac{1{,}62\cdot 10^{-18}AZ^{2/3}}{\tau\beta_0 d}\int_{\varepsilon_0}^0\frac{0{,}67h+\varepsilon}{kf_e\varepsilon+hf_nB_f}e^{-\frac{t(\varepsilon)}{\tau}}\langle\cos\Phi\rangle\frac{d\varepsilon}{\sqrt{\varepsilon}}, \tag{28}$$

where $B_f=1+0.67kf_e/f_n$, $h=0.483$, and

$$t(\varepsilon)=3{,}75\cdot 10^{-15}\frac{A^{3/2}}{Z^{1/2}d}\left[\frac{0{,}67}{f_nB_f}\ln\frac{\varepsilon_0}{\varepsilon}\frac{hf_nB_f/kf_e}{hf_nB_f/kf_e}+\frac{1}{kf_e}\ln\frac{\varepsilon_0+hf_nB_f/kf_e}{\varepsilon+hf_nB_f/kf_e}\right],$$
$$\langle\cos\Phi\rangle=(\varepsilon/\varepsilon_0)^{1/2}\left[\frac{\varepsilon_0+hf_nB_f/kf_e}{\varepsilon+hf_nB_f/kf_e}\right]^{1/2}.$$

In practical work with a given nucleus, the corresponding f_e and f_n are chosen empirically so as to best reproduce the known lifetimes for that nucleus. Usually $f_e=1$, so that in the reaction $(n,n'\gamma)$ one has $\beta<0.5\%$, and the electron interaction has practically no effect on the stopping process.

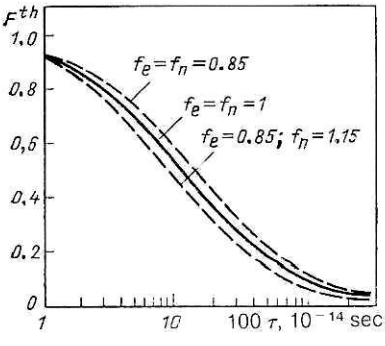

FIG. 3. Curves for F^{th}, corrected with $f_e\neq 1$ and $f_n\neq 1$.

TABLE I. F^{th} as a function of f_e and f_n.

τ, 10^{-15} sec	$f_e = 0.85$			$f_e = 1.00$			$f_e = 1.15$		
	f_n			f_n			f_n		
	0.85	1.00	1.15	0.85	1.00	1.15	0.85	1.00	1.15
1	0.997	0.997	0.996	0.997	0.996	0.996	0.996	0.996	0.996
3	0.990	0.988	0.987	0.989	0.988	0.986	0.988	0.987	0.986
7	0.975	0.973	0.970	0.974	0.971	0.968	0.972	0.970	0.967
10	0.965	0.961	0.957	0.963	0.959	0.955	0.961	0.957	0.953
30	0.896	0.884	0.872	0.890	0.878	0.866	0.884	0.872	0.861
70	0.769	0.744	0.721	0.757	0.733	0.711	0.746	0.723	0.700
100	0.687	0.657	0.630	0.673	0.644	0.618	0.660	0.632	0.606
300	0.382	0.352	0.327	0.369	0.341	0.317	0.356	0.330	0.307
700	0.198	0.179	0.164	0.190	0.172	0.158	0.182	0.166	0.152
1000	0.145	0.131	0.119	0.139	0.125	0.114	0.133	0.120	0.110

To find $f_n \neq 1$, it is simplest to calculate $F(\tau)$ using expression (28) with f_n equal to 0.85, 1, and 1.15, and to choose the value of f_n which best reproduces the known lifetimes for that nucleus, measured either by methods other than the DSA method or by the DSA method with heavy ions, where $\beta > 2\%$ and electronic stopping $(d\varepsilon/d\rho)_e$ dominates.

The curves $F^{th}(\tau)$ corrected with $f_e \neq 1$ and $f_n \neq 1$ are shown in Fig. 3. We see from this figure that there is a systematic difference between the corrected and uncorrected curves $F(\tau)$, with different magnitudes of this discrepancy in different time ranges.

In Table I we give the calculated values of $F^{th}(\tau)$ for the level 2.212 MeV in ^{27}Al using various combinations of the numerical values of f_e and f_n. We see from this table that if $F^{th}(\tau)$ is assumed to be a two-parameter function of f_e and f_n, i.e., $F(\tau, f_e, f_n)$, the dependence $F(\tau; f_e = 1, f_n)$ changes $F^{th}(\tau)$ more rapidly than the dependence $F(\tau; f_e, f_n = 1)$ (Fig. 4). This means that for small velocities β, as in the case of the reaction $(n,n'\gamma)$, nuclear stopping dominates, as expected.

We also see from this table that the corrections $f_e = 1$ and $f_n = 1$ do not affect $F^{th}(\tau)$ very strongly, so they weakly affect the results for the lifetime τ. This is shown in Table IX for the lifetimes of excited levels of ^{45}Sc, from which it follows that the difference between the uncorrected lifetime τ_k and the corrected τ_k is no greater than the experimental error. Nevertheless, the use of expression (28) instead of (15) is preferable from the viewpoint of future improvements in the experimental accuracy.

The correction arising from cascade population of the level. The case shown in Fig. 5 is frequently encountered in the decay schemes for the measured nuclei. The levels E^i_γ, $i = 2,3,4...$, are populated in the reaction $(n,n'\gamma)$, while the level E^1_γ is populated both in this reaction and by transitions from higher-lying levels E^i_γ. The practical effect of this is that when the level E^1_γ is populated not in the reaction, but by transitions from higher-lying levels E^i_γ, during the time for cascade population the recoil nucleus nearly or com-

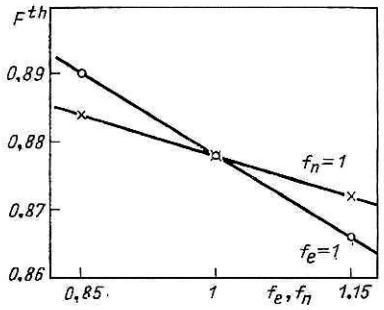

FIG. 4. $F^{th}(t)$ as a function of f_e (for fixed $f_n = 1$) and as a function of f_n (for fixed $f_e = 1$).

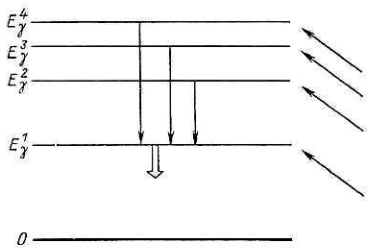

FIG. 5. Mechanism for cascade population of the level E^1_γ from higher-lying levels E^i_γ $(i = 2,3,4...)$.

pletely loses its velocity. Then a photon from the level E_γ^1 will be either weakly shifted or not shifted at all; however, in both cases it distorts the true Doppler effect by decreasing the actual Doppler shift. Therefore, a systematic error is introduced into the lifetime, tending to increase it.

To avoid this systematic error it is necessary to introduce corrections for cascade population. If $F_1(\tau_1)$ is the uncorrected attenuation factor for the level E_γ^1, the corrected factor is given by[18]

$$\overline{F(\tau_1)} = k_1 F_1(\tau_1) + \sum_{i\geqslant 2} \frac{\tau_i F_i(\tau) - \tau_1 F_1(\tau_1)}{\tau_i - \tau_1} \frac{k_i v_i(0)}{v_1(0)}, \quad (29)$$

where $v_i(t) = v_1(t)\langle \cos \Phi_i(t)\rangle$ and k_i is the population probability for the ith level at the time $t = 0$.

The following condition must be satisfied:

$$k_1 + \sum_{i\geqslant 2} k_i = 1.$$

It is usually assumed that $v_1(0) \approx v_i(0)$, which simplifies (29) to

$$\overline{F(\tau_1)} = k_1 F_1(\tau_1) + \sum_{i\geqslant 2} k_i \frac{\tau_i F_i(\tau) - \tau_1 F_1(\tau_1)}{\tau_i - \tau_1}. \quad (30)$$

In most cases $i = 2$, so we finally obtain

$$\overline{F(\tau_1)} = k_1 F_1(\tau_1) + (1 - k_1) \frac{\tau_2 F_2(\tau_2) - \tau_1 F_1(\tau_1)}{\tau_2 - \tau_1}. \quad (31)$$

The denominator of expressions (29)–(31) shows that this correction is important if $\tau_i \geqslant \tau_1$. Moreover, if there are no transitions from the levels E_γ^i to the level E_γ^1, this correction is not physically meaningful, as is clearly seen from the mechanism for this process.

In the reaction $(n,n'\gamma)$ the level population probability decreases rapidly with increasing excitation energy,[19] so it is usually not necessary to introduce corrections for cascade population. This is demonstrated for a specific example in Ref. 13, where for two levels of ^{59}Co the corrections to the calculated $F(\tau)$ are 3 and 6%, which is insignificant compared with the experimental error (14%).

2. INELASTIC SCATTERING OF FAST REACTOR NEUTRONS. THE REACTION $(n, n'\gamma)$

The object of study in the DSA method is a moving excited nucleus. The nucleus does not "remember" the excitation mechanism and the beginning of the motion, so that the deceleration and emission processes are identical for all nuclear reactions. In this sense, the reaction is the prehistory of the process in question, and has no direct relation to the results on the lifetime. It must be taken into account insofar as the initial velocity of the recoil nucleus depends on its kinematics. This is definitely true for the reaction $(n,n'\gamma)$, so we shall consider the reaction mechanism briefly and give more attention to the kinematics and the determination of the initial velocity of the recoil nucleus β_0.

The reaction mechanism

The inelastic scattering of fast neutrons was first studied theoretically by Hauser and Feshbach,[20] who assumed that there is no coupling between the entrance and exit channels of the reaction (formation of the compound nucleus and decay of its states). With this assumption the mechanism for the reaction $(n,n'\gamma)$ can be depicted schematically as in Fig. 6.

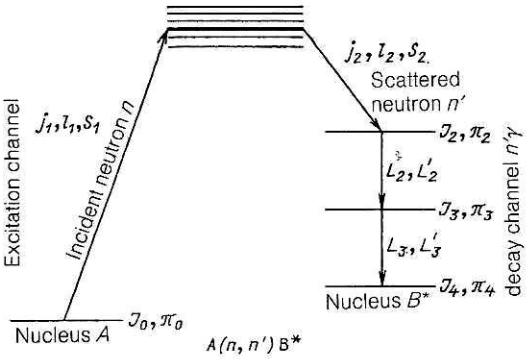

FIG. 6. Mechanism for the reaction $(n,n'\gamma)$.

Here the cross sections for the excitation of a level of the target nucleus with energy E_i by a neutron of energy E_n is given by[21]

$$\sigma(E_n, E_i) = \frac{\lambda^2}{8\pi(2I_0+1)} \sum_{l_1 j_1} T_{l_1}^{j_1}(E_n) \times \sum_{J_1} (2J_1+1) \frac{\sum_{l_2 j_2} T_{l_2}^{j_2}(E_n - E_i)}{\sum_{m l_2' j_2'} T_{l_2'}^{j_2'}(E_n - E_m)}, \quad (32)$$

where T are penetration coefficients characterizing the special features of the nucleus in the formation of a compound system.

Here the indices 1 and 2, respectively, refer to the entrance and exit channels, and the index m refers to all possible exit channels competing with channel 2. However, it is precisely this feature which makes the practical application of expression (32) difficult. In order to carry out the summation over m, it is necessary to know the quantum characteristics of the possible exit channels, and quite frequently they are also the object of study. Simplifying assumptions must be introduced to avoid this difficulty (see, for example, Ref. 21, p. 104). Exhaustive reviews on the mechanism for the reaction $(n,n'\gamma)$ can be found in Refs. 13, 19, and 21–23. The Hauser–Feshbach theory was developed further by Moldauer,[24–31] but this lies outside the scope of the present review.

Kinematics of the reaction $(n,n'\gamma)$. Determination of E^{ef} for the neutron and β_0 for the recoil nucleus

The number of reactor neutrons of energy $E_n \geqslant 1$ MeV (fast neutrons) obeys the relation $N(E_n) \approx \exp(\zeta E_n)$, where $N(E_n)$ is the number of fast neutrons with energy E_n. The quantity ζ lies in the range 0.4–0.8 MeV^{-1}, depending on the reactor construction.[19,32–34] In Ref. 13 it was shown that for $\beta = 0.65$ MeV^{-1}, $N(6\text{ MeV})/N(2\text{ MeV}) \approx 0.05$, i.e., in practice the reaction $(n,n'\gamma)$ can be used for excitation energies no greater than 6 MeV.

It is known from the kinematics of inelastic scattering that if a particle of mass m and energy E_{0m} is incident on a stationary scattering center of mass M, in the laboratory frame the center of the two masses moves with velocity

$$\beta_0 = (2m_0 E_{0m})^{1/2}/(M + m). \quad (33)$$

This expression is also valid for the system neutron + nu-

cleus in the reaction $(n,n'\gamma)$, where E_{0m} corresponds to E^{ef} for the neutron which excites the level E_0.

The reaction $(n,n'\gamma)$ is endothermic, i.e., a threshold reaction, so that the following condition must be satisfied:

$$E^{ef} = E_0\ \delta E, \tag{34}$$

where $\delta E = E_{n'} + E_{cms}$ is the energy which the neutron must have above the reaction threshold (Q) to excite the level E_0. In practice, the approximations $E_{cms} \approx E_{recoil}$ and $|Q| \approx E_0$ are sufficiently accurate,[13] so that expression (34) can be rewritten as

$$E^{ef} = E_0 + \Delta E^{ef},$$

where $\Delta E^{ef} \approx \delta E$ must be determined separately for each nucleus studied.

The authors of Ref. 19 proposed that the following expressions be used to calculate δE:

$$\int_{E_0}^{E_0+\delta E} \sigma(E_n)\, N(E_n)\, dE_n = \int_{E_0+\delta E}^{E_{max}} \sigma(E_n)\, N(E_n)\, dE_n, \tag{35}$$

where $\sigma(E_n)$ is the cross section for excitation of the level E_0 by a neutron of energy E_n.

This expression implies that E^{ef} is the point on the horizontal axis corresponding to the division of the area under the curve $\Phi(E_n) = \sigma(E_n)N(E_n)$ (Fig. 7) for the range (E_0, E_{max}) in half.

For most nuclei the value of δE thus obtained lies in the range 0.7–1.3 MeV. An important advantage of expression (35) is that it is independent of the LSS theory and, consequently, unrelated to the DSA method. However, this expression is complicated to use in practice, so in our experiments we followed a different approach. It consists of solving the inverse problem: using the known lifetime in a given nucleus τ_0, we find $F(\tau_0)$ for the energy E^{ef} at which $F^{th}(\tau_0) = F^{exp}$. In order to carry out this procedure, it is necessary to express F^{th} and F^{exp} as functions of E^{ef}:

$$F^{th}(\tau) = \varphi(E^{ef}), \tag{36}$$

$$F^{exp} = \psi(E^{ef}). \tag{37}$$

To obtain the explicit form of the function $\varphi(E^{ef})$, the attenuation factor is written as[6]

$$F^{th}(\tau_0) = 1 - \frac{\tau_0}{a} - \frac{d_n}{d_e \varepsilon_0(\beta_0)}\left[1 + \frac{A_2}{A_1} G \frac{d_n}{d_n'}\right]\frac{\tau_0}{a}, \tag{38}$$

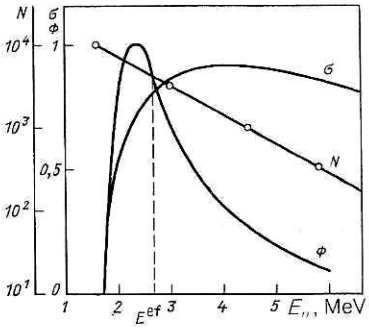

FIG. 7. Graphical determination of E^{ef} for the incident neutron from expression (35) as the point where the area under the curve Φ is divided in half.

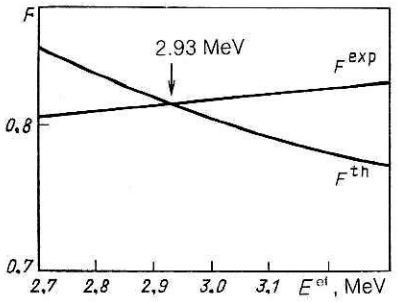

FIG. 8. Graphical method of finding δE as the intersection point of the functions $F^{th}(E^{ef})$ and $F^{exp}(E^{ef})$ for the level of energy 2.212 MeV in ^{27}Al.

where all the notation has been introduced above.

However,

$$\beta^0 = (2mE^{ef})^{1/2}/(M+m) = C\sqrt{E^{ef}} \tag{39}$$

and

$$\varepsilon^{1/2}(\beta) = 2300\, A^{1/2} Z^{-7/6} \beta = C' E^{ef}. \tag{40}$$

After substituting (39) and (40) into (38), we obtain

$$F^{th}(\tau_0) = \varphi(E^{ef}) = C_1 - C_2/\sqrt{E^{ef}}. \tag{41}$$

On the other hand, β_0 from expression (39) is substituted into the expression for the experimental attenuation factor

$$F^{exp} = \frac{\delta E}{E_\gamma^0 \beta_0 (\cos\theta_1 - \cos\theta_2)},$$

as a result of which we obtain the explicit form of the function $\Psi(E^{ef})$, i.e.,

$$F^{exp} = \Psi(E^{ef}) \sim C_3\sqrt{E^{ef}}. \tag{42}$$

In expressions (41) and (42), C_1, C_2, and C_3 are numerical constants depending on the nucleus in question and the transition from the level of interest. However, the determination of τ_0 requires fulfillment of condition $F^{ef}(\tau_0) = F^{exp}$, i.e., the root of the equation

$$\varphi(E^{ef}) = \Psi(E^{ef}) \tag{43}$$

gives the desired effective energy of the neutron exciting the level E_0.

This method of finding E^{ef} is shown in Fig. 8 (see also Table II), where it is applied to the excited level of energy 2.212 MeV in ^{27}Al.

TABLE II. F^{th} and F^{exp} as functions of E^{ef} for the level of energy 2.212 MeV in ^{27}Al.

E^{ef}, MeV	F^{th}	F^{exp}
2.7	0.806	0.852±0.025
2.8	0.811	0.836±0.025
2.9	0.815	0.822±0.025
3.0	0.820	0.808±0.025
3.1	0.824	0.795±0.024
3.2	0.827	0.782±0.024
3.3	0.831	0.770±0.024
3.4	0.834	0.760±0.023
3.5	0.837	0.748±0.023

TABLE III. F^{th} for the level of energy 3.003 MeV in ^{27}Al as a function of δE.

τ, 10^{-15} sec	$F^{th}(\delta E)$, MeV				
	$\delta E = 0.5$	0.6	0.7	0.8	0.9
1	0.997	0.997	0.997	0.997	0.997
3	0.989	0.989	0.989	0.989	0.989
7	0.974	0.974	0.975	0.975	0.975
10	0.962	0.963	0.964	0.964	0.965
30	0.889	0.891	0.893	0.894	0.896
70	0.755	0.758	0.762	0.765	0.768
100	0.669	0.674	0.678	0.682	0.686
300	0.364	0.368	0.372	0.376	0.380
700	0.186	0.189	0.191	0.194	0.196
1000	0.136	0.138	0.140	0.142	0.144
3000	0.049	0.049	0.050	0.051	0.052
7000	0.021	0.022	0.022	0.022	0.022

In this case $\tau_0 = 45 \times 10^{-15}$ sec (Ref. 35), and the experimentally measured Doppler shift $\Delta E = 7.24 \pm 0.23$ MeV of the transition 2.212–0 MeV was used to find the constants C_1, C_2, and C_3 in expressions (41) and (42). The curves $\varphi(E^{ef}) = F^{th}$ and $\Psi(E^{ef}) = E^{exp}$ for this case are shown in Fig. 8. The point where they intersect is the root of Eq. (43), so that $E^{ef} = 2.93 \pm 0.03$ MeV. Using this value and expression (34), we find $\delta E = 0.72 \pm 0.06$ MeV.

The value of δE thus obtained can be used to find E^{ef} for all the excited levels in a given nucleus. This is possible because the dependence $F^{th}(\delta E)$ is very weak. For this reason, even a large error in determining E^{ef}, i.e., δE, has practically no effect on $F^{th}(\tau)$. This is shown for a specific example in Table III, where $F^{th}(\delta E)$ for the level of energy 3.003 MeV in ^{27}Al is calculated for a wide range of values $\delta E = -0.5$–0.9 MeV. We see from this table that for different δE the values of $F^{th}(\tau)$ differ in the third decimal place. Therefore, in practice the expression

$$F_i^{ef} = E_{i0} + 0{,}72, \quad i = 1, 2 \ldots \tag{44}$$

can be used for all the excited levels E_{i0} of ^{27}Al with quite good accuracy.

Here, however, we should note that the determination of E^{ef} by this method, owing to the use of expression (38), involves the LSS theory together with all its conventions. Moreover, we see from expression (44) that E^{ef} is different for each level of a given nucleus. From the viewpoint of the DSA method, this fact indicates that there is a fundamental difference between reactions $(n,n'\gamma)$ and reactions with charged particles of constant energy. Therefore, when applying the DSA method to the reaction $(n,n'\gamma)$, we are forced to determine δE separately for each nucleus studied.

3. THE EXPERIMENT

The first nuclear spectroscopic studies using the reaction $(n,n\gamma')$ with fast reactor neutrons were carried out by Donahue,[36,37] where the γ spectra were measured using a scintillation technique. These studies were later extended to Ge(Li) detectors by Nichol and Kennett.[32–34]

The authors of Ref. 33 first pointed out the possibility in principle of using the inelastic scattering of fast reactor neutrons to measure the lifetimes of excited levels. However, these investigations were not pursued and the work of Ref. 33 is really significant for its pioneering nature.

The real development of the DSA method for the reaction $(n,n\gamma')$ with reactor neutrons occurred in the studies by the Alma-Ata group. This group carried out a number of important studies on the lifetimes of excited levels of nuclei in the range $50 \leqslant A \leqslant 70$ (Refs. 38–51). It should be pointed out that at the present time the Alma-Ata and Sofia groups are the only ones intensively applying the DSA method for the reaction $(n,n\gamma')$ with fast reactor neutrons. A detailed review of the work of the Alma-Ata group can be found in Ref. 13.

Our setup (Fig. 9) is installed in the horizontal channel of the ITR-2000 reactor at the Institute for Nuclear Research and Nuclear Power of the Bulgarian Academy of Sciences in Sofia. It is designed to measure lifetimes by the DSA method using two targets simultaneously, as proposed in Refs. 52 and 53.

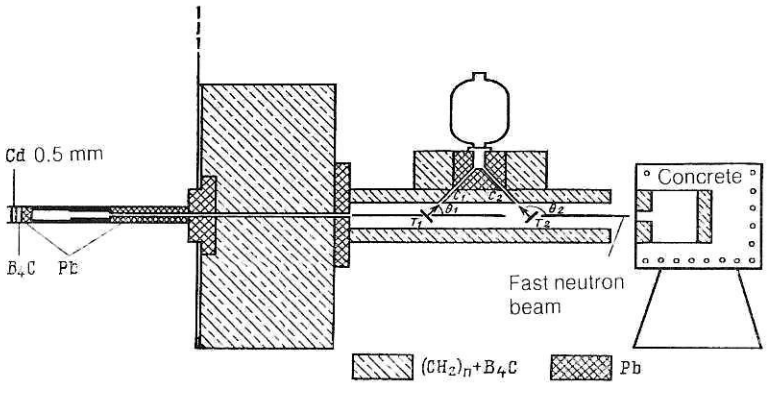

FIG. 9. Experimental setup for measuring the lifetimes of nuclear levels using the reaction $(n,n'\gamma)$ by the DSA method with two targets simultaneously.

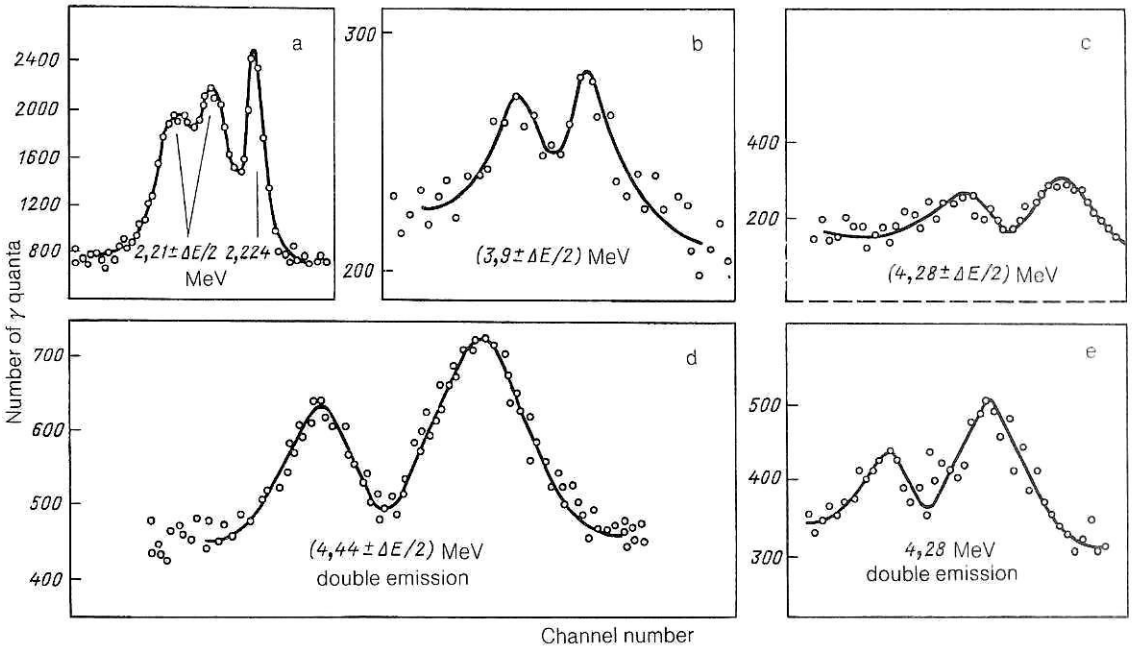

FIG. 10. Experimental spectra in which the γ peaks correspond to energies Doppler-shifted by an amount $\pm \Delta E/2$ from the exact value of the γ-transition energy.

A beam of fast neutrons of diameter 26 mm is extracted from the active zone of the reactor by means of a collimator. Thermal neutrons in the beam are suppressed by 0.5-mm Cd and 10-mm B_4C filters, and reactor radiation is suppressed by a 40-mm Pb filter.

The collimators C_1 and C_2 from the target to the detector are filled with $(CH_2)_n$ and LiF for shielding the Ge(Li) detector from scattered neutrons, which increase the γ background in the photoabsorption spectrum, owing to the $(n,n'\gamma)$ reaction in the germanium crystal. The collimators are located at angles of $\theta_1 = 45°$ and $\theta_2 = 135°$ to the direction of the neutron beam. For this geometry the detector records, via the collimator C_1, γ radiation from the target T_1, which is Doppler-shifted by $+\Delta E/2$ from the exact value of the transition energy. Radiation of energy $E_{\gamma 0} - \Delta E/2$ is detected via the collimator C_2, so, owing to the symmetry of the angles, the total shift is ΔE. This is the quantity used in expression (5) to find the experimental attenuation factor.

Since the first target scatters the beam to a known degree, the flux density at the location of the second target T_2 is smaller than the flux density at T_1. This decreases the specific volume activity of the target T_2, so either the target T_1 is made thinner, or it is made with slits. It has been found empirically that the areas of the two shifted (forward and backward) peaks become equal when the ratio of the thicknesses of the two targets is $d_2/d_1 \approx 6/5$. For this geometry the spectra obtained experimentally are as shown in Fig. 10.

In our studies we used three Ge(Li) detectors with different volumes and energy resolutions of the γ line of ^{60}Co of energy 1.33 MeV: 1) 28 cm^3 (2.6 keV); 2) 52 cm^3 (2.8 keV); 3) 75 cm^3 (3.0 keV). The target dimensions were $80 \times 60 \times 5.6$ mm and the distance between the targets was ≈ 70 cm.

The spectra were stored in a multichannel amplitude analyzer, and to obtain the centers of the peaks (E_γ^1, E_γ^2), were analyzed by the fully automatic program KATOK (Ref. 54).

The method of simultaneous measurements using two targets with fixed geometry has the following advantages over the method of making two measurements on a single

TABLE IV. Lifetimes of levels of ^{11}B, ^{23}Na, and ^{24}Mg.

Nucleus	E^{lev}, keV	E_γ, keV	τ, 10^{-15} sec	
			Data from the present study	Data from other studies (references in square brackets)
^{11}B	2124	2124	6,2±2,1	6.0±2,2 [55]; 5,5±0,9 [56]; 4,7±1,3 [57]
	4442	4442	1,4±1,0	1,2±0.5 [58]; 1,4±0,2 [59]; 0,9±0,1 [57]
^{23}Na	2076	1636	27±9	46±8 [35]; 49±11 [35]
	2640	2640	390±20	100±60 [35]; 200±80 [35]
	2703	2263	260±110	100±60 [35]; 200±100 [35]
^{24}Mg	4124	2754	56±19	55±10 [35]
	4239	4239	105±5	100±10 [35]
	6011	4642	115±20	85±20 [35]

TABLE V. Lifetimes of levels of ^{27}Al and ^{28}Si.

Nucleus	E^{lev}, keV	E_γ, keV	τ, $^{-15}$ sec	
			Data from the present study	Data from other studies (references in square brackets)
^{27}Al	2210	2210	45±8	44 [14]; 55±9 [60]
	2734	1720	14±9	16 [14]; 16±7 [60]
	2980	2980	15±5	15^{+4}_{-2} [14]; 14±6 [60]
	3003	3003	78±15	84^{+6}_{-9} [14]; 83±7 [60]
	3955	3955	4±4	4^{+6}_{-3} [14]; <2 [60]
	4509	2299	260±10	290±20 [14]; 300±30 [60]
^{28}Si	4618	2838	28±5	54±10 [35]; 39±2 [61]
	4979	3200	65±6	34±12 [35]; 60±20 [61]
	6275	4496	1900±200	810±490 [35]; 1500±400 [61]

target with interchange of the angles θ_1 and θ_2:

a) during the measurements the two shifted peaks have the same background conditions;

b) apparatus drift has no effect on the total Doppler shift, since the two peaks "drift" simultaneously in one or the other direction;

c) for a given reactor operation time, twice as many statistics are obtained, which decreases the statistical error by roughly a factor of $\sqrt{2}$, so that the reactor time and neutron beam are used more efficiently;

d) the need to calibrate the measured γ spectra for each angle θ_1 and θ_2 no longer exists.

4. RESULTS

Results on the lifetimes of excited nuclear levels

The results on the lifetimes of excited nuclear levels are obtained in the following sequence: from experiment we obtain the total Doppler shift ΔE; expression (5) is used to calculate the experimental attenuation factor F^{exp}; using expressions (15) or (26), the curve $F^{th}(\tau)$ is tabulated for the corresponding moderating medium—homogeneous (15) or inhomogeneous (26); the lifetime of a level is taken to be the value τ for which

$$F^{exp} = F^{th}(\tau)$$

(see Fig. 2).

In our experiments during 1982 we measured the lifetimes of excited levels of the following nuclei: ^{11}B, ^{23}Na, ^{24}Mg, ^{27}Al, ^{28}Si, ^{31}P, ^{32}S, ^{35,37}Cl, ^{38}K, ^{40}Ca, ^{45}Sc, ^{48}Ti, ^{51}V, ^{52}Cr, ^{55}Mn, ^{56}Fe, ^{59}Co, and ^{58,60}Ni.

The results are shown in Tables IV–XV.

Results for the reduced transition probabilities $B(\sigma L)$

We assume that only those states from which it is impossible to emit nucleons or nucleon structures are considered. Such states decay via electromagnetic transitions or by the emission of conversion electrons or electron–positron pairs.

The probability $\lambda(\sigma L)$ for each partial γ transition is written as

$$\lambda(\sigma L) = \frac{1}{\hbar L}\frac{8\pi(L+1)}{[(2L+1)!!]^2}\left[\frac{E_\gamma}{\hbar c}\right]^{2L+1} B(\sigma L), \qquad (45)$$

where L is the multipole order of the transition with energy E_γ and $B(\sigma L)$ is the reduced transition probability depending on the specific features of the model used for the given nucleus. Expression (45) contains the dependence of the probability $B(\sigma L)$ on the lifetime τ of the level from which the transition of energy E_γ occurs. Since $\lambda(\sigma L) = 1/\tau$, we have

$$\frac{\hbar}{\tau} = \frac{8\pi(L+1)}{L[(2L+1)!!]^2}\left[\frac{E_\gamma}{\hbar c}\right]^{2L+1} B(\sigma L). \qquad (46)$$

Knowing τ, L, and E_γ, we can use (46) to compute the total reduced probability for a given transition. However, it is necessary to take into account the fact that not only the transition E_γ can occur from this level, but also that this transition E_γ can be a mixture of two multipole orders. Using k to denote the relative yield of the transition E_γ from a given level and δ to denote the multipole mixing ratio for the transition probabilities, we obtain the following general expressions for $L = 1$ and $L = 2$:

$$\begin{aligned} B(\sigma 1) &= 6{,}288\cdot 10^{-16} E_\gamma^{-3}/\tau_{\sigma 1}\,[e^2\cdot \mathrm{F}^2]; \\ B(\sigma 2) &= 8{,}161\cdot 10^{-10} E_\gamma^{-5}/\tau_{\sigma 2}\,[e^2\cdot \text{фм}^4], \end{aligned} \qquad (47)$$

where σ is equal to E or M, and $\tau_{\sigma 1}$ and $\tau_{\sigma 2}$ are the partial lifetimes, calculated from the equations

$$\tau_{\sigma 1} = \frac{100}{k}(1+\delta^2)\tau; \quad \tau_{\sigma 2} = \frac{100}{k}\frac{1+\delta^2}{\delta^2}\tau. \qquad (48)$$

TABLE VI. Lifetimes of levels of ^{31}P.

E^{lev}, keV	E_γ, keV	τ, 10^{-15} sec		
		Data from the present study	Ref. 62	Ref. 65
3134	3134	9±7	<15	14±6
3295	2029	140±24	117±20	78±35
3414	2148	400±210	320±30	445±180
3505	3505	18±12	<10	12±6
4190	2924	90±15	>15	7±3
4259	4259	<20	<15	—
5530	2116	16±7	<15	<10

TABLE VII. Lifetimes of levels of ^{32}S, ^{35}Cl, and ^{37}Cl.

Nucleus	E^{lev}, keV	E_γ, keV	τ, 10^{-15} sec: Data from the present study	τ, 10^{-15} sec: Data from other studies (references in square brackets)
^{32}S	4281	4281	40±14	36±8 [64]; 48±13 [65]; 74±6 [66]
	4461	2230	127±30	130±30 [67]; 180±40 [65]; 140±25 [68]
	5006	2776	700±150	600±69 [69]; 800±60 [70]; 75±5 [68]
^{35}Cl	1219	1219	200±80	145±30 [71]; 175±20 [72]; 270±50 [73]
	2646	2646	270±90	200±30 [71]; 255±65 [72]; 350±90 [73]
	2694	2694	62±8	20±4 [71]; 21±3 [72]; 62±16 [73]
	3002	3002	72±12	16±5 [71]; 22±3 [72]; 31±13 [73]
^{37}Cl	1726	1726	206±20	220±25 [71]; 220±70 [73]
	3086	3086	100±34	$<$ 40 [71]; 66±15 [73]
	3103	3103	2100±600	$>$ 3500 [71]; $>$ 7000 [73]

Note. The lifetimes of levels of the isotopes ^{35,37}Cl were obtained from $F(\tau)$ calculated using Eq. (26).

TABLE VIII. Lifetimes of levels of ^{39}K and ^{40}Ca.

Nucleus	E^{lev}, keV	E_γ, keV	τ, 10^{-15} sec: Data from the present study	τ, 10^{-15} sec: Data from other studies (references in square brackets)
^{39}K	2523	2523	92±9	90±30 [74]; 71±19 [75]; 88±18 [76]
	3883	3883	26±10	20±7 [74]; $<$ 30 [75]; 28±20 [76]
	4083	4083	74±42	20±10 [74]; 43±15 [75]; 78±38 [76]
	4095	1572	90±70	115±30 [74]; 80±20 [75]; 110±60 [76]
	4127	1313	85±50 *	85±20 [74]; 45±15 [75]; 100±40 [76]
	4478	1955	350±30	210±90 [75]
	4520	923	110±20	285±70 [74]; 170±45 [75]
^{40}Ca	3904	3904	52±20	54±2 [35]; 58±10 [77]; 54±6 [78]

*With correction for cascade population.

Note. The lifetimes of levels of the isotope ^{39}K were obtained from $F(\tau)$ calculated using Eq. (26).

TABLE IX. Lifetimes of levels of ^{45}Sc.

E^{lev}, keV	E_γ, keV	τ, 10^{-15} sec: Data of the present study		Ref. 79
543	543	$>$ 400	$>$ 550 *	$>$ 800
720	720	170±130	220±150	220±60
939	926	$<$ 800	$<$ 1400	—
974	974	600±600	$>$ 600	$>$ 1900
1237	1237	1400±900	180±110	3400±2700
1409	1409	320±120	400±200	360±70
1433	1433	$50 < \tau < 650$	$8 < \tau_k < 90$	2800±1800
1662	1662	150±100	190±120	115±15
1801	1788	48±6	65±10	12±10
2094	2094	23±6	30±12	90±20
2223	1503	80±20	100±20	600±250
2304	2292	800±600	1200±1200	270±50
2343	2343	50±10	67±15	21±14
2780	2403	76±14	100±20	—

*The values of τ_k are given this column.

TABLE X. Lifetimes of levels of ^{48}Ti.

E^{lev}, keV	E_γ, kev	τ, 10^{-15} c: Data of the present study	Ref. 80	Ref. 81	Ref. 82
2421	1438	40±17	60±20	43±9	35±7
2998	2014	92±16	—	138±28	160±32
3371	2387	13±2	$<$ 40	$<$ 12	18±7
3616	2633	12±4	55±18	$<$ 12	—
3700	2716	21±6	35±3	—	—
3741	2757	26±10	—	—	16±3
3852	2868	140±95	70±20	39±8	—

TABLE XI. Lifetimes of levels of ^{51}V and ^{52}Cr.

Nucleus	E^{lev}, keV	E_γ, keV	τ, 10^{-15} sec	
			Data from the present study	Data from other studies (references in square brackets)
^{51}V	1813	1813	>400	900 [39]; 810±110 [83]; 920±280 [84]
	2411	2090	<190	20±3 [39]; 27±8 [83]; 28±9 [84]
	3083	2762	9±7	15^{+5}_{-3} [39]; >2 [83]; <3 [84]
	3264	2335	57±17	77^{+18}_{-10} [39]; 22±4 [83]; 21±4 [84]
	3386	1777	42±30	95±20 [84]
	3395	1785	<150	22±9 [83]; 22^{+13}_{-10} [84]
	3614	2005	86±28	270^{+50}_{+30} [39]; 90^{+150}_{-40} [83]; 80^{+150}_{-40} [84]
	3632	3311	20±6	16^{+7}_{-4} [39]; 17^{+21}_{-4} [83]; 18^{+20}_{-5} [84]
^{52}Cr	2965	1531	45±6	680±320 [85]
	3711	2337	16±2	—
	3948	1578	47±8	150±60 [85]
	4040	1670	37±7	390±17 [85]
	4563	3129	58±8	—

TABLE XII. Lifetimes of levels of ^{55}Mn.

E^{lev}, keV	E_γ, keV	τ, 10^{-15} sec			
		Data from the present study	Ref. 40	Ref. 86	Ref. 87
1529	1529	110±100	130±30	70±15	89±14
1884	1884	16±5	12±3	16±12	28±5
2198	1215	32±5	16±4	25^{+13}_{-16}	34±5
2252	2252	36±14	36±3	22±8	26±4
2269	2269	90±26	290±40	210^{+80}_{-30}	180±30
2366	2366	32±8	34±4	48±16	31±5
2563	2563	14±8	10±3	17±8	12±3
2727	2727	>70)	1000±200	1800±200	>1000
2978	2978	130±80	48^{+180}_{-130}	—	180±30
2993	2867	26±26	28±6	—	15±3

TABLE XIII. Lifetimes of levels of ^{56}Fe.

E^{lev}, keV	E_γ, keV	τ, 10^{-15} sec		
		Data from the present study	Ref. 45	Ref. 88
2658	1810	31±2	37±10	41±10
2960	2113	40±4	78±8	38±12
3120	2273	28±2	60±5	34±15
3123	1037	68±18	95^{+30}_{-27}	65±40
3370	2523	24±5	25^{+10}_{-7}	26±10
3445	1360	38±11	45±10	<40
3449	3449	7±3	—	<18
3602	3602	210±50	—	—
3607	2760	75±30	—	—
3755	1671	180±75	190^{+100}_{-50}	—
3831	2984	53±9	60±10	62±20
3856	1771	39±8	34±6	33±19
4049	3202	10±4	50^{+10}_{-7}	—
4101	3254	62±11	—	—
4120	2035	200±50	330^{+120}_{-80}	—
4395	3548	50±24	—	—
4509	3663	120±40	250^{+100}_{-60}	—

TABLE XIV. Lifetimes of levels of ^{59}Co.

E^{lev}, keV	E_γ, keV	τ, 10^{-15} sec		
		Data from the present study	Ref. 43	Ref. 89
1459	1459	450±270	1000^{+1000}_{-400}	2200^{+16000}_{-1100}
1481	1481	>80	260^{+150}_{-80}	200^{+50}_{-40}
1745	1745	>140	600±300	750±800
2062	2062	27±4	280^{+130}_{-70}	150^{+80}_{-50}
2088	2088	42±5	25^{+12}_{-8}	$400^{+\infty}_{-340}$
2183	2183	56±9	95±17	50^{+110}_{-40}
2204	2204	>1000	—	$1200^{+\infty}_{-1000}$
2396	2396	59±12	190±60	$100^{+\infty}_{-80}$
2481	2481	33±18	44±4	37^{+19}_{-12}
2544	2544	66±34	22±7	$240^{+\infty}_{-180}$
2587	2587	43±7	—	120^{+200}_{-60}
2786	2786	52±8	—	3^{+80}_{-3}
2826	2826	40±7	12)	80^{+30}_{-60}
2913	2913	62±12	—	

The Weisskopf units were calculated using the expressions

$$\left.\begin{aligned} B_W(M1) &= 0{,}0198e^2\cdot F^2;\\ B_W(M2) &= 0{,}01825A^{2/3}e^2\cdot F^4;\\ B_W(E1) &= 0{,}064A^{2/3}e^2\cdot F^2;\\ B_W(E2) &= 0{,}0594A^{4/3}e^2\cdot F^4. \end{aligned}\right\} \quad (49)$$

The values of the enhancement or attenuation of the experimentally obtained probabilities (47) relative to the one-particle estimates (49) were calculated from the simple relations

$$\left.\begin{aligned} |M|^2_E &= B(E/L)/B_W(EL)\ \text{W.u.}\\ |M|^2_M &= B(ML)/B_W(ML)\ \text{W.u.} \end{aligned}\right\} \quad (50)$$

The values of $B(\sigma L)$ (in W.u.) are given in Table XVI.

CONCLUSIONS

Finding the experimental values of the lifetimes and using them to calculate transition probabilities is only the first step in describing the structure of a given nucleus. The next step is to compare these data with model calculations and choose the model which best describes the available data for a given nucleus. Owing to the large number of nuclear models and their variants, such a comparison lies outside the scope of the present review.

The nuclear-level lifetimes and transition probabilities given in Tables IV–XV demonstrate convincingly that in the time range 10^{14}–10^{12} sec the DSA method using the $(n,n'\gamma)$ reaction is not inferior in accuracy to the variants of the method using charged-particle reactions. This method is therefore a reliable source of information on lifetimes and transition probabilities.

The DSA method with the reaction $(n,n'\gamma)$ is applicable in the mass-number range $10\leqslant A\leqslant 70$. For $A>70$ the initial momentum of the recoil nucleus is small, though the shift in the transition energy can only be measured with large error, making the error in F^{exp} large as well.

The method works well for level excitation energies in

TABLE XV. Lifetimes of levels of isotopes of Ni.

Nucleus	E^{lev}, keV	E_γ, keV	τ, 10^{-15} sec	
			Data from the present study	Data from other studies (references in square brackets)
^{58}Ni	1454	1454	42±12	920^{+140}_{-100} [90]
	2459	1005	19±5	1400 [90]
^{58}Ni	2776	1321	38±4	550^{+180}_{-130} [90]
	2903	1449	38±21	90±35 [90]
	3263	1809	63±31	36±5 [90]
	3420	961	28±10	380^{+320}_{-140} [90]
	3621	1162	<20	160^{+120}_{-70} [90]
	3776	1316	58±14	400^{+2000}_{-100} [90]
	4475	1698	34±12	27±11 [90]
^{60}Ni	2159	826	92±17	>800 [91]
	2285	952	12±12	>2100 [91]
	2505	1173	>60	750^{+2700}_{-350} [91]
	2626	1293	35±5	>700 [91]
^{64}Ni	1345	1345	25±12	—

TABLE XVI. Transition probabilities calculated using the lifetimes of excited levels measured in the present study.

Nucleus	E^{lev}, keV	E_γ, keV	Multipole mixing ratio δ	Reference	k	$I_i^\pi - I_f^\pi$	σL	$B(\sigma L)$ W.u.
^{23}Na	2076	1636	−0,19±0,02	[35]	91	7/2⁺—5/2⁺	$M1$	0.24±0.08
	2703	2263	0.00±0,03	[35]	64	9/2⁺—5/2⁺	$E2$	8.7±3.7
^{24}Mg	4124	2754	—	[35]	100	4⁺—2⁺	$E2$	22.4±7.6
	4239	4239	—	[35]	72	2⁺—0⁺	$E2$	1.0±0.05
	6011	4642	—	[35]	100	4⁺—2⁺	$E2$	0.8±0.1
^{27}Al	2210	2210	−0.47±0,12	[35]	100	7/2⁺—5/2⁺	$M1$	0,05±0.01
							$E2$	12.9±1.4
	2734	1720	−0.11±0,02	[35]	76	5/2⁺—3/2⁺	$M1$	0.33±0.19
							$E2$	7,2±4,1
	2980	2980	—	[35]	100	3/2⁺—5/2⁺	$M1$	0.08±0.03
	3003	3003	—	[35]	91	9/2⁺—5/2⁺	$E2$	7.9±1.5
		793	—	[35]	9	9/2⁺—7/2⁺	$M1$	0,07±0.01
	4509	2299	—	[35]	76	11/2⁺—7/2⁺	$E2$	7,7±0,3
^{31}P	3134	3134	—	[35]	100	1/2⁺—1/2⁺	$M1$	0.11±0.09
	3295	2029	−0.41±0,02	[35]	81	5/2⁺—3/2⁺	$M1$	0,02±0,003
							$E2$	3,3±0.6
	3414	2148	—	[35]	100	7/2⁺—3/2⁺	$E2$	7,6±3.9
	3505	3505	−0.42±0,02	[35]	62	3/2⁺—1/2⁺	$M1$	0.02±0.01
							$E2$	1,3±0.9
	4190	2924	0.17±0,07	[35]	76	5/2⁺—3/2⁺	$M1$	0,01±0,002
							$E2$	0,2±0.02
	5530	2116	−1.00±0,5	[35]	50	7/2⁺—7/2⁺	$M1$	0.05±0.02
							$E2$	51.7±22.6
^{32}S	2230	2230	—	[35]	100	2⁺—0⁺	$E2$	9.5±2.3
	4281	4281	—	[35]	100	2⁺—0⁺	$E2$	2.0±0.7
	4461	2230	—	[35]	100	4⁺—2⁺	$E2$	19.2±4.6
	5006	2776	—	[35]	96	3⁻—2⁺	$E1$	<0,0001
		5006	—	[35]	4	3⁻—0⁺	$E3$	20.3±4.3
^{35}Cl	1219	1219	0.13±0,06	[35]	100	1/2⁺—3/2⁺	$M1$	0.085±0.034
							$E2$	3,6±1.4
	2646	2646	—	[35]	91	7/2⁺—3/2⁺	$E2$	3.1±1.1
		882	0.25±0,05	[35]	9	7/2⁺—5/2⁺	$M1$	0.014±0.001
							$E2$	4.3±1.4
	2694	2694	0.17±0,08	[92]	79	3/2⁺—3/2⁺	$M1$	0,02±0.003
							$E2$	0,3±0.1
		930	0.09±0,03	[92]	14	3/2⁺—5/2⁺	$M1$	0.087±0.011
							$E2$	3,1±0,4
	3002	3002	0.09±0,03	[92]	100	3/2⁺—3/2⁺	$M1$	0,016±0,003
							$E2$	0.4±0.1
^{37}Cl	3086	3086	1.6±0,4	[93]	100	5/2⁺—3/2⁺	$M1$	0.003±0.001
							$E2$	2.8±0.9
	3103	3103	0,18±0,01	[93]	100	7/2⁺—3/2⁺	$M2$	0.21±0.06
							$E3$	3.7±1.1
^{39}K	2523	2523	0.69±0,13	[35]	100	1/2⁺—3/2⁺	$M1$	0.015±0.002
							$E2$	3.8±0.6
	3883	3883	0.06±0,07	[74]	100	5/2⁻—3/2⁺	$E1$	<0.001
							$M2$	0.72±0.09
	4083	4083	0.05±0,07	[74]	64	3/2⁻—3/2⁺	$E1$	<0,001
							$M2$	0.11±0.02
		1560	0.02±0,06	[74]	24	3/2⁻—1/2⁺	$E1$	≈0.0011
^{39}K		1064	−0,16±0,13	[74]	12	3/2⁻—3/2⁻	$M1$	0.062±0.015
							$E2$	4.6±1.1
	4095	1572	—	[74]	89	1/2⁺—1/2⁺	$M1$	0,079±0.009
		1076	—	[74]	11	1/2⁺—3/2⁻	$E1$	<0,01
	4127	1313	0.11±0,01	[74]	100	7/2⁻—7/2⁻	$M1$	0.22±0.04
							$E2$	5,0±0.9
	4520	923	−0,01±0,03	[74]	89	9/2⁻—9/2⁻	$M1$	0.28±0.06
							$E2$	0,12±0,02
		576	−0,05±0,05	[74]	9	9/2⁻—11/2⁻	$M1$	0.116±0.026
							$E2$	3,3±0,6
		393	−0,04±0,04	[74]	2	9/2⁻—7/2⁻	$M1$	0,081±0.018
							$E2$	3,2±0.6
^{40}Ca	3904	3904	—	[74]	100	2⁺—0⁺	$E2$	2.01±0.8
^{45}Sc	720	720	−0,09±0,06	[94]	96	5/2⁻—7/2⁻	$M1$	0.5±0.4
							$E2$	19.2±14.9
	974	974	0.09±0,12	[94]	59	7/2⁺—7/2⁻	$E1$	0,001±0,001
		431	0.24±0,14	[94]	11	7/2⁺—5/2⁺	$M1$	0.07±0.07
	1237	1237			100	11/2⁻—7/2⁻	$E2$	21.2±13.6
	1409	1409	2.62±0,62	[94]	91	7/2⁻—7/2⁻	$M1$	0.004±0,003
							$E2$	40.0±32.0
	1662	1662	0,47±0,05	[94]	69	9/2⁻—7/2⁻	$M1$	0,03±0.02
							$E2$	5.6±4.0
		942	—	[94]	9	9/2⁻—5/2⁻	$E2$	69.0±46.0
		425	0.03±0,13	[94]	13	9/2⁻—11/2⁻	$M1$	0.4±0,2
							$E2$	4,8±3,2
		253	—	[94]	9	9/2⁻—7/2⁻	$M1$	1,2±0,8
^{48}Ti	2421	2421	—	[94]	5	2⁺—0⁺	$E2$	1.2±0,5
		1438	−0,14±0,08	[95]	95	2⁺—2⁺	$M1$	0.25±0,14
							$E2$	5.8±2,6
	2998	2014	—	[95]	100	0⁺—2⁺	$E2$	25.8±4.5
	3371	3371	—	[95]	16	2⁺—0⁺	$E2$	2.25±0.39
		2387	0,2±0,1	[95]	84	2⁺—2⁺	$M1$	0,70±0.15
							$E2$	2,55±0.53
	3616	2633	—	[95]	92	2⁺—2⁺	$M1$	0.13±0.05
	3700	3700	—	[95]	37	1⁺—0⁺	$M1$	0.011±0.002
		2716	—	[95]	63	1⁺—2⁺	$M1$	0.046±0.012

TABLE XIV. *Continued.*

Nucleus	E^{lev}, keV	E_γ, keV	Multipole mixing ratio δ	Reference	k	$I_i^\pi - I_f^\pi$	σL	$B(\sigma L)$ W.u.
	3741	3741	—	[95]	28	$1^+ - 0^+$	$M1$	0,006±0,002
		2757	—	[95]	72	$1^+ - 2^+$	$M1$	0,042±0,015
	3852	2868	—	[95]	75	$3^- - 2^+$	$E1$	< 0,001
^{55}Mn	1529	1529	−0,2±0,06	[87]	97	$3/2^- - 5/2^-$	$M1$	0,075±0,070
							$E2$	2,67±2,49
	1884	1884	−0,16±0,01	[87]	57	$7/2^- - 5/2^-$	$M1$	0,203±0,064
							$E2$	3,03±0,96
		1758	−0,05±0,1	[87]	43	$7/2^- - 7/2^-$	$M1$	0,16±0,05
							$E2$	0,26±0,08
	2198	1215	0,18±0,13	[96]	33	$7/2^- - 5/2^-$	$M1$	0,18±0,04
							$E2$	8,0±1,6
		2072	0,27±0,10	[96]	61	$7/2^- - 7/2^-$	$M1$	0,06±0,01
							$E2$	2,2±0,5
	2252	2252	—	[96]	100	$3/2^- - 5/2^-$	$M1$	0,077±0,030
	2269	2269	0,15±0,01	[96]	72	$1/2^- - 5/2^-$	$E2$	0,19±0,06
		739	0,16±0,19	[96]	28	$1/2^- - 3/2^-$	$M1$	0,24±0,08
							$E2$	23,1±8,05
^{55}Mn	2366	2366	—	[96]	26	$5/2^- - 5/2^-$	$M1$	0,02±0,005
		2240	0,2±0,1	[96]	74	$5/2^- - 7/2^-$	$M1$	0,06±0,03
							$E2$	1,0±0,3
	2563	2563	0,09±0,01	[96]	100	$3/2^- - 5/2^-$	$M1$	0,134±0,077
							$E2$	0,341±0,196
	2978	2978	−0,29±0,04	[87]	73	$1/2^- - 5/2^-$	$E2$	0,122±0,078
^{56}Fe	2658	1810	−0,185±0,15	[97]	98	$2^+ - 2^+$	$M1$	0,16±0,02
							$E2$	3,5±0,4
		2658	—	[97]	2	$2^+ - 0^+$	$E2$	0,36±0,02
	2960	2113	0,25±0,01	[97]	98	$2^+ - 2^+$	$M1$	0,08±0,01
							$E2$	2,2±0,2
		2960	—	[97]	2	$2^+ - 0^+$	$E2$	0,15±0,015
	3123	1037	−0,003±0,010	[97]	99	$4^+ - 4^+$	$M1$	0,42±0,11
							$E2$	0,007±0,002
	3370	2523	0,15±0,06	[97]	85	$2^+ - 2^+$	$M1$	0,07±0,02
							$E2$	0,5±0,1
		3370	—	[97]	15	$2^+ - 0^+$	$E2$	0,9±0,2
	3445	788	0,85±0,35	[97]	1,4	$3^+ - 2^+$	$M1$	0,014±0,009
							$E2$	32,6±20,7
		1360	−0,11±0,01	[97]	20	$3^+ - 4^+$	$M1$	0,066±0,019
							$E2$	0,87±0,25
		2599	−0,28±0,02	[97]	78	$3^+ - 2^+$	$M1$	0,034±0,010
							$E2$	0,81±0,02
	3856	1771	−0,02±0,05	[97]	92	$3^+ - 4^+$	$M1$	0,14±0,03
							$E2$	0,04±0,01
		3010	0,06±0,05	[97]	6	$3^+ - 2^+$	$M1$	0,002±0,0004
							$E2$	0,002±0,0003
	4049	1964	0,22±0,03	[97]	19	$3^+ - 4^+$	$M1$	0,08±0,03
							$E2$	1,9±0,8
		3202	0,5±0,1	[97]	80	$3^+ - 2^+$	$M1$	0,06±0,03
							$E2$	3,0±1,5
	4101	2015	0,64±0,24	[97]	25	$4^+ - 4^+$	$M1$	0,011±0,004
							$E2$	2,3±0,9
		3254	—	[97]	60	$4^+ - 2^+$	$E2$	1,7±0,3
	4120	2035	−0,07±0,05	[97]	79	$3^+ - 4^+$	$M1$	0,015±0,004
							$E2$	0,04±0,01
		3273	0,42±0,04	[97]	18	$3^+ - 2^+$	$M1$	0,0007±0,0002
							$E2$	0,022±0,006
	4395	3548	0,30±0,02	[97]	90	$3^+ - 2^+$	$M1$	0,012±0,006
							$E2$	0,17±0,08

the range $2 \leqslant E^* \leqslant 6$ MeV. Owing to expressions (33) and (34), below $E^* \approx 2$ MeV the quantity E^{ef} is too small for obtaining a sufficiently large initial velocity of the recoil nucleus, which again leads to a tiny shift ΔE. For excitation energies above $E^* \approx 6$ MeV the method is inapplicable, owing to the technical limitation that the number of fast neutrons in the reactor spectrum decreases exponentially with increasing energy. For this reason, the γ yield from the excited level in question is insufficient for sufficiently accurate measurements. It should be noted that these restrictions on the use of the DSA method with the reaction $(n,n'\gamma)$ regarding both mass number and excitation energy are not rigid, and they depend on the current state of nuclear electronics and detector technology. Further improvement in the resolving capability of the spectrometer component will broaden the range of the method both in mass number and in excitation energy.

An important problem concerning the general use of the DSA method with the reaction $(n,n'\gamma)$ is the reliable description of the recoil-nucleus stopping process by the LSS theory. For this we recommend the article by Kosyak in the collection of Ref. 13.

The experience which we have gained during the last six years allows us to state that the DSA method with the reaction $(n,n'\gamma)$ is a reliable way of determining the lifetimes of excited nuclear levels. The accurate description of nuclear structure now depends on the possibility of finding a model which corresponds uniquely with the data. This will be accomplished in the future as the theoretical and computational techniques are further developed.

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