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HYPERFINE INTERACTIONS OF HEAVY IONS RECOILING INTO VACUUM

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Сверхтонкое взаимодействие тяжелых ионов отдачи в вакууме

Предполагается возможность приближенного описания коэффициентов ослабления при помощи смешанного, зависящего от времени и статического взаимодействия. В качестве иллюстрации дается анализ экспериментальных результатов.

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Hyperfine Interactions of Heavy Ions Recoiling into Vacuum

An approximate description of the attenuation coefficients $G_k(t)$ by means of a mixed, time-dependent and static interaction is discussed. As an illustration, an analysis of experimental results is presented.

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1. Introduction

The use of nuclear products recoiling into vacuum is more difficult than that in a gas from a point of view of studying the mechanism of hyperfine interactions. When the method of implantation in a gas is applied, we have a possibility of controlling and changing the very important parameter, correlation time τ_c. However, experimentally the recoiling into vacuum is easier and more perspective. In addition, in such experiments as a measurements of nuclear lifetimes by the recoil-distance Doppler-shift method, the knowledge of the perturbed gamma-ray angular distribution is very important.

In 1968, Ben Zvi et al. /1/ showed that for the recoil of excited ions into a gas the hyperfine attenuation of gamma-ray angular distribution could be well described in terms of the Abragam and Pound theory (the AP theory) /2/ with a pure magnetic interaction. A.Brenn et al. /3/ showed that the time dependence of attenuation coefficients is more complicated as compared with the simple exponential character predicted by the AP theory. For a better explanation of the perturbing mechanism, a FOGA (fixed-orientation Gaussian-approximation) model was developed /4/, in which the two conditions, $<\omega_M^2>\tau_c^2 \ll 1$ and $\tau_c < \tau_N$, under which the AP theory is applicable, may be not fulfilled (τ_N denotes the nuclear level lifetime, and $<\omega_M>$ is the mean Larmor precession frequency of the magnetic moment). The studies of Ben Zvi et al. /5/ and Polga et al. /6/ showed that in addition to the magnetic interaction, an admixture of an electric quadrupole interaction was necessary to fit the data if the AP theory was still applicable. D.Ward et al. /7/ were able to obtain a good fit to their own very accurate data. In this work $\langle\omega_M^2\rangle\tau_c$ and $\langle\omega_E^2\rangle\tau_c$ were taken as free parameters. Very recently, such measurements as those of the Coulomb excitation of $^{146,148,150}Nd$ ref. /8/ have proved the dependence of the attenuation coefficients on the electric quadrupole moment. Of other attempts to describe the perturbed gamma ray angular distribution, we can mention the theory of Blume /9/ and the work of Dillenburg and Maris /10/.

For nuclear levels with longer lifetimes, of the order of a few nanoseconds, the perturbing mechanism seems to be entirely different. In that case, the magnetic static interaction described by Alder /11/ can be used. The first attempts to observe the static interaction in recoils into vacuum were made in Strasbourg /12/.

For the explanation of the measurements for nuclear level lifetimes of the order of hundred picoseconds, a formalism is required which would include both the time-dependent and the static interactions. In the present work the "sewing together" of the AP theory and a formalism like that described in ref. /13/ by Matthias et al. is proposed. The case of a static free atom, where no changes in the value or direction of the electron spin take place, is very similar to the case of a source implanted into demagnetized ferromagnetic foil.

2. The Basis of the Semi-Differential Measurements

The plunger technique /14/ may be employed to obtain the time differential dependence of the coefficients A_2 and A_4. The recoil atoms, after interactions with a heavy-ion beam, have in vacuum a velocity of the order of a few percent of the velocity of light. They are stopped in a polished stopper and the distance between the target and the stopper may be varied. During the flight time in vacuum there occurs a hyperfine interaction which changes the coefficients A_2 and A_4. If the stopper is manufactured

from a material in which the hf interaction probability is very small, semi-differential measurements are possible. As was indicated in ref. /7/, a complete time-differential analysis requires the measurement of the angular distribution of the "stopped" component and it has been found to be absolutely essential that the 90° point to be included in the angular distribution. Since at this angle it is impossible to distinguish between the "stopped" and the "moving" components, their sum is analysed.

If $G_k(t)$ and $\bar{G}_k(t)$ denote the calculated and the actually observed attenuation coefficients, we obtain

$$\bar{G}_k(t) = \lambda_N \int_0^t G_k(t') \exp(-\lambda_N t')\,dt' + G_k(t)\left[\lambda_N \int_t^\infty G_k^{stop}(t'-t) \exp(-\lambda_N t')\,dt'\right], \qquad (1)$$

where $\tau_N = 1/\lambda_N$ is the lifetime of the nuclear level, t is the flight time of the ion recoiling from the thin target to the stopper, and G_k^{stop} is the attenuation coefficient for the stopper. The expression in brackets can be presented as $G_k(\infty)\exp(-\lambda_N t)$. The quantity $G_k(\infty)$ is a constant independent of the target-to-stopper distance and for some materials it is close to 1. The first term of eq.(1) corresponds to nuclei that decay in flight, while the second one is related to those undergoing decay at rest in the stopper.

3. Model Calculations

As was predicted by the AP theory, the attenuation coefficient of the angular distribution has the form as follows

$$G_k(t) = \exp(-\lambda_k t), \qquad (2)$$

where

$$\lambda_k = \frac{1}{3} k(k+1)\tau_c \{<\omega_M^2> + \frac{9}{5}<\omega_E^2>[4I(I+1) - k(k+1) - 1]\}$$ (3)

$$<\omega_M^2> = \frac{g^2 \mu_N^2 <H^2>}{\hbar^2}, \quad <\omega_E^2> = (\frac{eQ}{4I(2I-1)\hbar})^2 <V_{zz}^2> .$$ (4)

The dependence of the observable attenuation coefficients given by (1) on the lifetime of a nuclear level is shown in fig. 1.

It is noteworthy that, in order to fit the experimental data, we can use as free parameters either λ_2 and λ_4, or $<\omega_M^2>\tau_c$ and $<\omega_E^2>\tau_c$. This kind of fitting gives us only information about the product $\omega^2\tau_c$ and the ratio $<\omega_E>/<\omega_M>$.

The paper of Matthias et al. /13/ describes the attenuation coefficients $G_k(t)$ for the case of a static magnetic interaction for a demagnetized ferromagnetic foil with implanted radioactivities. For a demagnetized source the magnetic domains may be randomly oriented, and the strength of the magnetic field in each domain is constant. Figure 2 shows an example of the attenuation coefficients $G_2(t)$ and $\bar{G}_2(t)$ calculated using the formula from ref. /13/.

$$G_k(t) = \frac{1}{2k+1} \sum_{N=-k}^{N=+k} \cos N\omega_L t .$$ (5)

When the lifetime of a nuclear level is long enough, the behaviour of the nucleus recoiling into vacuum is very similar. For the ground atomic state, the electron spin J has a constant value, but its direction in every atom is oriented quite randomly. In actual experiment, the value of J can be different because of the charge distribution of the recoiled atoms, but states with $J=0$ and $J=1/2$ can be found very frequently. If this is the case, the gradients of the electric field vanish, and for long-lived states we do not observe electric quadrupole interactions.

For $J=1/2$ the values of $G_k(t)$ calculated on the basis of the formalisms from ref. /11/ and /13/ are very close.

In this paper we propose a simplified MIX formalism, which takes into account both the time-dependent and the static interactions and may be useful for the description of recoiling atoms with the nuclear level lifetimes of the order of a few hundred picoseconds. The time-dependent interactions take place immediately after recoiling, and shorty afterwards they are outweighted by the static interactions. To fulfil such conditions, the following expression may be suggested.

$$G_k(t) = \exp(-\lambda t)\exp(-\lambda_k t) + \frac{1-\exp(-\lambda t)}{2k+1} \sum_{N=-k}^{N=+k} \cos N <\omega_M> t .$$ (6)

The new parameter λ provides some information about the time during which all the atomic configurations change. At $\lambda=0$ there is a pure time-dependent interaction (AP), and when the value of λ is large, the static interaction is dominating (STAT). The time dependences of G_2, $\bar{G}_2$, G_4 and $\bar{G}_4$ are shown in figs. 3 and 4. The calculations were made with $\lambda = 0.001$ psec^{-1}, the other parameters were the same as those in the AP and STAT cases.

4. Comparison with Experiment and Discussion

Until recently, only little experimental data have been published, among which those obtained by Ward et al. /7/ seem to be most accurate. These data were fitted to the MIX model proposed here. Computations were made on the BESM-6 computer using the FUMILI procedure /15/. Both the parameters derived from eq. (6) of the MIX model and those obtained using the AP theory were fitted to the same experimental data. The coefficients $\bar{G}_2$ (the free parameters λ, λ_2 and $<\omega_M>$) and $\bar{G}_4$ (λ, λ_4 and $<\omega_M>$) were fitted independently. The value of the parameter λ_N was fixed, $\tau_N = 1/\lambda_N = 68$ psec. ref. /16/. The following limitations were imposed on the calculations (in psec.$^{-1}$)

$0 < \lambda < 0.05$

$0 < \lambda_k < 0.1$

$0.02 << \omega_M >< 0.1$.

The least squares χ^2 divided by the number of free parameters were comparable for AP and MIX fits. The parameters λ and $<\omega_M>$ calculated independently from $\bar{G}_2$ and $\bar{G}_4$ have close values within error limits. Their mean weighted values are equal to

$\lambda = (2.74 \pm 1.50) \times 10^{-3}$ psec^{-1}

$<\omega_M> = (5.19 \pm 0.40) \times 10^{-2}$ psec^{-1}.

The other parameters have the values

$\lambda_2 = (2.37 \pm 0.06) \times 10^{-2}$ psec^{-1}

$\lambda_4 = (5.79 \pm 0.16) \times 10^{-2}$ psec^{-1}.

If one assumes the proposed MIX model to work well and mean Larmor precession frequency to be constant during the observation time, it would be possible to get very interesting information on the correlation time τ_c and the mean precession frequency of the electric quadrupole interaction $<\omega_E>$. From expression(3)we derive two unknown parameters, τ_c and $<\omega_E>$. By substituting the calculated values for $<\omega_M>$, λ_2 and λ_4 we obtain

$<\omega_E> = 0.0065$ psec^{-1},

$\tau_c = 2.97$ psec,

which agrees with ref. /17/, where $\tau_c(VAC) \approx 3$ psec was derived from the experiments with recoiling into a gas. The ratio $<\omega_E>/<\omega_M>_{/7/} = 0.125$ also agrees well with the value found in ref. /7/. Since we can deduce from the experimental data both $<\omega_M>$ and $<\omega_E>$, by using $g = (0.318 \pm 0.017)$ from ref. /5/ and $Q = (-1.25 \pm 0.2)$ barn from ref. /18/ we can obtain the values of the mean magnetic field and the mean electric field gradient, acting on the Sm nuclei:

$<H> = (34.0 \pm 4.5)$ MG

$<V_{ZZ}> = (8.2 \pm 2.0) \times 10^{17}$ V/cm^2.

The value of $<H>$ agrees with the value of (36 ± 3) MG obtained using the FOGA model /8/. An advantage of the MIX model consists in the possibility of independent determination of the values of the parameters τ_c, $<\omega_M>$ and $<\omega_E>$.

It should be noted that the fitting to the experimental data for $^{146,148,150}Nd$ from ref. /8/ was also made. These calculations gave very close values of the parameters and the least values of the normalized χ^2 we obtained. In particular, the values of $<\omega_M>$ were obtained to be about 0.045 psec^{-1}, which results in τ_c of the order of 3 psec. Because λ is of the order of (0.01 - 0.001) psec^{-1} and the mean magnetic field $<H>$ is about 30 MG, an analysis of the experimental data made using the MIX model gives the best results for nuclear level lifetimes of the order of a few hundred psec. This method seems to work well for the lifetimes of the order of a few tenths of psec to a few nsec. For a better checking of this model more experimental data are required, which should be obtained at different target-stopper distances and not only for short times after recoiling.

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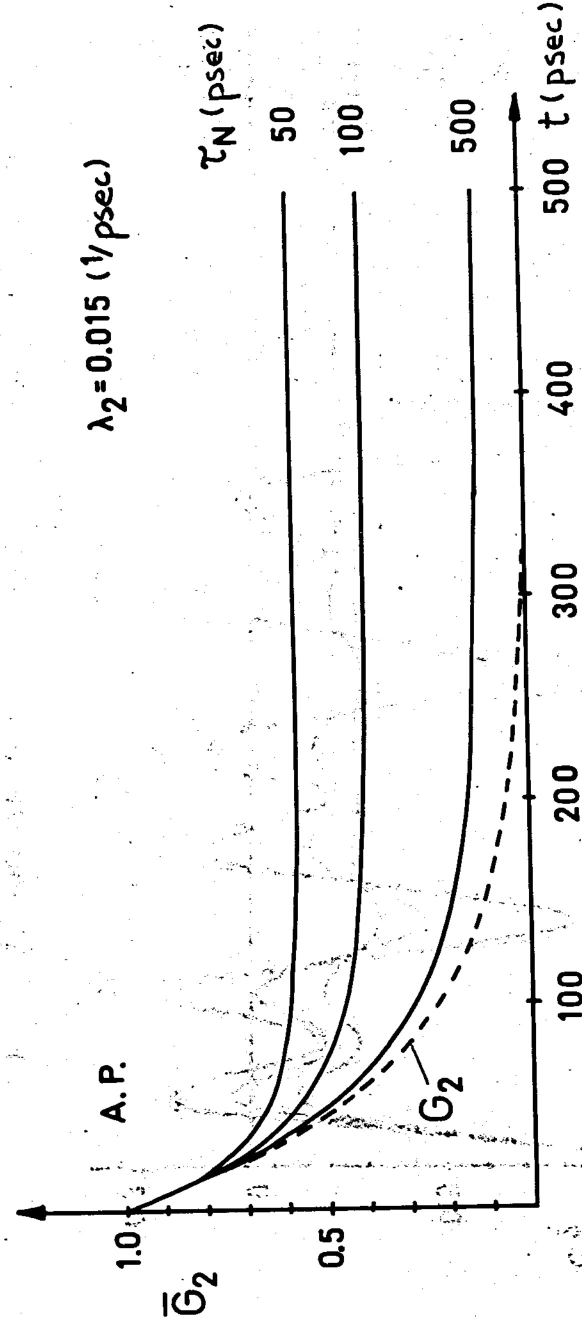

Fig. 1. The theoretical behaviour of the coefficients $G_2(t)$ and $\bar{G}_2(t)$ according to the AP theory. At τ_c = 3 psec and g = 0.333 the parameter λ_2 = 0.015 psec^{-1} for a pure magnetic interaction gives $<\omega_M>$ = 0.05 psec^{-1} and $<H>$ = 31.3 MG.

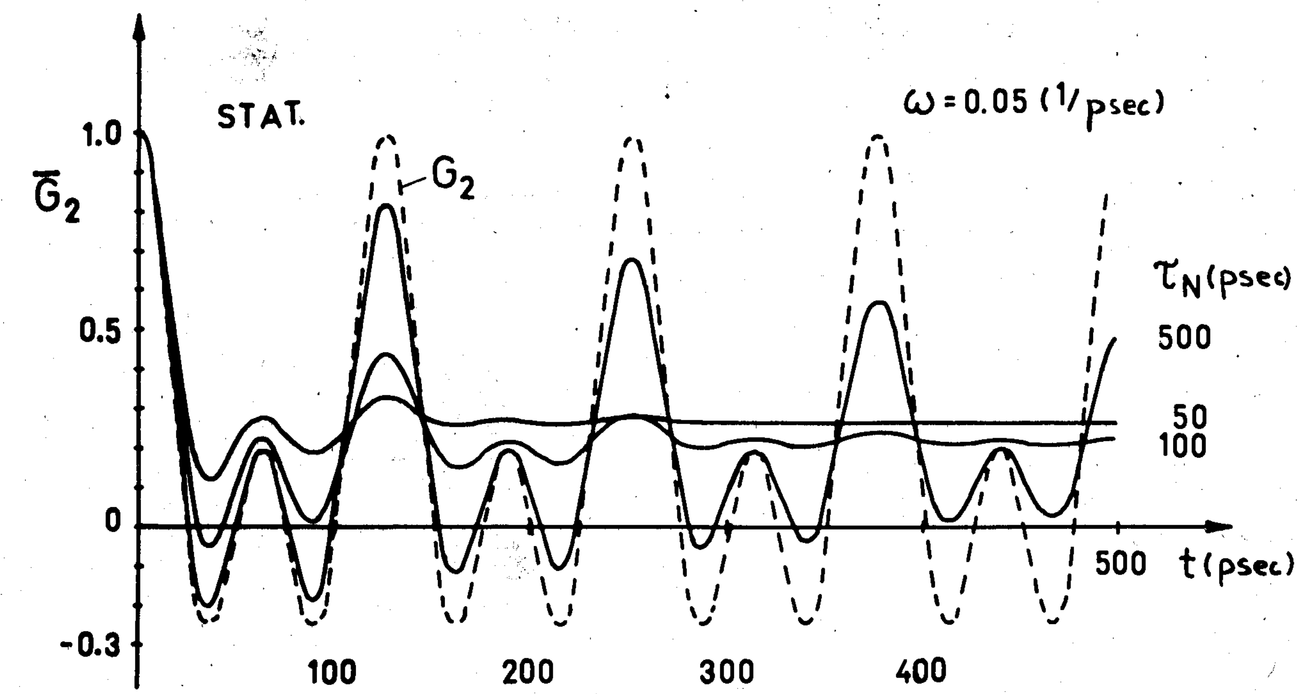

Fig. 2. The theoretical behaviour of the coefficients $G_2(t)$ and $\bar{G}_2(t)$ according to the expression similar to that of Matthias et al./13/.

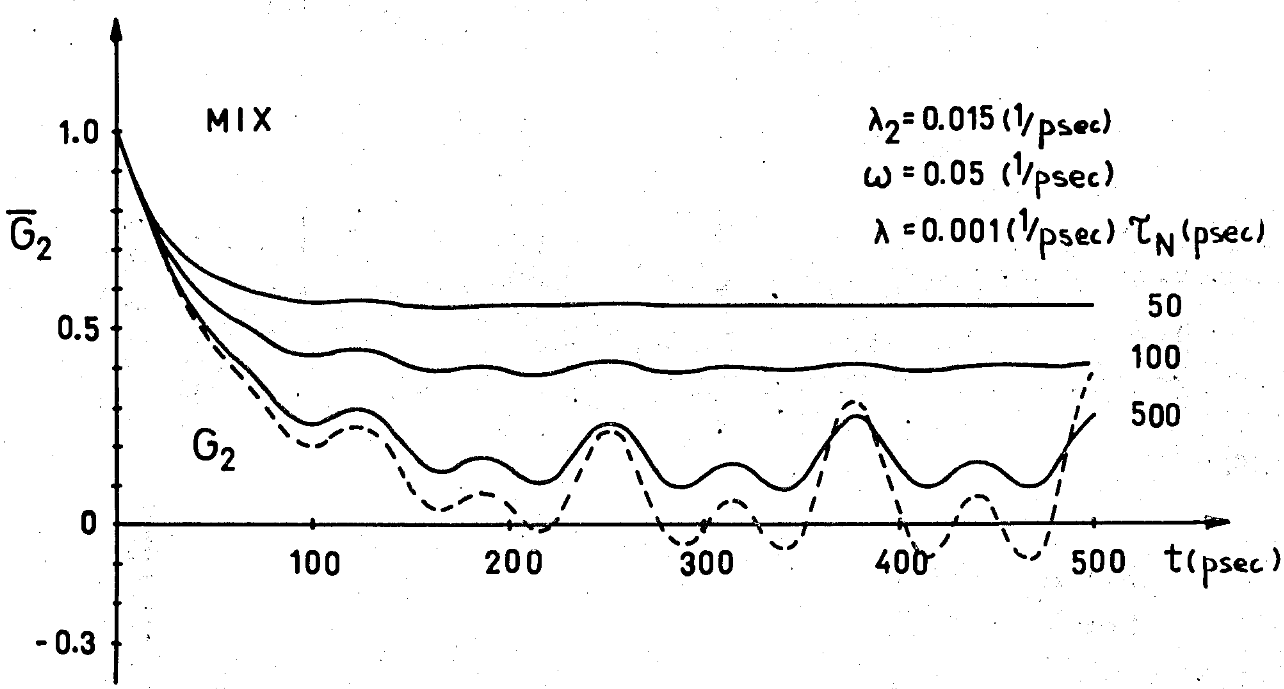

Fig. 3. The theoretical behaviour of the coefficients $G_2(t)$ and $\bar{G}_2(t)$ according to expression (6) from the MIX model.

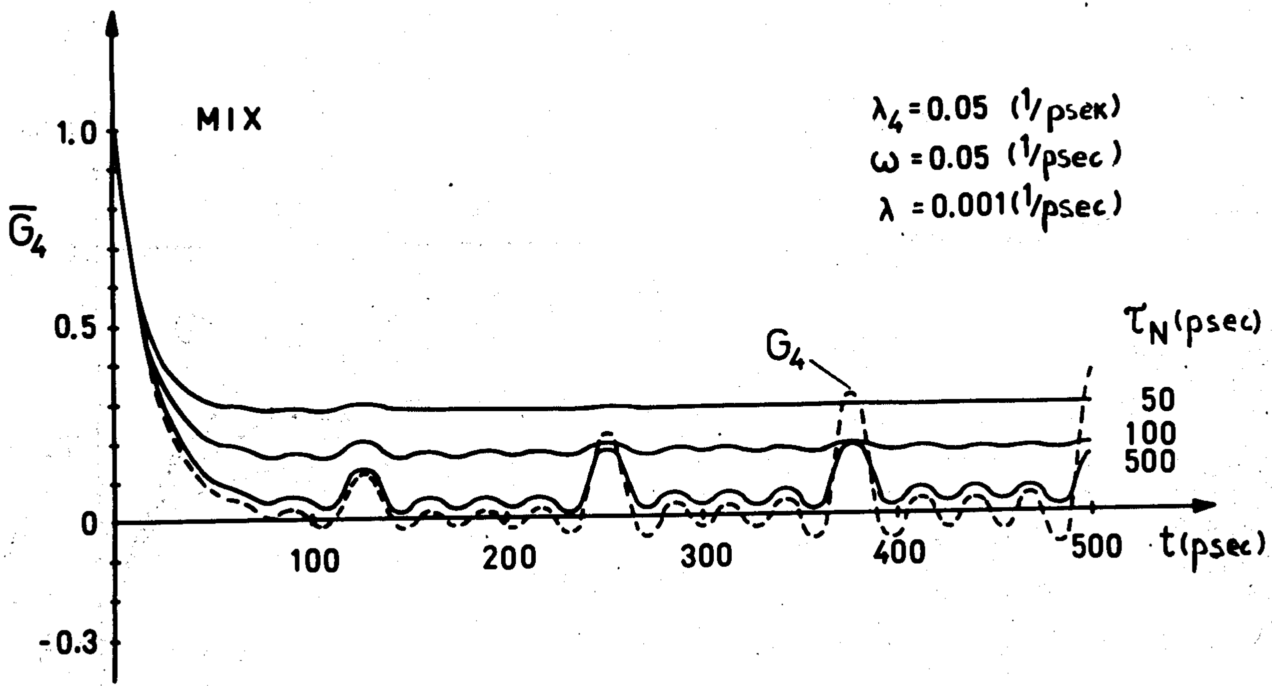

Fig. 4. The theoretical behaviour of the coefficients $G_4(t)$ and $\bar{G}_4(t)$ according to expression (6) from the MIX model.