

Scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (19 May 1999)

A scientific session of the Division of General Physics and Astronomy of the Russian Academy of Sciences (RAS) was held at the P L Kapitza Institute for Physical Problems, RAS, Moscow.

The following reports were presented at the session:

(1) **Basiev T T** (Institute of General Physics, RAS, Moscow) “Spectroscopy of new SRS-active crystals and solid-state SRS lasers”;

(2) **Krasyuk I K** (Institute of General Physics, RAS, Moscow) “Application of laser-driven shock waves in studies of thermal and mechanical material properties”;

(3) **Lyapin A G, Brazhkin V V, Gromnitskaya E L, Stal’gorova O V, Tsiok O B** (Institute of High-Pressure Physics, RAS, Troitsk, Moscow region) “Transformations in amorphous solids under high pressures”.

An abridge version of the reports is given below.

PACS numbers: 33.20.Fb, 42.55.Ye, 42.65.Dr, **78.30.-j**

Spectroscopy of new SRS-active crystals and solid-state SRS lasers

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The 70th anniversary of the discovery of spontaneous combination (Raman) scattering (RS) was commemorated last year. The finding was made simultaneously and independently by C V Raman and K S Krishnan for liquids [1] and G S Landsberg and L I Mandel’shtam for crystals [2].

The inclusion of stimulated processes in Raman scattering can be found even in the general theory constructed by G Placzek [3] soon after the discovery of the effect of RS. However, stimulated Raman scattering of light (SRS) was not discovered until the advent of laser radiation sources, the advancement to which Russian scientists N G Basov and A M Prokhorov made a contribution that gained world-wide recognition. The effect of SRS was discovered by E J Woodbury and W K Ng in 1962 [4] in the course of their investigation into Q -switching of a ruby laser, employing a Kerr cell around nitrobenzene. In the laser spectrum, they observed an intense IR radiation component shifted in frequency by 1345 cm^{-1} relative to the laser line, which was later attributed to the effect of SRS [5].

Since then, this fascinating nonlinear phenomenon and its applications to laser spectroscopy and laser engineering have attracted considerable attention of physicists (see, for

instance, reviews [6–15]). It comes as no surprise, because two-photon radiative transitions in a material medium (atoms, ions, and molecules in gas, liquid, glass, or crystal) are responsible for stimulated (induced) RS, as for spontaneous RS. In this case, the resonance nature of the two-photon process makes it possible to study not only the macroscopic behavior of substances interacting with high-power laser radiation, but also the microphysics of individual atoms, ions, and molecules characterized, for their part, by selection rules, transverse (phase) and longitudinal (energy) relaxation rates. As regards applications, SRS permits high-power coherent radiation to be obtained at new wavelengths.

The process of RS is conveniently represented as a two-photon resonance, when the difference of two optical frequencies, of absorption ν_L and emission ν_S , is equal to the frequency of an atomic vibration quantum in a molecule or a crystal:

$$\nu_L - \nu_S = \nu_v.$$

The cross sections of this two-photon optical process of RS are very small ($\sigma \sim 10^{-30}\text{ cm}^2$). Even in modern times this effect is hard to observe without recourse to sources of highly directional high-power monochromatic radiation (lasers), which testifies to the fundamental importance of the discovery of spontaneous RS.

According to theoretical investigations [3, 5, 8–10], the intensity of stimulated Stokes scattering is proportional to the occupation densities of the states of three interacting fields: laser pump photons (N_L), photons of the generated Stokes wave (N_S), and crystal phonons (molecular vibrations) in the ground or excited state ($N_v = N_0 - N_1$):

$$\frac{dN_S}{dz} \propto N_L N_S (N_0 - N_1).$$

For stationary SRS, the intensity of Stokes radiation is simple in form [8] and may be presented as

$$I_S(l) = I_S(0) \exp(g I_L l),$$

where I_L is the pump intensity, l is the interaction length of radiation with the SRS-active medium, I_S is the Stokes radiation intensity, and

$$g = \frac{\lambda_L \lambda_S^2 N_v}{\pi c \hbar n_S^2 \Delta \nu} \frac{d\sigma}{d\Omega}$$

is the SRS gain. The cross sections of resonance two-photon processes are far less (by 10–15 orders of magnitude) than those of single-photon processes. As a consequence, the progress in SRS converters turned out to be dependent on

the development of laser radiation beams with distinctive properties (high peak power, coherence, broad spectral range of laser frequencies) and imposed stringent requirements on SRS-active media.

According to estimates, it is necessary to ensure a gain–pump–length product (increment) of $gI_L l = 30$ to attain the threshold of SRS, when $I_S \approx I_L$. For the values $g = 1–3 \text{ cm GW}^{-1}$ typical of gaseous and liquid SRS-active media (for hydrogen $g = 1.5 \text{ cm GW}^{-1}$, for nitrobenzene $g = 3 \text{ cm GW}^{-1}$), this necessitates either active media of meter length ($l = 30–100 \text{ cm}$) or above-gigawatt pump intensities ($I_L > 1 \text{ GW cm}^{-2}$).

The advantages of SRS-active media involving molecular gases (H_2 , N_2 , O_2 , CH_4) are the optical homogeneity, the ease of forming the active medium, the high frequencies of SRS-active vibrations ($2,000–4,000 \text{ cm}^{-1}$), and the large frequency shifts $\nu_S = \nu_L - \nu_V$ of the SRS radiation. Of vital importance is the small spectral width of an SRS-active vibration ($\Delta\nu = 10^{-3}–10^{-1} \text{ cm}^{-1}$) and, hence, the relatively large peak RS cross section for an individual molecule [11, 12].

The SRS-active media on the base of molecular gases have several disadvantages. First, the low particle number density even for pressures far greater than atmospheric pressure ($N \leq 10^{21} \text{ cm}^{-3}$ for 10 bar). This calls for a drastic increase in the optical interaction length (up to several meters) and, as a result, makes it more difficult to ensure the high threshold pump intensity (above 10^9 W cm^{-2}) over the whole path length. Second, the problem of low thermal conductivity of gases. This problem can be solved by applying bulky and costly injection systems, which drastically complicates the system, especially for high pressures.

The advantages of the SRS-active media around liquids [11, 12] are the simplicity of preparing an optical SRS cell and the high number density of active particles (10^{22} cm^{-3}). In this case, the line broadening of vibrational transitions undeniably increases, especially for high temperatures ($\Delta\nu \approx 0.1 \text{ cm}^{-1}$ for $T = 77 \text{ K}$, $\Delta\nu \approx 1–4 \text{ cm}^{-1}$ for $T = 300 \text{ K}$), which somewhat reduces the peak scattering cross section for individual molecules. However, the adverse effect of line broadening does not cancel out the beneficial effect of density increase, and in general SRS-active media based on molecular liquids provide higher gain coefficients ($g \approx 3 \text{ cm GW}^{-1}$) and are of smaller bulk than the gaseous ones.

The chief drawbacks of liquid SRS-active media are the low thermal conductivity (in combination with the difficulties associated with the formation of highly homogeneous laminar streams in the working fluid injection) and the large magnitude of dn/dT , resulting in significant thermal optical distortions owing to Stokes losses in the medium. The large values of the nonlinear index of refraction n_2 give rise to self-channelling and self-focusing of the pump beam, which reduces the interaction path length, impairs the divergence, and may result in the optical breakdown of the medium.

Cryogenic molecular liquids (N_2 , O_2) possess a high density, a small line broadening, and a large scattering cross section (17 cm GW^{-1} [12]). Here, the main problems are associated with the production and maintenance of cryogenic temperatures in the SRS-active medium, the thermal insulation of optical windows, and the ease of origination of a large number of gas bubbles, which distort the wave fronts of the pump and the SRS-radiation generated.

Many of the above-named problems can be circumvented by going over to solid optical bodies, particularly to crystals.

In doing this, an effort should be made to retain and enhance the good points of the media considered above.

The high densities of substances in the crystalline state ($n \approx 10^{23} \text{ cm}^{-3}$) make it possible to ensure the best (most compact) interaction of the exciting light with an SRS-active material and high gains [14]. The high symmetry of the arrangement of atoms and molecules in crystals inhibits the scatter in frequencies and linewidths (caused by particle rotations, collisions, and also the fluctuations of their velocities, force constants, and separations, as is observed in liquids and gases) and provides an exact tuning of all the SRS-active particles to resonance. The absence of frequency scatter, i.e. the minimum inhomogeneous line broadening in the spectrum of SRS-active vibrations, enhances the collective effect of laser pump radiation–crystal interaction. This manifests itself in a reduction of the interaction threshold, and an increase in the gain and the SRS conversion efficiency.

A broad spectrum of crystals occurring in nature and especially synthesized artificially in the last decades, provides a great diversity of their properties: types of chemical bond (ionic, ionic–molecular, covalent crystals), transparency range (from 100 nm to 100 μm), and a wide range of resonance vibration frequencies active in the RS process ($10–2000 \text{ cm}^{-1}$).

The chief factor that hampers the use of crystals is the diversity and the complexity of the physical phenomena in the interaction of molecular vibrations with each other and with collective excitations of the crystal lattice (phonons). These phenomena are responsible for shifts, splitting, and inhomogeneous or homogeneous broadening of narrow SRS-active vibrational modes, reducing the efficiency of their interaction with the laser pump radiation.

The first SRS effects in solids and the first SRS lasers were realized with natural crystals of calcite (CaCO_3) and diamond, and later with synthetic CaWO_4 , LiNbO_3 , and LiIO_3 crystals (see papers [6, 7, 11–15] and references cited therein). As shown by the studies of the last decades, among new synthetic crystals there exist those which possess the set of parameters needed to implement efficient SRS converters of laser radiation.

In particular, in the 80s two new synthetic crystals were produced, which furnished progress in SRS lasers for several years. The case in point is the crystal of barium nitrate $\text{Ba}(\text{NO}_3)_2$ (see Refs [16, 17]) and the crystal of potassium–gadolinium tungstate $\text{KGd}(\text{WO}_4)_2$ (see works [18, 19]). The former crystal is distinguished for its record-high gain in the nanosecond range and high radiation resistance but is very soft, plastic, and hygroscopic. The latter is mechanically much stronger, possesses a higher thermal conductivity, and admits laser activation by ions of neodymium, erbium, etc. Regrettably, its laser radiation stability turned out to be much worse, as did the peak SRS cross section. However, this did not prevent its use in picosecond lasers.

The first investigations into SRS conversion with $\text{Ba}(\text{NO}_3)_2$ crystals were undertaken in the visible range, the green radiation of the second harmonic of a neodymium laser ($\lambda_L = 532 \text{ nm}$) serving as a pump [20]. The SRS converters made it possible to advance significantly from the pump frequency to the Stokes (yellow and red) spectral region, domain employing multistage conversion [20–22]. One limitation is that SRS converters produce discrete frequencies ($\nu_S = \nu_L - \nu_V$) and wavelengths (560, 598, 639 nm). The SRS converters have a strong competitor in the visible range on the part of dye lasers, which also convert coherent

radiation to the Stokes (relative to the pump) region and in addition permit its wavelength to be tuned over wide limits.

Radically new possibilities are opened up by the anti-Stokes SRS conversion. In the process, additional energy is gained from the thermal crystal vibrations and increases the frequency of the optical radiation (spectral range conversion: red-to-yellow, yellow-to-green, and so forth). However, the efficiency of this process so far is moderate (only a few percent) [21].

The situation in the IR range is different in that there are no good laser dyes with a high quantum yield, photo and thermal stability, while development of each new crystal laser is highly consuming of resources and time. To do this would require the study and the optimization of the dynamics of excitation and oscillation for every spectral range, the development of a new laser crystal, the technology of synthesizing a compound and growing a monocrystal of high optical quality. Here, SRS crystals have a great advantage because they can operate throughout the whole range of optical transparency: from the UV (0.2–0.3 μm) to the IR (2–10 μm) range.

It is pertinent to note that the advance to the IR spectral range is fraught with increasing difficulties, because the SRS-amplification cross section decreases fourfold with a twofold increase in the pump wavelength. As an example, for $\text{Ba}(\text{NO}_3)_2$ the value $g = 47 \text{ cm GW}^{-1}$ for $\lambda = 532 \text{ nm}$, while $g = 11 \text{ cm GW}^{-1}$ for $\lambda = 1064 \text{ nm}$ [23, 24].

By the early 80s, we developed unique tunable lasers for the near IR range employing LIF crystals with F_2^- and F_2^+ color centers [25–27]. Their tuning range in the IR region was bounded by a wavelength of 1.3 μm . To advance further in the IR region, novel SRS-active crystals, $\text{Ba}(\text{NO}_3)_2$ and $\text{KGd}(\text{WO}_4)_2$, were employed.

Investigations [28] showed that $\text{Ba}(\text{NO}_3)_2$ crystals advantageously operate in the near IR range (right up to 1.7 μm) with efficiencies of up to 60% and with intensities of the nanosecond pump well below the threshold of laser-induced damage. A limitation is the intrinsic absorption edge near 1.8 μm , which paves no way for proceeding further to the IR range. For $\text{KGd}(\text{WO}_4)_2$ crystals, the IR transparency domain extends much further (to 5 μm). These crystals also permit the IR radiation to be converted to the Stokes region. However, small gains g and a low radiation resistance retard their application in nanosecond lasers.

The development of SRS lasers employing $\text{Ba}(\text{NO}_3)_2$ crystals enabled us for the first time to extend the spectral range of tunable solid-state lasers to the 1.3–1.7- μm domain and to implement a near IR laser spectrometer complex (0.82–1.66 μm). With its second harmonics (obtained with the use of nonlinear crystals), it spans the visible range (0.42–0.82 μm) and (on repeat frequency doubling or nonlinear frequency mixing) the UV range (0.25–0.45 μm). Thereby implemented was a triple-range (UV, visible, and IR) laser complex involving exclusively crystal laser technologies [14, 27–29].

Interest in SRS lasers next quickened in the early 90s, when lasers found so wide a use that laser accident prevention became a pressing problem. The development of laser technologies safe for human eyes proved to be the most important issue. The standard of the wavelength safe for human eyes was established at $\lambda = 1.54 \mu\text{m}$, whereas the majority of previously developed lasers found themselves in the prohibited wavelength area $\lambda < 1.5 \mu\text{m}$: as an example, the radiation of YAG lasers at 0.53, 1.06, and 1.32 μm , of

ruby at 0.69 μm , alexandrite at 0.78 μm , and Ti:sapphire at 0.7–1.1 μm .

The number of lasers of this kind now runs into the thousands, and huge resources were spent on their development. One way of solving the problem under the present circumstances is to devise small-bulk inexpensive solid-state wavelength converters: for instance, 1.064 \rightarrow 1.5 μm , 1.32 \rightarrow 1.5 μm . We set ourselves this task and fulfilled it over the 1990–1995 period [30–37].

Use was made of SRS-active $\text{Ba}(\text{NO}_3)_2$ crystals 30–50 mm in length and a compact cavity with dichromatic mirrors specifically designed for optimal generation of the first, second, and third Stokes waves. This made it possible to obtain single-mode radiation in new spectral ranges (1.2–1.4 μm , 1.5–1.6 μm), including that safe for human eyes, with a radiation-to-radiation conversion efficiency of 20–50% [30–33].

Recourse to the intracavity pump of an SRS-active crystal, when the pump laser (for example, Nd:YAG) and the SRS laser have one common cavity or two optically coupled cavities, enabled the radiation-to-radiation conversion efficiency to be brought up to 90% [34–37]. In this case, the effect of nonlinear cavity unloading makes it feasible to shorten the pulse and increase its peak power in comparison with the pump pulse. An important additional advantage is that SRS lasers improve the spatial quality of the output laser radiation in comparison with the pump radiation, decrease the beam divergence ('pulse cleansing'), and thus enhance its brightness [13, 31–33, 38].

In parallel with the development of novel SRS converters and IR lasers, we set up and solved a number of problems in the physics of SRS-active vibrational excitations in solids, which determine the nature of light scattering and its properties on the time and spectrum scales. Our work performed in the early 80s made it possible to reveal the complex inhomogeneous nature of the SRS resonance in fused quartz at a frequency of 450 cm^{-1} [39]. Taking advantage of the tunable lasers developed by us from crystals with color centers and of the techniques of biharmonic pump in combination with SRS amplification spectroscopy, we were able for the first time to measure the homogeneous width of inhomogeneously broadened vibrational spectrum of fused quartz. This result is unique in the scientific literature.

Our subsequent series of studies involved elucidation of the nature of anomalously high SRS amplification in $\text{Ba}(\text{NO}_3)_2$ crystals. To study the physics of SRS processes in $\text{Ba}(\text{NO}_3)_2$ at different temperatures (down to liquid-helium temperatures), we resorted to the latest advances in laser spectroscopy — nanosecond SRS amplification spectroscopy with high spectral resolution [40] and transient picosecond spectroscopy of coherent anti-Stokes scattering [41]. It was found for the first time that the completely symmetric high-frequency (1047 cm^{-1}) A_{1g} mode of the NO_3 groups exhibits anomalously low magnitudes of homogeneous and inhomogeneous line broadening ($\Delta\nu = 0.4 \text{ cm}^{-1}$ at room temperature), which is indicative of an anomalously weak coupling to other quasi-molecular and lattice modes [40]. The directly measured dephasing time T_2 of the vibrational A_{1g} mode proved to be surprisingly long (the value $T_2(300 \text{ K}) = 26 \text{ ps}$) and increased nearly tenfold on cooling to liquid-helium temperatures [$T_2(11 \text{ K}) = 220 \text{ ps}$] [41]. These values exceed the T_2 values for diamond, calcite, NaNO_3 , etc. crystals by factors of several tens.

Going above room temperature (up to 400–600 K) results in a more rapid growth of the homogeneous line broadening $\Delta\nu(T)$ and dephasing rate T_2^{-1} , which still lags far behind the line broadening in other matrices. Experimental data on the dephasing rate $T_2^{-1}(T)$ were obtained by two modern techniques (those of RS amplification and picosecond CARS) in the range $T = 11–600$ K. These data were described employing the theory of multiphonon decay, absorption, and dephasing of vibrational excitations in a crystal. The analysis showed that the primary cause for the anomalously long lifetime of the A_{1g} mode in $\text{Ba}(\text{NO}_3)_2$ crystals is the absence of three-phonon decay processes (when one high-frequency RS-active vibration decays into two lower-frequency vibrations) [40, 41]. It is precisely these three-phonon processes that dominate at other frequencies and in other SRS-active materials in the 11–300 K range, determining the high dephasing rates and significant homogeneous line broadening [17].

It turned out that the rate of dephasing in $\text{Ba}(\text{NO}_3)_2$ crystals is caused not only by the allowed four-phonon decay processes $\nu_{1047} \rightarrow \nu_{817} + \omega_{144} + \omega_{81}$, which prevail at low temperatures (4–77 K), but by six-phonon decay processes $\nu_{1047} \rightarrow \nu_{731} + 4\omega_{81}$ as well. The latter, despite a substantially lower probability, exhibit a rapid growth with elevation of temperature and make a significant contribution to the line broadening at above-room temperatures [40, 41].

In connection with the growing use of SRS-active crystals, the diversity of their properties, and the wide scatter in the data available from the scientific literature, in recent years there arose the problem of comparison quantitative analysis of the known SRS-active media and of the search, investigation, and development of novel and more perfect crystals for the generation of SRS.

During the last four years, we made search and comparison investigations involving tens of different crystals, both known ones and potentially useful crystals for solid-state SRS lasers [42–46]. The case in point are the carbonate, nitrate, phosphate, tungstate, niobate, iodate, bromide, borate, and silicate crystals. The frequencies and the linewidths of the most intense quasi-molecular SRS-active vibrations arising from the motion of oxygen ions in the $[\text{CO}_3]$, $[\text{NO}_3]$, $[\text{PO}_4]$, $[\text{ClO}_3]$, $[\text{WO}_4]$, $[\text{NbO}_6]$, $[\text{IO}_3]$, $[\text{B}_3\text{O}_6]$, $[\text{BrO}_3]$, $[\text{SiO}_2]$, $[\text{SO}_4]$, $[\text{NH}_4]$, and $[\text{NbO}_4]$ anion groups were compared.

The relative line intensities (integral and peak) of spontaneous RS were measured for more than 30 synthetic crystals by comparing them with each other and with a reference diamond crystal (100%). They were studied in relation to the crystal orientation with respect to the exciting laser and scattered radiation (see Table 1) [42–44].

It was shown that among the above-listed crystals only the iodate, niobate, and tungstate crystals possess significant integral scattering cross sections for high-frequency RS lines (600–900 cm^{-1}). With the exception of lithium niobate crystals (166%), these values are somewhat lower than for diamond crystals (100%) but are several times larger than the relevant values for the known SRS-active crystals of calcite (6%) and nitrates (20%).

A different situation arises with the peak values of the scattering cross sections, which determine the threshold and the SRS gain in the stationary mode with a nano- and subnanosecond pump duration. The small broadening of RS lines in nitrate crystals results in record peak values (44–63%) even for quite moderate values of the integral cross sections (21–23%).

A consideration of the tabular data shows that the implementation of low-threshold laser SRS frequency converters calls for the production of materials with a large integral RS cross section and a small RS transition broadening. One of the classes which shows promise for the purpose is the class of tungstates, which possess large integral RS cross sections (40–60%) but substantial line broadening: from 5 to 15 cm^{-1} for the presently known crystals.

The processes of decay broadening (similarly to up-conversion and dephasing) of high-frequency SRS-active vibrational modes are due to their interaction with lattice phonon modes. With this point taken into account, we sought to reduce the frequencies of the latter by selecting crystals bearing the heaviest cations in its class.

We undertook a purposeful synthesis [43–44] and investigation of simple alkaline-earth metal (Ca, Sr, and Ba) tungstates with a scheelite structure. As is evident from Table 1, the CaWO_4 crystal frequently encountered in the scientific literature possesses a very modest peak scattering cross section — 18%, which is three times smaller than in the $\text{Ba}(\text{NO}_3)_2$ crystal and even falls short of the value for $\text{KGd}(\text{WO}_4)_2$. This results from the significant broadening of its RS line ($\Delta\nu = 6.95 \text{ cm}^{-1}$). Replacing calcium ions with heavier strontium and barium ions made it possible to moderate the relaxation processes dramatically and narrow the spectral line severalfold — down to 1.63 cm^{-1} at room temperature.

As the cation mass increases, the maximum frequency ω_{lat} of lattice phonons in the crystal does decrease in the series Ca, Sr, and Ba (from 274 to 194 cm^{-1}). In addition, the increase of the lattice constant and the ion radius of a cation result in an elevation of the frequency of a completely symmetric RS-active A_{1g} mode of the $[\text{WO}_4]$ complex (see Table 1). The two factors are responsible for the attenuation of vibron–lattice interactions and a significant narrowing of the RS-active vibration spectrum, which should manifest itself in a growth of the peak scattering cross section and the SRS gain.

We observed the like regularities in the series of alkaline-earth molybdates with a scheelite structure: CaMoO_4 , SrMoO_4 , and BaMoO_4 (see Table 1). The experiments performed made it possible to predict [43] and subsequently to confirm experimentally [44] the existence of record-high peak values of RS cross sections (and then the SRS gains) in the crystals of barium and strontium molybdates and tungstates.

Table 1 shows the relative values of integral and peak scattering coefficients. As is evident, even with broader RS lines, the novel crystals, BaWO_4 and BaMoO_4 , surpass in peak cross section the unique $\text{Ba}(\text{NO}_3)_2$ crystal, while the SrWO_4 and SrMoO_4 crystals approach its values.

The findings of comparison studies of the peak spontaneous RS cross sections were subsequently confirmed by the direct techniques of measuring SRS amplification [45–46] and SRS generation (threshold measurements). This allows us to state with confidence that the newly developed crystals hold much promise for SRS amplifiers and SRS lasers.

The results outlined above, in our opinion, amply demonstrate the potential of laser spectroscopy of spontaneous and stimulated Raman scattering of light for studying the most important physical processes of excitation and relaxation of vibrational states in solids. Moreover, these results allow new crystal materials to be purposefully designed for SRS generators, predicting their properties and applications in laser physics and quantum electronics.

Table 1. Parameters of spontaneous Raman scattering in crystals.

Material	Lattice space group	Molecular group	RS frequency ν_v , cm^{-1}	RS linewidth $\Delta\nu$, cm^{-1}	Integral cross section, rel. units	Peak intensity, rel. units	Scattering and excitation geometry	
							K	E
Diamond	O_h^7	—	1332.9	2.7	100	100	$\parallel C_3$	$\perp C_3$
<i>Nitrates and calcite</i>								
Ba(NO ₃) ₂	T_h^6	[NO ₃]	1048.6	0.4	21	63	$\parallel C_4$	$\parallel C_4$
NaNO ₃	D_{3d}^6	—	1069.2	1.0	23	44	$\parallel C_3$	$\perp C_3$
CaCO ₃	D_{3d}^6	[CO ₃]	1086.4	1.2	6.0	10.6	$\parallel C_3$	$\perp C_3$
<i>Tungstates</i>								
CaWO ₄	C_{4h}^6	[WO ₄]	910.7	6.95	47	18.6	$\perp C_4$	$\parallel C_4$
SrWO ₄ *	—	—	921.5	3	—	—	—	—
BaWO ₄	—	—	926.5	1.63	47	64	—	—
NaGd(WO ₄) ₂ *	—	—	919	14 *	—	—	—	—
NaY(WO ₄) ₂ *	—	—	918	15 *	—	—	—	—
Sc ₂ (WO ₄) ₃ *	—	—	1024	15	—	—	—	—
In ₂ (WO ₄) ₃ *	—	—	1023	13	—	—	—	—
LiIn(WO ₄) ₂ *	—	—	920	8	—	—	—	—
NaSr(WO ₄) ₂ *	—	—	924	2.5	—	—	—	—
Na ₂ WO ₄ *	O_h^7	—	929.2	1.8	—	—	—	—
KGd(WO ₄) ₂	C_{2h}^6	[WO ₆]	901	5.4	50	35	$\perp C_2$	$\perp C_2$
—	—	—	901	5.4	43	30	$\perp C_2$	$\parallel C_2$
—	—	—	768	6.4	19	9.2	$\perp C_2$	$\perp C_2$
—	—	—	768	6.4	59	37	$\perp C_2$	$\parallel C_2$
KY(WO ₄) ₂	—	—	905.6	7	46	35	$\perp C_2$	$\perp C_2$
—	—	—	905.6	7	41	30	$\perp C_2$	$\parallel C_2$
—	—	—	767.4	8.4	17	10	$\perp C_2$	$\perp C_2$
—	—	—	767.4	8.4	58	35	$\perp C_2$	$\parallel C_2$
KYb(WO ₄) ₂	—	—	908	7.4	48	34	$\perp C_2$	$\perp C_2$
—	—	—	908	7.4	48	34	$\perp C_2$	$\parallel C_2$
—	—	—	757	15 **	18 **	13.8 **	$\perp C_2$	$\perp C_2$
—	—	—	757	15 **	58 **	30 **	$\perp C_2$	$\parallel C_2$
<i>Molybdates</i>								
CaMoO ₄	C_{4h}^6	[MoO ₄]	879.3	5.0	64	34	$\perp C_4$	$\parallel C_4$
SrMoO ₄	—	—	887.7	2.8	55	51	$\perp C_4$	$\parallel C_4$
BaMoO ₄	—	—	892.4	2.1	52	64	$\perp C_4$	$\parallel C_4$
<i>Iodates and niobates</i>								
LiIO ₃	C_6^6	[IO ₃]	821.6	5.0	54	25	$\parallel C_2$	$\perp C_2$
LiNbO ₃	C_{3v}^6	[NbO ₆]	872	21.4	44	5	$\parallel C_3$	$\perp C_3$
—	—	—	632	27	166	18	$\perp C_3$	$\parallel C_3$
—	—	—	250	28	—	22	$\perp C_3$	$\parallel C_3$
LaNbO ₄	C_{2h}^3	[NbO ₄]	805	9	22	7.1	$\perp C_2$	$\parallel C_2$
<i>Phosphates</i>								
Ca ₃ (PO ₄) ₃ F	C_{6h}^2	[PO ₄]	964.7	2.8	3.4	3.8	$\perp C_6$	$\parallel C_6$
Sr ₃ (PO ₄) ₃ F	—	—	950.3	2.8	3.4	3.8	$\perp C_6$	$\parallel C_6$
LiPO ₄ *	—	—	951	7.7	—	—	—	—
<i>Miscellaneous</i>								
NaClO ₃ ***	—	[ClO ₃]	937	4.9 **	—	—	—	—
NaBrO ₃ ***	—	[BrO ₃]	799.5	2.5 **	—	—	—	—
NH ₄ Cl ***	O_h^1	[NH ₄]	1712	6	—	—	—	—
—	—	—	3052	85 **	—	—	—	—

Continued Table 1

Material	Lattice space group	Molecular group	RS frequency ν_r , cm^{-1}	RS linewidth $\Delta\nu$, cm^{-1}	Integral cross section, rel. units	Peak intensity, rel. units	Scattering and excitation geometry	
							K	E
<i>Miscellaneous</i>								
NH_4SO_4 ***	—	[SO_4]	976.5	3.5	—	—	—	—
$\text{Ba}_3(\text{B}_3\text{O}_6)_2$	C_{3v}^6	[B_3O_6]	636	4.5	1	0.6	$\parallel C_3$	$\perp C_3$
SiO_2	D_3^6	[SiO_4]	464	7	2.2	1.2	$\perp C_3$	$\parallel C_3$

* Polycrystalline sample.

** Inhomogeneously split line.

*** Unoriented crystal.

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PACS numbers: 42.62.-b, 61.80.Ba

Application of laser-driven shock waves in studies of thermal and mechanical material properties

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Lasers furnish a unique opportunity to study the physical properties of a material at high energy density [1]. As revealed by laser fusion research, for instance, at the center of spherical shell targets exposed to pulse laser radiation it is possible to attain a significant compression of the target material (1000 g cm^{-3}) and to heat it to high temperatures (100 keV).

Under typical conditions, a high-temperature plasma forms at the target surface under laser pulse irradiation. The hydrodynamic plasma expansion is responsible for the