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Spin-alignment and g-factor measurement of the $I^\pi = 12^+$ isomer in ^{192}Pb produced in the relativistic-energy fragmentation of a ^{238}U beam

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Abstract. The feasibility of measuring g-factors using the TDPAD method applied to high-energy, heavy fragmentation products is explored. The 2623 keV $I^\pi = 12^+$ isomer in ^{192}Pb with $\tau = 1.57\,\mu$s has been produced using the fragmentation of a 1 A GeV ^{238}U beam. The results presented demonstrate for the first time that such heavy nuclei produced in a fragmentation reaction with a relativistic beam are sufficiently well spin-aligned. Moreover, the rather large value of the alignment, 28(10)% of the maximum possible, is preserved during the separation process allowing the determination of magnetic moments. The measured values of the lifetime, $\tau = 1.54(9)\,\mu$s, and the g-factor, $g = -0.175(20)$, agree with the results of previous investigations using fusion-evaporation reactions.

1 Introduction

g-factors are sensitive probes of the nuclear wave function which allow detailed tests of model predictions. They can provide reliable information on the single-particle structure of nuclear levels, help to assign spin and parity to the nuclear state, and in favorable cases details of its wave function can be deduced.

Therefore, the feasibility of the g-factor measurements is important, particularly for nuclei far from stability

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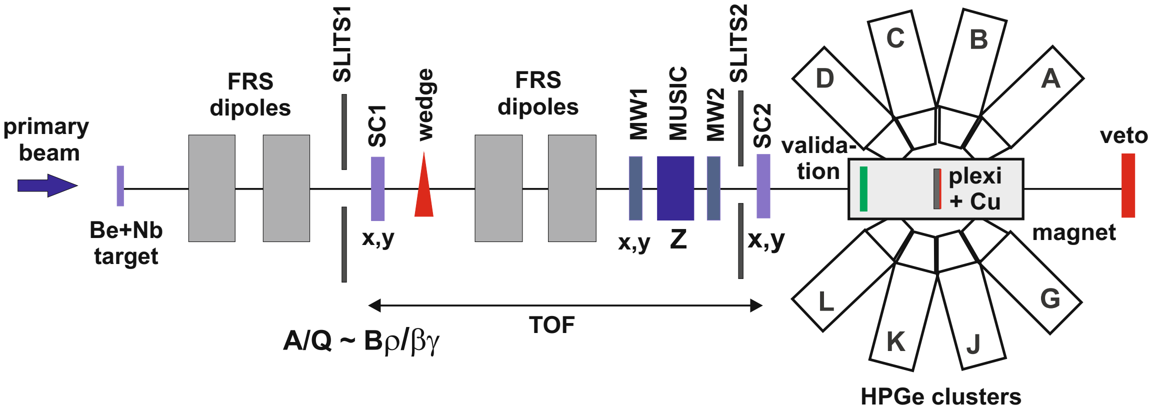

Fig. 1. The experimental set-up: the FRS with the detectors for the isotope selection, the stopper in the center of the magnet, the Ge array and ancillary detectors (validation and veto).

(see *e.g.* [1–4] and references therein) where nuclear structure often does not follow a systematic behavior and experimental observables providing details about the nuclear structure are of great importance. Fragmentation reactions can populate a wide range of exotic nuclei simultaneously, and sophisticated analyzing systems can uniquely separate, select or identify a specific nucleus on an ion-by-ion basis. These nuclei can be implanted into a stopper and, if they have a suitable lifetime (ns to μs), their γ decay can be measured and correlated with the ions implantation time. If the spin orientation induced in an ensemble of nuclei by reaction is not isotropic, but spins are oriented preferentially along or perpendicular to the beam direction ("spin-aligned") also their Larmor precession in an applied magnetic field can be measured and the g-factor determined.

Fragmentation reactions have been employed rather in few experiments for investigations of electromagnetic moments in isomeric states in light and medium mass nuclei [1,2,5–7]. The mechanism by which the nuclear spin-alignment or polarization is produced in such processes is only partly understood [5,6,8,9]. The spin orientation of nuclei produced in the reaction can be reduced or even lost due to the hyperfine interaction with its randomly oriented electron spin during the flight path through the mass separator. By producing fully stripped nuclei and maintaining them fully stripped all the time when passing through the analyzing system —with magnets, particle detectors and absorbers— the nuclear spin orientation can be preserved [1,2,5,6].

To conserve a high fraction of the spin-alignment, the beam impinging on the stopper has to be of very high energy. As hyperfine interactions posses Z^3-dependence [10], their effect on destroying the spin-alignment will be much more severe for heavy nuclei. For isotopes of $A \approx 200$ this requires production of fragments with an energy higher than $\approx 250\,A\,\mathrm{MeV}$ up to the last piece of solid material before the perturbation free stopper (*e.g.* made from copper material). In consequence, a high fraction of fully stripped ions is preserved, since the probability for picking-up electrons is inversely proportional to the fragments velocity.

In addition, even for not fully stripped ions, in the present case the effect of static hyperfine interactions is limited. As discussed by Nordhagen *et al.* [11], in the absence of external fields, the total spin $\boldsymbol{F}$, which couples the nuclear spin $\boldsymbol{I}$ with the atomic spin $\boldsymbol{J}$, is conserved. For a high-spin isomer, $\boldsymbol{I} \gg \boldsymbol{J}$ so $\boldsymbol{I}$ is kept almost parallel to the total spin $\boldsymbol{F}$ when the external field acts on $\boldsymbol{J}$.

So far, successful measurements of magnetic moments with the fragmentation reactions have only been performed for nuclei around Ni and some lighter nuclei. Only very recently, we have undertaken such experiments within the gRISING campaign at GSI, for the measurement of the g-factor in ^{127}Sn [3] and, presently, for ^{192}Pb. Such fragmentation reactions may become an essential tool to investigate heavy nuclei far off the stability line.

The latter case, presented in this paper, is to stress upon the feasibility test for such measurements in the Pb region using U-fragmentation. To obtain information on alignment preserved in this type of experiment, the g-factor of the 12^+ isomer at 2623 keV in ^{192}Pb has been measured with the fragmentation of a $1\,A\,\mathrm{GeV}$ ^{238}U beam and compared to the known value determined before in a fusion-evaporation reaction [12,13].

2 Experiment

The experiment was performed at the SIS/FRS facility in GSI. A ^{238}U primary beam at an energy of $1\,A\,\mathrm{GeV}$ bombarded an $1.023\,\mathrm{g/cm^2}$ ^{9}Be production target backed by a $0.221\,\mathrm{g/cm^2}$ Nb stripper foil to increase the fraction of fully stripped ions. The target thickness was chosen not to influence significantly the momentum spread. Pb isotopes were produced via fragmentation and separated using the FRagment Separator (FRS) [14] presented schematically together with the associated detectors in fig. 1. The beam intensity was ca. 10^8 pps, and the rate of the ions implanted into the catcher reached in average about 60 pps per Pb isotope. (The time for the measurement was about 47 hours excluding the time for setting up the apparatus and calibrations.) The ions were identified event-by-event using several detectors to determine position (multiwire counters —MW1 and MW2), atomic number Z (MUSIC —ionization chamber) and time of flight (fast scintillators —SC1 and SC2— measuring also the position) [15]. Mass identification was performed by measuring both the magnetic rigidity ($B\rho$) and the velocity obtained from time of flight. The scintillators were placed at the middle and the final focal planes of the spectrometer. The measured position of ions *versus* A/Q, in both foci (see fig. 3 for the final focus SC2), enabled the fragments to be identified and allowed the selection of the isotopes of interest ion-by-ion. For more details about the identification procedure see, for example, ref. [16].

In the present experiment, the primary beam energy of $1\,A$ GeV was high enough to produce Pb ions with a remaining energy of $\approx 290\,A$ MeV just before the stopper. As a result 90% of the ^{192}Pb ions was fully stripped at the final focal plane, reducing the chance of a substantial loss of alignment by hyperfine interactions.

The spin-alignment of ions produced in fragmentation reactions is correlated with the momentum of the products [5]. Nuclei with lower (or higher) momentum than the mean of the momentum distribution correspond to fragments to which the linear momentum has been transferred either parallel or antiparallel to the beam direction. The angular momentum of the outgoing nucleus, calculated empirically as the vector product of the impact parameter and transferred momentum, is about perpendicular to the beam as in fusion-evaporation reactions, so the low values of magnetic substate $|m|$ prevail. This constraint does not apply to the nuclei with momentum around the mean value, consequently substates with higher values of $|m|$ can be populated. Gamma angular distributions generated by nuclei with different selection of momentum may then have, in an extreme case, even opposite concavity. Those two types of alignment may lead, if not separated, to a cancellation of the measured anisotropy of the γ-radiation. So, in order to increase the effect of the spin-alignment of the selected ^{192}Pb nuclei, a cut was imposed on the momentum distribution. This was done by closing the slits (denoted SLITS1 in fig. 1) asymmetrically (to the positions 0 and -20 mm) to select the low momentum tail of the distribution, *i.e.* ions possessing spins about perpendicular to the beam direction. Such measurement condition was required also to reduce the counting rate for the detector SC1. The momentum distribution calculated with the LISE++ code [17,18] for open and closed slits is presented in fig. 2.

The incoming ions were slowed down in a 2 cm Plexiglas ($(C_5O_2H_8)_n$) plate which was glued to a 2 mm Cu foil that served as a perturbation-free host for the stopped nuclei (see [1,2]). The copper stopper had been annealed prior to the experiment. The stopper was placed in the center of the magnet providing a vertically oriented external magnetic field $B = 0.160(1)$ T (measured by the Hall probe). The polarization of the magnetic field was alternated up and down every three hours. The stopper was surrounded by 8 HPGe detectors from the RISING set-up [15], placed at $\pm 45°$, $\pm 75°$, $\pm 105°$ and $\pm 135°$, to measure delayed γ-rays from the isomeric decay. An additional scintillator was placed at the entry to the magnet (validation detector) to select only the ions incoming to the magnet. A veto detector placed after the magnet served to monitor nuclei that had not been stopped and reject the coincident γ-rays.

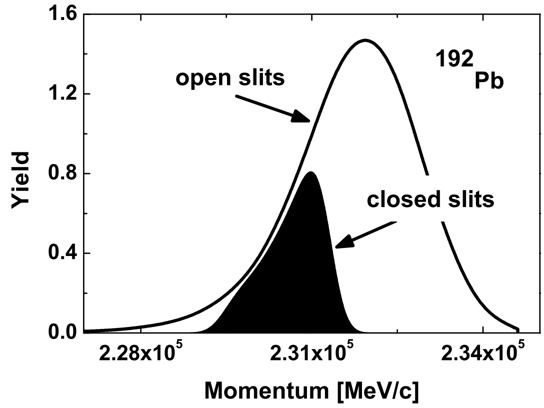

Fig. 2. The momentum distribution of ^{192}Pb calculated using the LISE++ code at the SC1 position for open (line) and closed (black area) SLITS1. The beam energy was $\approx 590\,A$ MeV at this point.

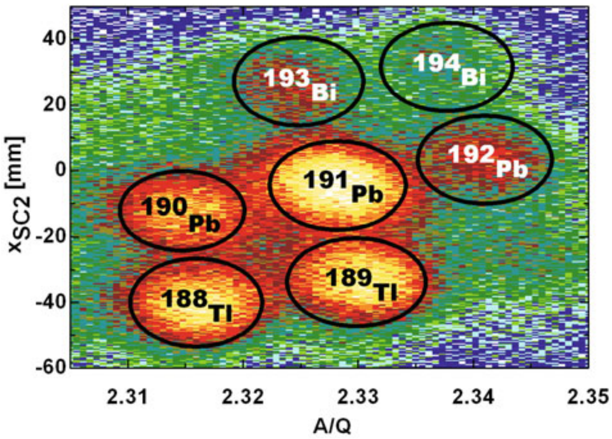

Fig. 3. The isotopes produced in ^{238}U beam fragmentation reaction selected at the final focus of the FRS.

The data analysis of the separated isotopes was performed with the use of the SPY/CRACOW software [19]. The result of the selection obtained at the final focus plane of the FRS (SC2) is shown in fig. 3. Since the FRS was set up to choose only the lowest part of the momentum distribution of the ^{192}Pb ions, the observation of other nuclides —mainly ^{191}Pb— is relatively enhanced. To analyze the γ-rays associated with ^{192}Pb, the appropriate two-dimensional gate on the SC2 position *vs.* A/Q was set. N.B.: with the time settings used in our experiment no significant isomeric γ transitions were present for gates set on other than ^{192}Pb isotopes visible in fig. 3.

3 Analysis

The Larmor precession frequency of the isomeric spins is $\omega_L = g\mu_N B/\hbar$, where g is the nuclear gyromagnetic factor, μ_N is the nuclear magneton, and B is the strength of the external magnetic field. For a state with a μs isomeric

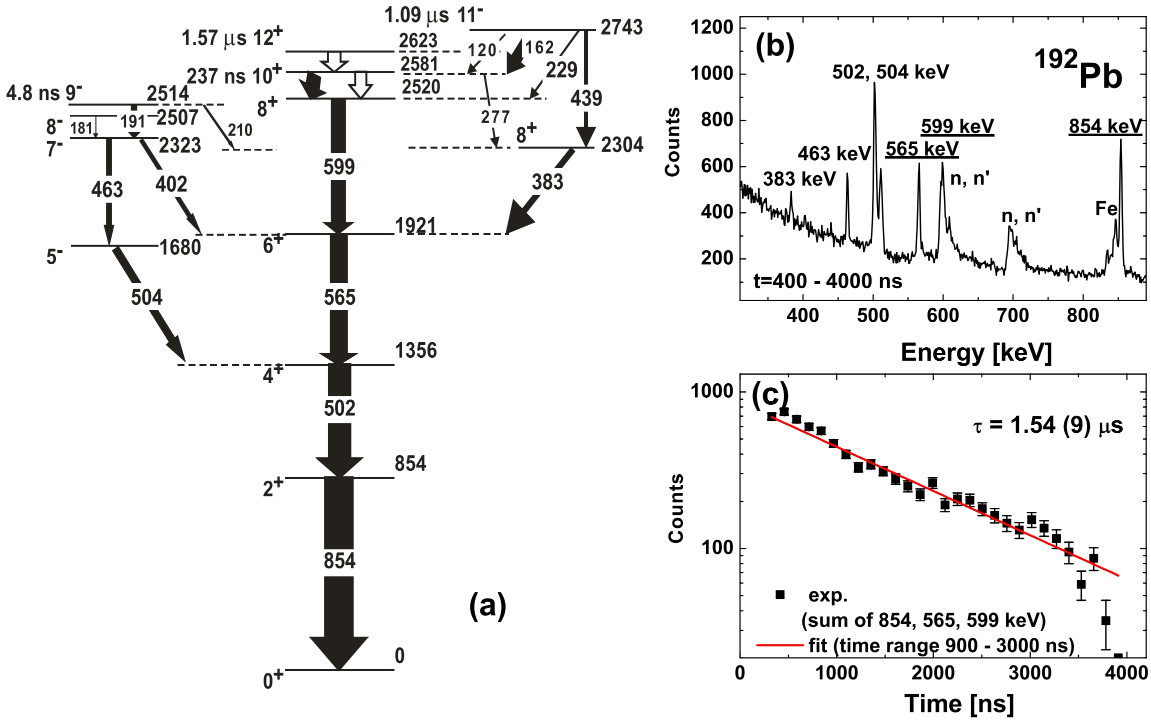

Fig. 4. (a) Partial level scheme of ^{192}Pb and intensities taken from ref. [21]. (b) The delayed γ-ray energy spectrum associated to the 12^+ isomeric state decay in ^{192}Pb. (c) The time spectrum obtained by gating on $E2$ γ transitions 599, 565 and 854 keV with the fit determining the lifetime.

lifetime, such as the $I^\pi = 12^+$ isomer in ^{192}Pb, the ω_L can be measured by the Time Differential Perturbed Angular Distribution (TDPAD) method [20,1] since it is most suitable for investigation of g-factors of isomeric states with lifetimes in the $\tau = 10\,\text{ns}$–$100\,\mu\text{s}$ range. In this method, the Larmor frequency is observed as a modulation of the time spectra of the isomeric decay. The known field B and ω_L evaluated from the time spectra provide the g-factor.

As a result of the experiment described in sect. 2, the time spectra of decaying nuclei measured in coincidence with the appropriate γ-ray energies were obtained. The delayed (for a time of $400\,\text{ns} < t < 4\,\mu\text{s}$) γ-ray energy spectrum with the indicated energies of γ-rays from the decay of ^{192}Pb is shown in fig. 4b. At shorter delay times the spectrum was not analyzed as it was affected by the atomic bremsstrahlung [15] caused by the stopping of the high-energy ($\approx 290\,A\,\text{MeV}$) ions in the Plexiglas plate. The time spectra for the g-factor evaluation were obtained gating on the 599, 565 and 854 keV stretched $E2$ transitions (cf. the partial level scheme in fig. 4a). The statistics from the individual detectors was too small to determine the g-factor. Therefore we choose four detectors which could be used to obtain $R(t)$ according the formula given in the next section. Summed time spectra for the aforementioned transitions were obtained for the detectors (denoted A, L, D, and G in fig. 1) at $\pm 45°$ and $\pm 135°$ and both field directions. One common background spectrum was generated as the total projection on the time axis of the γ energy *versus* the γ time matrix. This spectrum was subtracted from the individual time spectra associated with each considered γ transition after normalizing its intensity to the background under the respective γ line in the energy spectrum.

The sum of the background-subtracted time spectra (fig. 4c) was fitted by an exponential function giving a lifetime of $\tau = 1.54(9)\,\mu\text{s}$ for the $I^\pi = 12^+$ isomer in ^{192}Pb in agreement with the value measured in fusion-evaporation reactions ($1.57(6)\,\mu\text{s}$ [21,22]).

4 Results and discussion

From the time spectra measured with the detectors denoted A, L, D, and G (see fig. 1), and the two opposite directions of the magnetic field, the two combined spectra were obtained: $a = A\uparrow + L\uparrow + D\downarrow + G\downarrow$, $b = A\downarrow + L\downarrow + D\uparrow + G\uparrow$ (see [23] for more details). In this notation, letters mean spectra taken with given HPGe detectors while arrows show the directions of the magnetic field, *e.g.* A↑ is the time spectrum measured with detector A (at 45°) with the field vector pointing upwards.

From these spectra the experimental ratio $R(t)$ defined as $R(t) = \frac{a-b}{a+b}$ was created which for the chosen detector angles ($90° \pm 45°$) is described by the function $R(t)_{th} = \frac{3A_2B_2}{4+A_2B_2}\sin(2\omega_L t)$ that contains only the angular-distribution coefficients A_2B_2 and the Larmor frequency. The A_4B_4 term of the angular distribution was neglected.

The experimental $R(t)$ data were fitted by $R_{fit} = A\sin(2\omega_L t - \phi)$ using the χ^2 minimization procedure. The

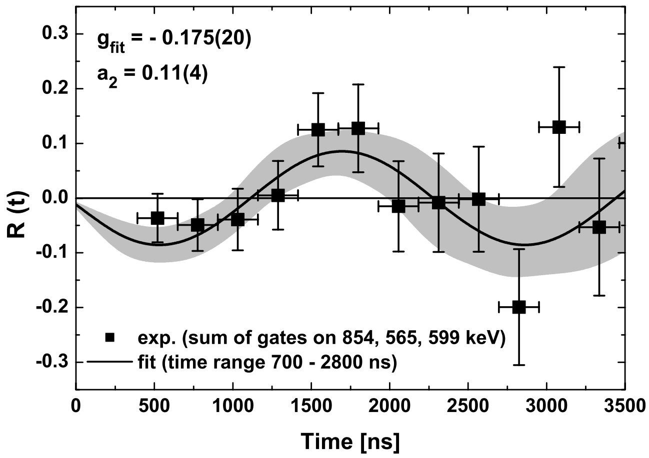

Fig. 5. The experimental $R(t)$-function (filled squares) and the result of the fit (solid line) (see the text for explanation). The quality of the fit is shown by the uncertainty depicted as a shaded area around the fitting function. This region represents all possible $R_{fit}(t)$-functions calculated for parameters ω_L, A and ϕ within the error limit obtained from the fit.

fit function $R_{fit}(t)$ included a phase ϕ which should be zero if one uses a zero-degree spectrometer (such as the FRS) and if only a single isomer is involved. In the ^{192}Pb case the γ cascade from the 12^{+} state passes through the also isomeric 10^{+} state with $\tau = 237$ ns. However, as the dominant wave function configuration of both the 12^{+} and 10^{+} isomers is the neutron $i_{13/2}^{-2}$ [12,13], both states have very similar g-factors, and consequently the nuclei in both isomeric states precess with the same frequency. Therefore no phase shift in the $R(t)$-function is expected.

The experimental $R(t)$-function is presented in fig. 5 together with the best fit curve. The amplitude, frequency and phase obtained from the fit to the experimental data are $A = 0.087(30)$, $\omega_L = 0.00135(16)\,\mathrm{ns}^{-1}$ and $\phi = 0.14(50)^{\circ}$, respectively.

From the ω_L value for $B = 0.16$ T, the g-factor, $g_{fit} = -0.175(20)$, was deduced. The negative sign of the g-factor comes from the negative value of the $R(t)$-function for the first half-period of the oscillation (see fig. 5) and from the $A_2 > 0$ values of the stretched $E2$ transitions chosen to obtain $R(t)$. The deduced g-factor is in agreement with the value $-0.173(2)$ measured in fusion-evaporation reactions [12,13]. Also the fitted phase is zero within the error bars $(0.1(5)^{\circ})$ as it is expected.

The possible influence of the higher-lying 11^{-} isomer on the perturbed $R(t)$ pattern, and on the deduced g-factor value, is negligible. The most intense 162 keV transition as well as the 439 keV γ-ray which directly feeds the 8^{+} level at 2304 keV excitation energy (see fig. 4a), are not observed. The presence of the 383 keV transition de-exciting the 8^{+} state can be understood as arising from the population of this state through the 12^{+} decay.

The main result of the present work is the value of the amplitude, A, of the fit function $R_{fit}(t)$, which gives the amount of preserved alignment after the implantation [24]. It contains information on the coefficient $a_2 = A_2 B_2$, where A_2 is the angular-distribution coefficient (which depends on the multipolarity of the transition) while B_2 is the orientation parameter (depending on the orientation mechanism and the spin of the nuclear state). The obtained $a_2 = 0.11(4)$, calculated from the measured $A = \frac{3a_2}{4+a_2}$, can be compared to the value corresponding to the maximum possible angular-distribution coefficient in a stretched $E2$-cascade, *i.e.* for full alignment of the 12^{+} isomer. This value, taken from Yamazaki [25], is $a_{2max} = 0.40$. Comparing them one can say that the alignment remaining after production, transportation, selection and implantation is around $28\% \pm 10\%$ of the maximum. It is sufficiently large, as can be judged from fig. 5, to apply the TDPAD method for determining a g-factor.

5 Summary

We have presented the results of the g-factor measurement with the TDPAD method for the 12^{+} state in the ^{192}Pb nucleus produced in a fragmentation reaction using a relativistic beam. The obtained values of the lifetime and g-factor of this state are in satisfactory agreement with the previous results of measurements using fusion-evaporation reactions [12,13,21,22]. This was the first g-factor measurement for such heavy mass nucleus produced in fragmentation reaction. Up to now similar measurement was done for the much lighter ^{127}Sn [3], but without deriving information on the alignment. The main aim of the present experiment was to check if for very heavy nuclei produced in fragmentation reactions of the relativistic beam a sufficient alignment can be produced and preserved until the ions are stopped. This has clearly been proven.

The obtained value of the coefficient $a_2 = 0.11(4)$, containing information on alignment, might be compared with the result $a_2 = 0.30$ for the fusion-evaporation reaction [12,13] and the maximum possible value $a_2 = 0.40$ for stretched $E2$ transitions and complete alignment [25]. The achieved value can be also related to the alignment measured for medium mass nuclei produced in the fragmentation of intermediate projectile energy [2,6] and found to be around 15%.

The alignment obtained in the present work for ^{192}Pb proves the feasibility of the g-factor measurement for very heavy nuclei, using fragmentations of relativistic beams. It shows that such reactions can indeed be used as a key tool in investigations of electromagnetic moments of heavy nuclei far from the stability line, probably also for nuclei with extreme neutron-to-proton ratios. Very low cross-sections for the reaction channels to reach those exotic nuclei can be overcome by increasing the intensity of the primary beam (what will be possible at FAIR facility) and the use of the more efficient detector arrays.

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