Absolute level widths in ^{27}Al below 4 MeV

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A nuclear self-absorption measurement was carried out on the nucleus ^{27}Al with a bremsstrahlung photon-beam endpoint energy of 4.2 MeV. For a number of states, commonly used as calibration standards in photon-scattering (NRF) experiments, the self absorption was measured. Thereby the level widths and lifetimes were determined absolutely. In addition it was found that the level energy of the 2212.01-keV level deviates from the literature value.

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In the last decade experiments with continuous-energy photon beams resulting from bremsstrahlung have proven to be a very useful tool in nuclear physics. Valuable results have been achieved with bremsstrahlung experiments, e.g., in nuclear resonance fluorescence (NRF) experiments [1–4] as well as with photoactivation of x-ray isomers [5,6] regarding their importance for possible γ-ray lasers [7] or for interstellar nucleosynthesis [8]. An accurate data analysis for these experiments always requires a detailed knowledge of the photon flux used for the excitation. However, a simple closed formula able to describe the spectral behavior of a bremsstrahlung beam does not exist for energies between 1 and 20 MeV. Only the Schiff formula [9] which was deduced in the limit of an infinitesimally thin bremstarget is able to describe the spectral intensity of a part of such beams under small angles quite well [10,11].

In most bremsstrahlung experiments it is therefore necessary to carry out an independent photon flux calibration. For that purpose photons are resonantly scattered off nuclei whose excited states have well-known ground-state decay widths of several meV. The observed resonance scattering intensity N is proportional to the resonance scattering cross section σ and to the beam intensity Φ_b at the resonance energy,

$$N(E) \propto \Phi_b(E)\,\sigma(\Gamma)\ . \tag{1}$$

The energy-integrated cross section is approximately a linear function of the level width Γ. The relative beam intensity can now be measured at some nuclear resonance energies if the widths of those "calibration states" are known.

In NRF experiments this relative photon-flux calibration is done simultaneously with the actual measurement. Therefore, the nucleus which is used for calibration has to fulfill certain requirements. It must be stable and it must have several states with large resonance cross sections, i.e., with large total widths Γ and large ground-state branching ratios Γ_0/Γ in the considered energy range. It should have a small nuclear charge Z to minimize the nonresonant background which scales with Z^2. All these conditions are fulfilled by the only stable aluminum isotope ^{27}Al. Hence ^{27}Al has been used as a calibration standard in many (γ,γ') experiments in the energy range 2 – 5 MeV.

Absolute values for the natural widths of some of the ^{27}Al states have been measured since the early 1960s [12,13]. These data have largely been used in NRF experiments as a calibration standard. But recently a discrepancy between similar well-established literature values and newly determined experimental widths for ^{13}C was discovered [14]. Therefore, the importance of the ^{27}Al data for the lifetimes determined in NRF experiments made a new measurement of ^{27}Al highly desirable.

The measurement of the nuclear self-absorption of the nuclear states [15,16] offers a method for determining their widths independently of any photon-flux calibration. The self-absorption experiment was carried out at the well-established bremsstrahlung facility of the Stuttgart Dynamitron accelerator as described below.

It is possible to determine the natural level width Γ by measuring the cross section for photons elastically scattered off this resonance. But the determination of the absolute intensity of the photon beam with the necessary accuracy is rather difficult [17]. Therefore, it is easier to carry out a relative measurement. The beam intensity passed through an ^{27}Al absorber at the resonance energy is compared to the intensity passed through an absorber without such a resonance. If both the absorbers show the same atomic attenuation, i.e., photoeffect, Compton effect, and pair production, then the stronger reduction of the beam intensity at the resonance energy with the ^{27}Al absorber is only due to resonance absorption.

Figure 1 shows a schematical drawing of the experimental setup. The bremsstrahlung beam from the radiator target passes through the absorber and hits the NRF scattering target consisting of a piece of aluminum. The scattered photons are detected by high-resolution Ge detectors. The number of resonantly scattered quanta detected is proportional to the beam intensity at resonance energy. Because of resonance absorption by ^{27}Al-nuclei, the scattering intensity is less with the aluminum absorber. The cross section of the resonance absorption is determined by comparing the areas of the resonance scattering peaks for the cases of resonant and atomic attenuation. That means that by measuring the nuclear self-absorption the resonance cross section and thus the

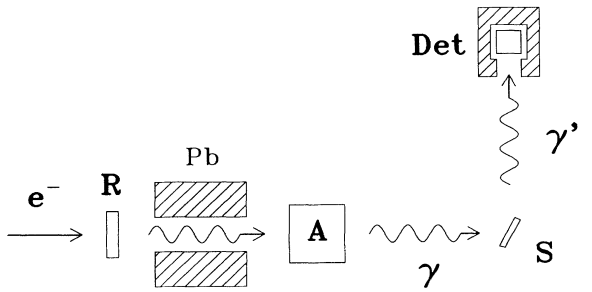

FIG. 1. Schematic drawing of a self-absorption measurement. The electron beam with an energy of 4.2 MeV is stopped in the radiator target (R) where the continuous spectrum of bremsstrahlung is produced. The absorber (A) attenuates the photon beam by its atomic absorption and in the case of the ^{27}Al absorber additionally by its resonant absorption. This modified photon beam irradiates the scatterer (S). The scattered photons are observed by lead-shielded high-resolution Ge γ detectors.

level width Γ can be deduced. The functional relation between Γ and the self-absorption will be clarified in the following.

The nuclear self-absorption R is defined as the normalized difference of the resonance scattering intensities $N_{\rm res}, N_{\rm at}$ while either the resonant or the atomic absorber attenuate the beam in front of the scatterer, as denoted by subscripts in the following,

$$R = \frac{N_{\rm at} - N_{\rm res}}{N_{\rm at}} \ . \tag{2}$$

The atomic absorption of both absorbers is supposed to be equal. But this is an idealized demand. The self-absorption is actually measured by comparing the detected peak areas $A_{\rm res}$ and $A_{\rm at}$ normalized to the beam charge that has been stopped in the radiator target and corrected for the relative atomic absorption $g = \exp[-(\mu d)_{\rm at}]/\exp[-(\mu d)_{\rm res}]$ of the different absorbers that ideally should be equal to 1 and actually was about 0.99,

$$R = 1 - g\,\frac{A_{\rm res}}{A_{\rm at}} \ . \tag{3}$$

On the other hand, the self-absorption is calculated as a function of the natural state width Γ,

$$R(\Gamma) = 1 - \frac{I_\Gamma(\bar{n}_{\rm res} + \bar{n}_{\rm sc}) - I_\Gamma(\bar{n}_{\rm res})}{I_\Gamma(\bar{n}_{\rm sc})} e^{\bar{n}_{\rm res}\kappa} \ . \tag{4}$$

Here $\bar{n}_{\rm res}$ and $\bar{n}_{\rm sc}$ denote the target thicknesses of the resonant absorber and the scatterer, respectively. The integral $I_\Gamma(\bar{m})$ can be written explicitly as

$$I_\Gamma(\bar{m}) = \sqrt{\pi} K' \bar{m} \sum_{i=0}^{\infty} \frac{(-K'\bar{m})^i}{(i+1)!} \times \sum_{j=0}^{i} \frac{1}{\sqrt{j+1}} \binom{i}{j} \left(\frac{\kappa}{K'}\right)^{i-j} , \tag{5}$$

where $K' = K/f$ while $K = \frac{\sqrt{\pi}}{2}\sigma_0 \frac{\Gamma}{\Delta}$ denotes the resonance absorption attenuation coefficient. The factor f is a first-order correction to the approximation of the Doppler-broadened resonance absorption cross section $\sigma_a(E) = \sigma_0 \Psi(x,t)$ by the Doppler cross section $\sigma_a^D(E) = K \exp[-(\frac{E-E_r}{\Delta})^2]$ that is only valid in the limit $\Gamma \ll \Delta$. If this is not the case, then σ_a^D overestimates the true cross section σ_a near the resonance energy where the main part of the self-absorption happens. Therefore f is defined as

$$f = \frac{\int_{E_r-\Delta}^{E_r+\Delta} \sigma_a^D(E)dE}{\int_{E_r-\Delta}^{E_r+\Delta} \sigma_a(E)dE} \ . \tag{6}$$

Only for the levels at 2982 and 3957 keV is a value of $f = 1.01$ used. In all other cases the deviation of f from unity is negligible compared to experimental errors. Also an angular dependence of the self-absorption due to different path lengths through the scatterer material is neglected because its influence is less than 0.5%.

The nuclear self-absorption experiment on ^{27}Al was performed at the bremsstrahlung facility of the Stuttgart Dynamitron accelerator [18]. Electrons were accelerated to an energy of about 4.2 MeV. This cw beam with currents of 150–200 μA hit a radiator target consisting of a water-cooled 4-mm-thick gold block completely stopping the electrons. The low-energy photon flux was attenuated by a beam hardener of 3 mm lead. The beam was defined by a lead collimator of 98 cm length with a 10 mm bore, through which it entered the well-separated experimental area. There the photon cone penetrated the

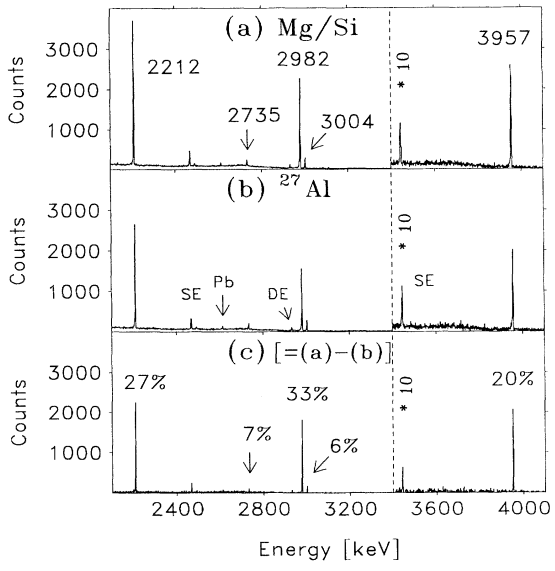

FIG. 2. Photon scattering spectra off ^{27}Al with atomic (a) and resonant absorber (b). In the energy range above 2 MeV one observes five nuclear resonances at 2212, 2735, 2982, 3004, and 3957 keV. There are also three single and one double escape peaks and a Pb peak from the background visible in the spectra. The difference of these resonance scattering intensities (c) is proportional to the relative number of photons resonantly scattered off the ^{27}Al absorber. The corresponding self-absorption (in %) is indicated in the figure.

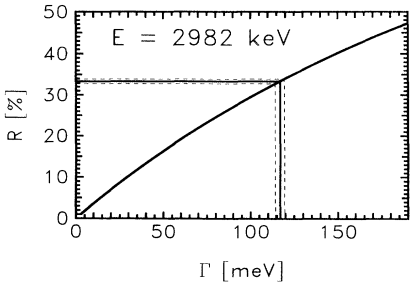

FIG. 3. Determination of the width of the nuclear state at 2982 keV. The measured self-absorption R is compared to the calculated curve using (4). The dashed lines indicate the experimental errors.

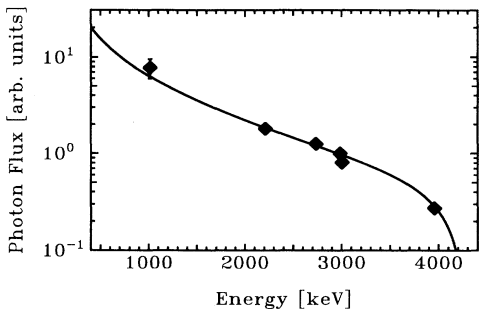

FIG. 4. Shape of the thick target bremsstrahlung spectrum at the Stuttgart facility. The squares indicate ^{27}Al calibration points obtained from a ^{27}Al photon scattering spectrum using (1) and the values given at the bottom of Table I. The solid curve displays a fit to the data using the Schiff formula [9]. The end point energy and a normalization factor have been treated as free parameters.

absorbers used in the respective experimental sections. The resonant absorber consisted of an Al disk [0.1447(6) atoms/barn ^{27}Al]. At resonance energy the beam attenuation was due to both atomic and resonant absorption. For comparison an atomic absorber was used consisting of 0.0770 atoms/barn Mg and 0.0738 atoms/barn Si. Behind the absorber the beam irradiated the ^{27}Al scatterer with a thickness of 0.0367 atoms/barn. For 2 weeks photon scattering spectra were taken by three (HP)Ge detectors located under angles of about 90°, 130°, and 150° relative to the incident beam axis. Figure 2 shows the energy range from 2 MeV to the end point of two spectra from the 130° detector without any background subtraction. Very sharp resonance lines with peak areas of up to 12 000 counts can be seen in these photon scattering spectra.

In Fig. 2 the upper spectrum was obtained while the atomic absorber attenuated the beam and the middle one while the resonant absorber attenuated the beam. The histograms are normalized to the beam charge stopped in the radiator target. For every level the resonance scattering intensity is less for the ^{27}Al absorber because of its resonant absorption. The amount of this resonance absorption can be seen if one compares the observed resonance scattering intensities. The lower panel of Fig. 2 shows the difference of the spectra above. This difference is proportional to the number of photons which were resonantly absorbed in the ^{27}Al absorber and so proportional to the self-absorption. Its measured value is indicated in Fig. 2 (see also Table I).

With Eq. (4) the measured self-absorption was fitted by varying the level width Γ. For example Fig. 3 shows the determination of the level width for the state at 2982 keV excitation energy. The solid curve was numerically computed using Eq. (4) and the specific data of this state, e.g., spin, excitation energy, ground-state decay branching ratio, Doppler width, and atomic absorption at that energy. The experimentally observed self-absorption is marked as a horizontal line. The corresponding level width is indicated by the vertical line. All results are summarized in Table I.

The absorbers used were designed to get as precise results as possible in the limited measuring time for those ^{27}Al levels having ground-state transitions most strongly excited in nuclear resonance fluorescence experiments. Therefore, the precision of the measured level widths for the 2212 keV and the 3957 keV states is comparable to that of the adopted value of all older measurements. The precision of the most important calibration state at 2982 keV could be increased by a factor of 2. In all cases studied in this paper the literature values agree with the measurement. Therefore, this finding confirms the data evaluation in all bremsstrahlung experiments using ^{27}Al

TABLE I. For six ^{27}Al levels below 4 MeV the nuclear self-absorption was measured. The determined level widths and lifetimes $\tau = \hbar/\Gamma$ confirm the literature values in all cases. The last row displays an error-weighted mean value from the results of this measurement and the literature data (recommended best values). The level energy 2212.01(10) which we obtained deviates from the literature.

E	[keV]	1014.45(3)	2212.01(10)	2734.9(7)	2982.00(5)	3004.2(8)	3956.8(4)
R	[%]	10(12)	26.56(58)	7.1(28)	33.34(59)	5.6(23)	19.9(17)
τ^a	[fs]	> 240	38.1(10)	14(6)	5.63(13)	93(39)	3.94(40)
Γ^a	[meV]	< 2.7	17.29(46)	46(19)	116.9(27)	7.1(30)	167(17)
$\Gamma_{lit}{}^b$	[meV]	0.306(15)	17.14(40)	51(7)	115(6)	7.74(46)	183(15)
Γ^c	[meV]	0.306(15)	17.19(31)	51(7)	116.7(25)	7.74(46)	177(11)

[a]This work.
[b]See [13].
[c]Weighted mean value from a and b.

for photon-flux calibration purposes.

Additionally we ran a NRF measurement on ^{27}Al with simultaneous ^{56}Co energy calibration to increase the precision of the level energy of the level at 2212 keV. We obtained a recoil-corrected level energy of 2212.01(10) keV that is displayed in Table I together with the literature values from the Nuclear Data Sheets for the other levels. This value disagrees with the previously published [13] value of 2211.1(6) keV.

The shape of a typical bremsstrahlung spectrum used for nuclear resonance fluorescence experiments in Stuttgart is shown in Fig. 4. The data points have been obtained using a photon scattering spectrum of ^{27}Al, the values given at the bottom of Table I and Eq. (1). The solid curve displays the prediction of the Schiff formula.[1] Only two parameters representing the end point energy and a normalization factor were used in a fit to the data that cover a range of nearly two orders of magnitude.

In conclusion we want to state that the measurement of the nuclear self-absorption yields high-precision data of level widths and therefore of the lifetimes of very short-lived nuclear states. For five nuclear states of ^{27}Al the lifetime could be deduced from nuclear self-absorption. The literature values agree in all cases within the experimental errors and the precision of the data could be increased. No systematical error has been made in recent bremsstrahlung experiments using those values for ^{27}Al photon-flux calibration. The photon spectrum at the Stuttgart bremsstrahlung facility can be described to a good approximation as a simplified Schiff spectrum.

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[1] In the derivation of the formula we neglect the recoil of the nucleus which scatters the incident electron.

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