# On masses of narrow $\Upsilon$ states

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# Outline: masses of narrow $\Upsilon$ states

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## $\Upsilon(1S)$ MASS

| *VALUE* (MeV) | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|
| **9460.30±0.26 OUR AVERAGE** | Error includes scale factor of 3.3. | | |
| 9460.51±0.09±0.05 | [1] ARTAMONOV 00 | MD1 | $e^+e^- \rightarrow$ hadrons |
| 9459.97±0.11±0.07 | MACKAY 84 | REDE | $e^+e^- \rightarrow$ hadrons |

Discrepancy of $3.25\sigma$!

## $\Upsilon(2S)$ MASS

| *VALUE* (MeV) | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|
| **10023.26±0.31 OUR AVERAGE** | | | |
| 10023.5 ±0.5 | [1] ARTAMONOV 00 | MD1 | $e^+e^- \rightarrow$ hadrons |
| 10023.1 ±0.4 | BARBER 84 | REDE | $e^+e^- \rightarrow$ hadrons |

## $\Upsilon(3S)$ MASS

| *VALUE* (MeV) | *DOCUMENT ID* | *TECN* | *COMMENT* |
|---|---|---|---|
| **10355.2±0.5** | [1] ARTAMONOV 00 | MD1 | $e^+e^- \rightarrow$ hadrons |

[1] Reanalysis of BARU 92B and ARTAMONOV 84 using new electron mass (COHEN 87).

Problems:

- Incorrect radiative correction accounting in
  W. W. MacKay *et al.*, PRD **29**(1984),2483 (CUSB@CESR),
  D. P. Barber *et al.*, PLB **135**(1984),498 (ARGUS+CB@DORIS)
- Use of obsolete electron mass value in these two works
- Ignoring of the interference effect in all three measurements
- Discrepancy of MD-1 and CUSB results on $\Upsilon(1S)$ mass due to difference in analyses

Goal:

- To urge PDG update values of masses as was done for quarkonia electronic widths after J. P. Alexander *et al.*, Nucl.Phys.B **320**(1989)45

Why now?

- Preparation to new experiment of KEDR@VEPP-4M with expected accuracy of about 50 keV

Experimental aspects of the works stay untouched!

# Resonant depolarization method

The electron beam in the accelerator spontaneously becomes polarized, the spin precesses around guiding field with the frequency

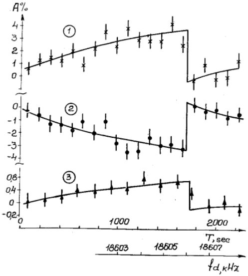
$$\Omega_{\text{spin}} = \omega_{\text{rev}}\,(1+\mu'/\mu\,\gamma) \text{ depending on the beam energy } E = \gamma\, m_e$$

External electromagnetic field of variable frequency $f_d$ depolarizes the beam at the resonance condition

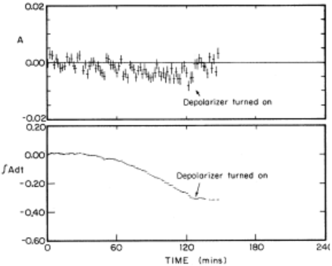
$$\Omega_{\text{spin}} = m \cdot \omega_{\text{rev}} + n \cdot f_d \quad (\Upsilon(1S) \text{ at VEPP-4: } m = 11, n = 1)$$

Measurement $f_d$ and $\omega_{\text{rev}}$ at the moment of depolarization allows for the beam energy determination with accuracy $\sim 10^{-6}$

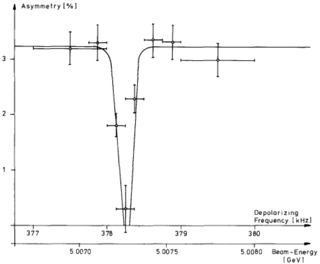
The moment of depolarization was detected using asymmetry in scattering of longitudinally polarized photons on the transversely polarized electron beam:



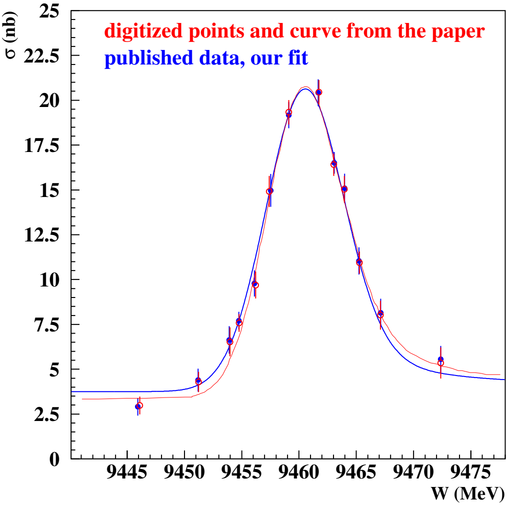

VEPP-4 (synchrotron radiation)




CESR (laser)




DORIS (laser)




Our fit of published data with identical radiative corrections accounting gives the mass value 0.375 MeV higher than the published one.

Misprint in the data?

The data form the journal figure were restored as good as possible, points coincide, unlike the curves.

The mass difference is due to calculation of the resonance curve. We have tried a few independent implementations, the result is stable.

One misprint has been found and fixed in the table of assignment of 22 runs of the experiment to 13 points of the fit.

*) *CUSB — Columbia University – Stony Brook*

# Correction to radiative corrections

The first published paper on r.c. to the production of narrow resonances:
Ya.I.Azimov, A.I.Vainshtein, L.N.Lipatov, V A.Khoze, JETP Lett. **21**(1975)172,
in a few months a good alternative appeared:
M.Greco, G.Pancheri-Srivastava, Y.Srivastava, Nucl.Phys. **B101**(1975)234
However, the most analysis of $\psi$ and $\Upsilon$ before 1985 were performed according to
J.D.Jackson and D.L.Scharre, NIM **128**(I975)13

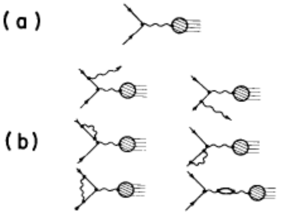



Fig. 1. e⁺e⁻ annihilation via one-photon exchange. (a) Lowest order diagram; (b) Higher order diagrams, the top two involving real (soft) photon emission and the next four each involving one additional virtual photon.

The 'radiative gaussian' $G_R$ was derived with convolution of the gaussian energy spread $G$ and the probability of energy radiation in the approximation of zero resonance width.

The radiation of additional soft photons we accounted in the case (a), but not in (b)

$$\sigma(W) \propto G_R(W-M)+\delta_v \cdot G(W-M) \quad \text{instead of} \quad (1+\delta_v)\cdot G_R(W-M)$$

Mass shift depends on the energy spread, $\sim$ 100 keV for $\Upsilon$

Resonant depolarization method gives the mean Lorentz factor of beam electrons thus the beam energy is proportional to electron's mass $m_e$. In 1983 the accuracy of $m_e$ was about 2.8 ppm, that corresponds to 26 keV uncertainty is $\Upsilon(1S)$ mass.

«The 1986 adjustment of the fundamental physical constants»,
E.R.Cohen and B.N.Taylor, Rev.Mod.Phys. **59**(1987)1121:
the value of $m_e$ was shifted to -8.5 ppm with reduction of uncertainty to 0.3 ppm due to refining of $e/h$ value

The results from VEPP-4 were recalculated in Phys.Lett. **B474**(2000)427
The shifts of masses were -80, -85 и -88 keV for $\Upsilon(1S)$, $\Upsilon(2S)$ и $\Upsilon(3S)$, respectively

The results from CESR and DORIS stayed unchanged

# Resonance-continuum interference

Ya.I. Azimov *et al.*, JETP Lett. **21**(1975)172

contribution of a resonance to a final state $f$ in soft photon approximation (needs small modifications nowadays):

$$\sigma^{\Upsilon\to f}(W)=\frac{12\pi}{M^2}\left(1+\frac{3}{4}\beta\right)\left[\frac{\Gamma_{ee}\Gamma_f}{\Gamma M}\,\mathrm{Im}\,f(W)-\frac{2\alpha\sqrt{R\,\Gamma_{ee}\Gamma_f}}{3W}\,\lambda\,\mathrm{Re}\,\frac{f(W)}{1-\beta/6}\right]$$

$$\text{where}\quad f(W)=\left(\frac{M/2}{M-W-i\Gamma/2}\right)^{1-\beta},\quad \beta=\frac{4\alpha}{\pi}\left(\ln\frac{W}{m_e}-\frac{1}{2}\right)$$

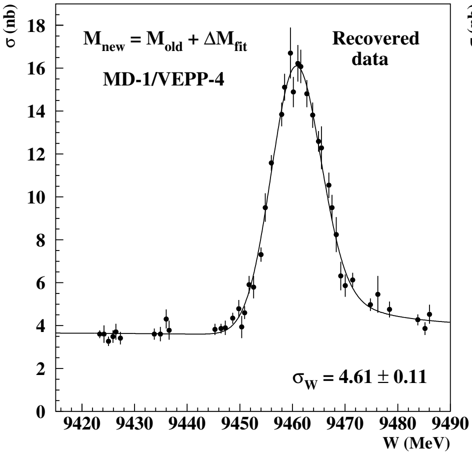
The parameter $\lambda$ determines the strengths of interference effects, $\lambda=1$ for $f=\mu^+\mu^-$. For the sum of hadronic modes ($b_m$ and $\mathcal{B}_m^{(s)}$ are relative mode probabilities in electromagnetic and strong decays, respectively, $\phi$ is the interference phase of electromagnetic and strong amplitudes)

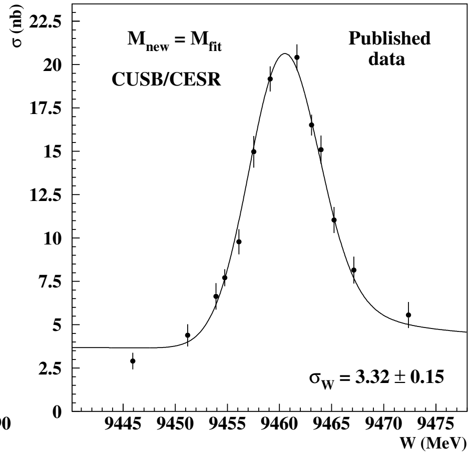
$$\lambda=\sqrt{\frac{R\mathcal{B}_{ee}}{\mathcal{B}_h}}+\sqrt{\frac{1}{\mathcal{B}_h}}\sum_m\sqrt{b_m\mathcal{B}_m^{(s)}}\,\langle\cos\phi_m\rangle\;. \qquad (1)$$

At the parton model level the strong $3g$ decays and the electromagnetic $q\bar{q}$ decays do not interfere thus the sum in the left part of (1) must be zero.

$\Upsilon$ mass shifts grows with the energy spread, $\sim$ 100 keV

# $\Upsilon(1S)$ mass (MeV)




$M_{old} = 9460.51 \pm 0.09 \pm 0.05$

$M_{new} = 9460.40 \pm 0.09 \pm 0.04$

$\Delta(int) = -0.112$

MD-1 – CUSB: $3.25\sigma \to 1.83\sigma$

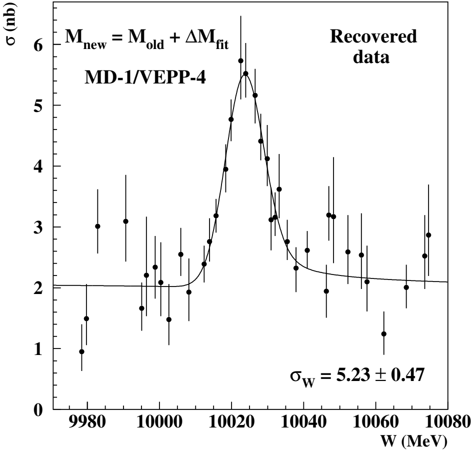
$M_{old} = 9459.97 \pm 0.11 \pm 0.07$

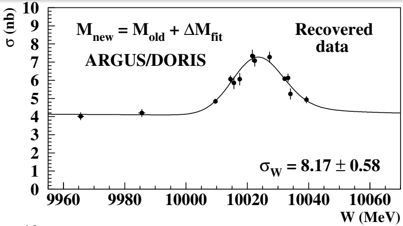
$M_{new} = 9460.11 \pm 0.11 \pm 0.07$

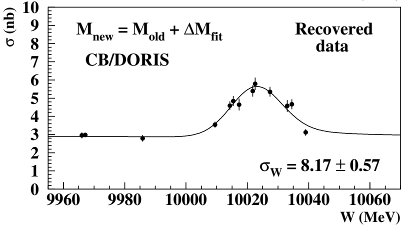
$\Delta(int) = -0.071$ $\Delta(m_e) = -0.081$

$\Delta(JS) = -0.081$ $\Delta(fit) = +0.375$

# $\Upsilon(2S)$ mass (MeV)



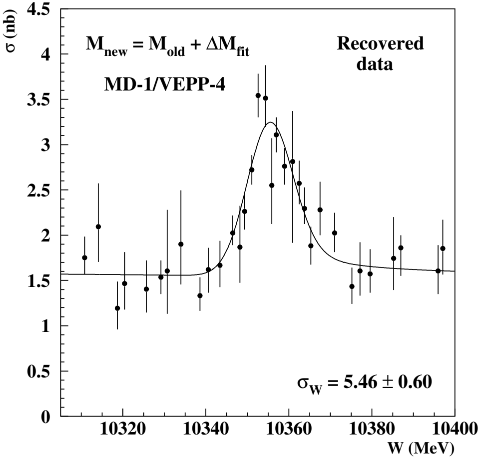




$$M_{old} = 10023.5 \pm 0.5$$
$$M_{new} = 10023.4 \pm 0.5$$
$$\Delta(int) = -0.105$$

$$M_{old} = 10023.1 \pm 0.4$$
$$M_{new} = 10022.7 \pm 0.4$$
$$\Delta(int) = -0.168 \quad \Delta(m_e) = -0.086$$
$$\Delta(JS) = -0.181$$

MD-1 – (ARGUS+CB): $0.62\sigma \rightarrow 1.06\sigma$

# $\Upsilon(3S)$ mass (MeV)




$$M_{old} = 10355.2 \pm 0.5$$
$$M_{new} = 10355.1 \pm 0.5$$
$$\Delta(int) = -0.130$$

# Summary on masses

- It was demonstrated that the analysis of CUSB/CESR data on mass of $\Upsilon(1S)$ was not fully correct, the mass was shifted by -0.375 MeV
- When necessary, published mass values were corrected to:
  - Improper radiative correction accounting
  - Use of obsolete electron mass value in these two works
  - Resonance-continuum interference

| | | | | |
|---|---|---|---|---|
| $\Upsilon(1S)$: | $9460.51 \pm 0.09 \pm 0.05$ | $\rightarrow$ | $9460.40 \pm 0.09 \pm 0.04$ | MD-1 |
| | $9559.97 \pm 0.11 \pm 0.07$ | | $9460.11 \pm 0.11 \pm 0.07$ | CUSB |
| $\Upsilon(2S)$: | $10023.5 \pm 0.5$ | $\rightarrow$ | $10023.4 \pm 0.5$ | MD-1 |
| | $10023.1 \pm 0.4$ | | $10022.7 \pm 0.4$ | ARGUS+CB |
| $\Upsilon(3S)$: | $10355.2 \pm 0.5$ | $\rightarrow$ | $10355.1 \pm 0.5$ | MD-1 |

- The discrepancy in MD-1 and CUSB results on $\Upsilon(1S)$ mass reduced from $3.25\,\sigma$ to $1.83\,\sigma$

The average $\Upsilon(1S)$ mass value calculated accoring PDG rules is

$$9460.29 \pm 0.15 \text{ MeV}$$

# Forthcoming experiment KEDR@VEPP-4M (1)

Experience of KEDR@VEPP-4M:

"Final analysis of KEDR data on $J/\psi$ and $\psi(2S)$ masses" PLB **749**(2015)50

- 6 $J/\psi$ and 7 $\psi(2S)$ high precision scans in 2002–2008
- systematic uncertainty in one scan 7÷10 keV (2.5 ppm)
- more than 15 sources of the uncertainty were considered

Difference between $\psi$ and $\Upsilon$ conditions:

$\psi$: Injection from VEPP-3 to VEPP-4M at the energy of scan point
$\Upsilon$: Acceleration at VEPP-4M from 1.9 to 4.73 GeV
$\Upsilon$: Some systematic uncertainties $\propto E_{beam}^2$

Goals for $\Upsilon(1S)$:

- Systematic uncertainties $< 30$ keV (6.3 ppm)
- Statistical uncertainty on mass $M < 40$ keV
- Statistical uncertainty on electronic width $\Gamma_{ee} < 1\%$

Luminosity $\simeq 10$ pb$^{-1}$, $\simeq 200$ runs, optimistic time estimate $\simeq 2$ months

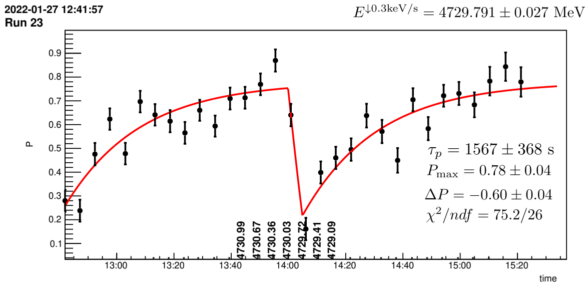
$\Upsilon(2S),\Upsilon(3S)$: much more difficult, $\Delta M \simeq 100$ keV ?

# Forthcoming experiment KEDR@VEPP-4M (2)

Status of preparation:

- Test scan of $\Upsilon(1S)$ without beam energy measurement was done
- Work to improve energy stability of VEPP-4M
- Polarization was obtained at $E_{beam} = 4.73$ GeV
- Laser polarimeter is in operation
  - First dozen of energy calibrations were done
  - Works to improve performance are in progress
  - Study of systematic uncertainties started (polarimeter+accelerator)

Example of energy calibration with the new polarimeter:




★ Hope to start experiment in 2023

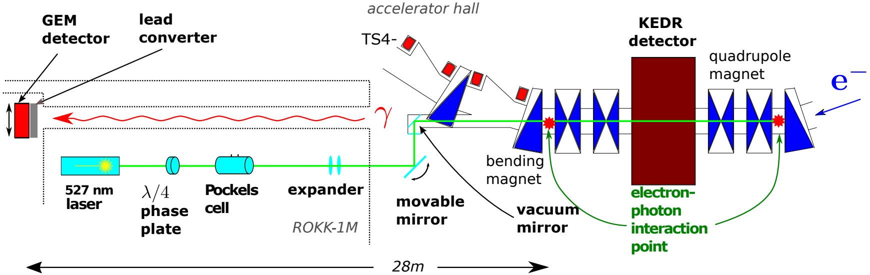
# Backup

Systematic uncertainties in $J/\psi$ scans (keV):

| *Uncertainty source* | 2002 | 2005 | 2008 | Common |
|---|---|---|---|---|
| Energy spread variation | 3.0 | 1.8 | 1.8 | 1.8 |
| Energy calibration accuracy | 1.6 | 1.9 | 1.9 | 1.6 |
| Energy assignment to DAQ runs | 3.7 | 3.5 | 3.5 | 2.5 |
| Beam separation in parasitic I.P.s* | 0.9 | 1.7 | 1.7 | 0.9 |
| Beam misalignment in the I.P. | 1.8 | 1.5 | 1.5 | 1.5 |
| $e^+$-, $e^-$-energy difference | 1.2 | 1.3* | 1.2 | 1.2 |
| Symmetric distortion of the energy distribution | 1.5 | 1.3 | 2.1 | 1.3 |
| Asymmetric distortion of the energy distribution* | 2.1 | 1.9 | 1.9 | 1.9 |
| Beam potential | 1.9 | 1.9 | 1.9 | 1.9 |
| Detection efficiency instability | 2.3 | 1.7 | 1.8 | $<0.1$ |
| Residual machine background | 1.0 | 0.7 | 0.7 | $<0.1$ |
| Luminosity measurements | 2.2 | 1.7 | 1.7 | 1.1 |
| Interference in the hadronic channel | 2.7 | 2.7 | 2.7 | 2.7 |
| *Sum in quadrature* | $\approx 7.7$ | $\approx 7.0$ | $\approx 7.2$ | $\approx 5.8$ |

* — correction uncertainty

Layout of the laser polarimeter:




V. E. Blinov *et al.*, JINST **15** (2020) C08024