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Precision measurement of the η-meson mass at COSY-ANKE

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Abstract. A value for the mass of the η meson has been determined at the COSY-ANKE facility through the measurement of a set of deuteron laboratory beam momenta and associated ^{3}He center-of-mass momenta in the $dp \to {}^3\mathrm{He}\,X$ reaction. The η meson was identified by the missing-mass peak and the production threshold determined. The value obtained, $m_\eta = (547.873 \pm 0.005_{\mathrm{stat}} \pm 0.027_{\mathrm{syst}})$ MeV/c^2, is consistent and competitive with other recent measurements, in which the meson was detected through its decay products.

Recent measurements on the η meson mass performed at different experimental facilities resulted in very precise data but differ by up to more than ten standard deviations, i.e. 0.5 MeV/c^2 [1]. Experiments in which the η meson was identified through a missing-mass peak in a hadronic production reaction have all reported a lower value for the mass in contrast to experiments reconstructing the η through the detection of its decay products. In order to clarify this situation a new and more refined missing mass measurement using the ANKE spectrometer at COSY - the COoler SYnchrotron of the Forschungszentrum Jülich has been realized [2] [3].

For a simple η mass determination with a missing mass analysis in principle the kinematics of a two-body reaction like $dp \to {}^3\mathrm{He}\,\eta$ have to be measured only at one single fixed accelerator beam energy. However, the η mass can be determined more precisely by the determination of the production threshold. Therefore, twelve data points at low excess energies in the range of $Q = 1 - 11$ MeV were investigated. The final state momentum p_f of the ^{3}He-particles in the center-of-mass (c.m.) frame

$$p_f(s) = \frac{\sqrt{\left[s - \left(m_{^3\mathrm{He}} + m_\eta\right)^2\right]\left[s - \left(m_{^3\mathrm{He}} - m_\eta\right)^2\right]}}{2\sqrt{s}} \tag{1}$$

measured with the ANKE spectrometer, is very sensitive on the η mass and the total energy $\sqrt{s}$, where the latter one is completely defined in a fixed target experiment by the masses of the initial particles and the laboratory momentum, p_d, of the deuteron beam:

$$s = 2m_p\sqrt{m_d^2 + p_d^2} + m_d^2 + m_p^2\,. \tag{2}$$

The final-state momentum $p_f = p_f(p_d, m_\eta)$ depends only on the beam momentum, the η mass and other well measured masses. If one can fix the production threshold, $p_f(s) = 0$, the η mass can then be determined from knowledge of the corresponding p_d. For a robust threshold extrapolation both quantities, (p_d, p_f) have to be measured with highest accuracy.

The beam momentum for each fixed excess energy was determined using the resonant depolarization technique, a method developed at the electron-positron machine VEPP at Novosibirsk using the spin dynamics of a polarized beam [4]. Thereby the spin precession frequency of a relativistic particle is disturbed by an artificial spin resonance induced by a horizontal rf-magnetic field of a solenoid leading to a depolarization of the polarized accelerator beam. The depolarizing resonance frequency f_r

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depends on the kinematical γ-factor (i.e. with $p = m\sqrt{\gamma^2 - 1}$ on the beam momentum) and the beam revolution frequency f_0 via the resonance condition:

$$f_r = (k + \gamma G)\, f_0\,, \tag{3}$$

where k is an integer and G the gyromagnetic anomaly of the beam particle. By measuring these two frequencies the beam momentum can be determined with a precision below $\Delta p/p < 10^{-4}$. For the first time this method was used at COSY with a vector polarized deuteron beam and the accuracy could be increased by more than an order of magnitude compared to the conventional method. The momenta in the threshold range of 3.1 - 3.2 GeV/c were determined with an accuracy of $\Delta p/p = 3 \cdot 10^{-5}$, i.e. with ≈ 100 keV/c [5].

The correct final state momenta for the twelve different energies of the ^{3}He-nuclei of the reaction $dp \to {}^3\mathrm{He}\,\eta$ can only be extracted fulfilling two conditions: i) a precise detector calibration and ii) a clear identification of the reaction of interest. At ANKE the produced ^{3}He-nuclei can be identified using the energy loss and time of flight information. By this the background, consisting mainly of protons and deuterons of the dp elastic scattering and the deuteron break-up, can be suppressed effectively. For a two-body reaction at a fixed center of mass energy $\sqrt{s}$ the final state momenta in the c.m. frame are distributed on a momentum sphere with constant radius p_f, which can be visualized by plotting the reconstructed transverse c.m. momentum $p_\perp$ against the longitudinal c.m. component p_z, as shown in Fig 1a). According to Eq. 1, one expects a centered circle with a fixed radius $p_f = (p_x^2 + p_y^2 + p_z^2)^{1/2}$, indicated in Fig. 1a as solid lines. The feature that the ANKE facility has full geometrical acceptance for the reaction $dp \to {}^3\mathrm{He}\,\eta$ near threshold up to 15 MeV allows to verify and improve the detector calibration by studying the kinematics of this two-body reaction. The principle of the refined spectrometer calibration is the requirement that the momentum sphere should be completely symmetric in p_x, p_y, and p_z (or ϑ and ϕ). Therefore it is necessary to study the reconstructed momentum p_f carefully as a function of the polar and azimuthal angles ϑ and ϕ

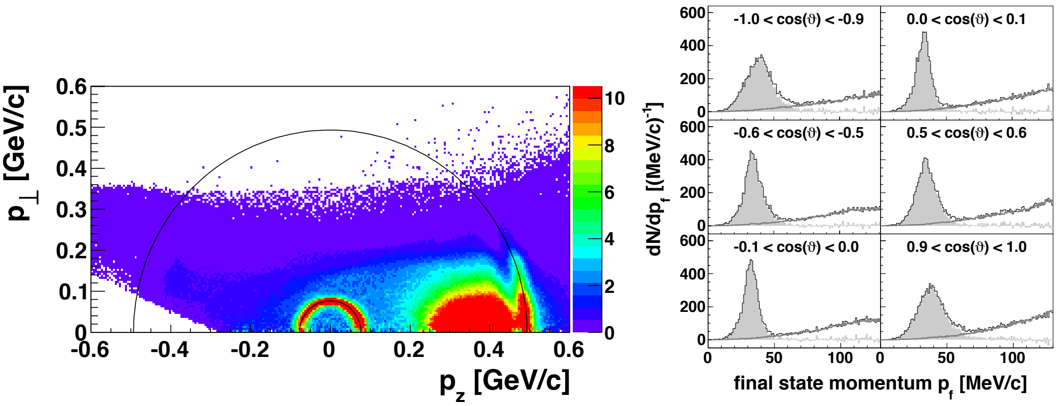

Fig. 1. a) The reconstructed transverse c.m. momentum $p_\perp$ is plotted against the longitudinal c.m. component p_z for an excess energy $Q = 6.3$ MeV with respect to the η threshold. The small and large circles correspond to the kinematic loci for the $dp \to {}^3\mathrm{He}\,\eta$ and $dp \to {}^3\mathrm{He}\,\pi^0$ reactions, respectively. ANKE covers the full solid angle for η production near threshold whereas, for pions, only the forward and backward ^{3}He are detected. **b)** c.m. distributions of the ^{3}He momentum from the $dp \to {}^3\mathrm{He}\,X$ reaction for six typical polar angle bins at the lowest excess energy measured, $Q = 1.1$ MeV. The experimental data summed over ϕ are shown by black lines and the background estimated from sub-threshold data by gray lines. The resulting background-subtracted $dp \to {}^3\mathrm{He}\,\eta$ signal is shaded gray.

$$p_f = p_f(\cos\vartheta) \qquad\qquad p_f = p_f(\phi)\ .$$

Deviations from the symmetric shape will indicate the need of an improvement of the standard ANKE calibration. This requires a clean separation of the $^3\mathrm{He}\,\eta$ signal from the background.

The background left after cutting on ^{3}He-nuclei (see Fig. 1b), originating mainly from the multi pion production, can be subtracted by data taken below the η production threshold at an excess energy of $Q \approx -5$ MeV, but analyzed as if they were taken above. The details of this technique are described for missing-mass spectra in Ref. [6], but the method is equally applicable to p_f spectra. Due to the very high statistics of the current experiment, the distribution in p_f could be investigated for twenty bins each in ϑ and ϕ. This is illustrated in Fig. 1b), where examples of the p_f spectra summed over ϕ are shown for six $\cos\vartheta$ bins for the energy closest to threshold, $Q = 1.1$ MeV. A similar picture is found for the ϕ dependence after summing over θ. Mean values of the ^{3}He momentum p_f and peak widths for different ϑ and ϕ bins were extracted from the background-subtracted $dp \to {}^3\text{He}\,\eta$ distributions by making Gaussian fits. A variation of the width of 4–12 MeV/c (rms) was found, as well as a displacement of the mean value. This striking effect results from different resolutions of the ANKE forward detector system in p_x, p_y and p_z. Assuming that the individual momentum components are gaussian distributed with different widths, Monte Carlo simulations have shown that the final state momentum, i.e., the shape of the momentum sphere, is stretched to values $\cos\vartheta \to \pm 1$ and shows an oscillation in ϕ. However, p_f should be symmetric in $\cos\vartheta$ and ϕ.

The mean values of the measured p_f for background-subtracted $dp \to {}^3\text{He}\,\eta$ distributions are shown in Fig. 2a) for twenty individual $\cos\vartheta$ and ϕ bins, before and after the improvement of the calibration. The results for the standard calibration, presented in the upper panels, show that the momentum sphere is neither centered nor symmetric. The momentum sphere is shifted to higher p_z, i.e., on average p_f is higher for ^{3}He produced in the forward direction than in the backward. The oscillations in the ϕ spectrum are also far from being symmetric, and this is particularly evident at $\phi \approx \pm 90°$, where the p_y momentum component dominates. This asymmetric pattern is rather similar at all twelve energies and this stresses the need for improvement of the detector alignment. By making minor changes of the ANKE calibration parameters such that the mean values of the final-state momenta are distributed on a centered and perfectly symmetric sphere in $\cos\vartheta$ and ϕ, the detector alignment can be significantly improved, as shown in the lower part of Fig. 2a). This procedure was carried out using the data at all twelve energies simultaneously.

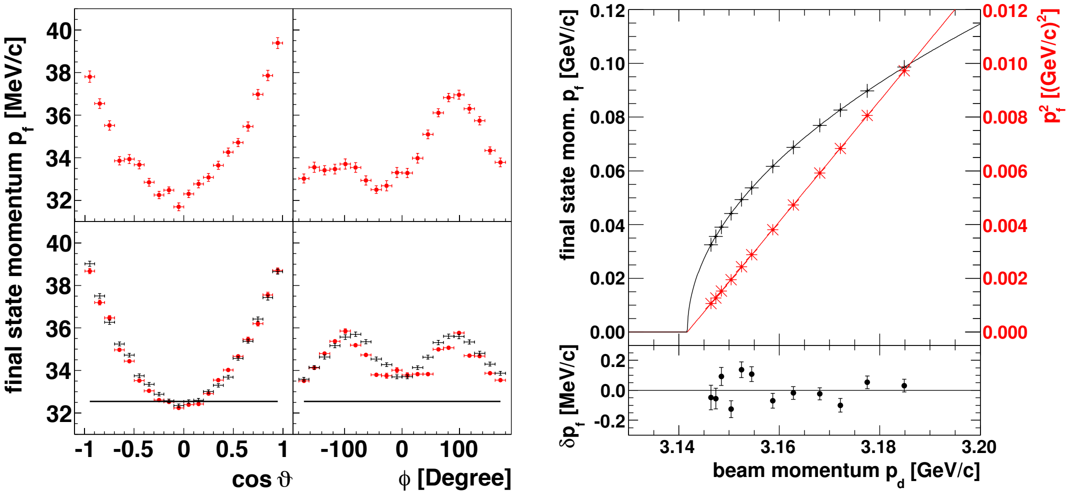

Fig. 2. a) Mean values of the p_f distributions are shown for individual $\cos\vartheta$ and ϕ bins for the standard (top) and improved (bottom) calibration at $Q = 1.1$ MeV (red circles). The results of Monte Carlo simulations are shown without (black horizontal line) and with momentum smearing (black points). The comparison of the data with the simulation leads to a determination of the momentum resolutions in p_x, p_y and p_z. **b)** Final-state momentum p_f (black crosses) and p_f^2 (red stars) plotted against the deuteron laboratory momentum p_d. The extrapolation to threshold is carried out on the basis of Eq. 1. The lower panel shows the deviations of the experimental data from the fitted curve in p_f. The errors shown here do not include the overall systematic uncertainty.

The improved spectra, shown in the lower half of Fig. 2a) for one of the twelve energies, allow one to study the momentum resolution in the three directions. With the extracted momentum resolution parameters the data can be very well described with Monte Carlo simulations (black crosses). The determination of the η mass has to take these kinematic resolution effects into account because, without so doing, the value extracted for m_η would depend on the production angle. For the current ANKE experiment, differences in m_η of up to 0.5 MeV/c^2 are found between $\cos\vartheta = \pm 1$ and $\cos\vartheta = 0$. Owing to the resolution effects shown in the lower half of Fig. 2a), the reconstructed average of the final-state momentum over all $\cos\vartheta$ and ϕ is shifted to a higher value than the true one (black horizontal line). By comparing the averages resulting from the Monte Carlo simulations with and without momentum smearing, correction parameters were calculated for all twelve energies. The correction is about 2.22 MeV/c for the lowest momentum and decreases steadily with p_f to 0.7 MeV/c for the highest. Compensation for the momentum resolution effects is essential for an accurate determination of the production threshold. Without this correction, the value obtained for the η mass would be lower by about 150 keV/c^2. The good statistics of $\approx 1.3\times 10^5$ ^{3}He η events for each energy meant that the value for p_f could be extracted with an uncertainty of < 100 keV/c, whereas the uncertainty is dominated by the precision of the correction parameters.

To obtain a robust value for the mass of the η meson, it is necessary to extrapolate the experimental data set (p_d, p_f) in order to determine the value of the deuteron beam momentum at threshold. The extrapolation of the data to threshold is illustrated in Fig. 2b) for both p_f and p_f^2 versus p_d. Whereas, to first order, p_f^2 depends linearly on p_d, the analysis considers the full dependence $p_f = p_f(m_\eta, p_d)$, as given by Eqs. 1 and 2. Only the η mass, chosen as a free parameter, defines the production threshold. The overall fit to the data in Fig. 2b) has a $\chi^2/\mathrm{NDF} = 1.28$ and the best value of the mass is $m_\eta = (547.873 \pm 0.005)$ MeV/c^2, where the error is primarily statistical. The corresponding deuteron beam momentum at threshold is $p_d = (3141.688 \pm 0.021)$ MeV/c.

By far the dominant systematic errors arise from the determinations of the absolute value of the beam momentum and the p_f correction parameters. All other sources, such as effects from the time stability of the data, further contributions from the fine calibration, the event selection, the background subtraction for the p_f distributions, as well as contributions of the η mass assumed in Monte Carlo simulations, are negligible in comparison. The uncertainty in the beam momentum translates into one in the mass of $\Delta m_\eta = \frac{m_p p_d}{(m_{^3\mathrm{He}} + m_\eta)E_d}\Delta p_d = 23\ \mathrm{keV/c^2}$, and hence, taken together with all other systematic uncertainties, to a final value of

$$m_\eta = (547.873 \pm 0.005_{\mathrm{stat}} \pm 0.027_{\mathrm{syst}})\ \mathrm{MeV/c^2}. \tag{4}$$

The value obtained at COSY-ANKE differs by about 0.5 MeV/c^2 from earlier missing-mass evaluations and is consistent with all the recent measurements where the meson decay products were studied. The precision achieved is similar to these works and the deviation from the PDG best value [1] is only 20 keV/c^2. The COSY-ANKE result [3] shows that, with care, a missing-mass approach can be competitive with experiments in which meson decays are measured.

References

1. K. Nakamura *et al.* (Particle Data Group), Journal of Physics G**37**, (2010) 075021.
2. A. Khoukaz, COSY Proposal and Beam time request No. 187, available from www2.fz-juelich.de/ikp/anke/en/proposals.shtml .
3. P. Goslawski *et al.*, Physical Review D **85**, (2012) 112011.
4. Ya. S. Derbenev *et al.*, Particle Accelerators **10**, (1980) 177.
5. P. Goslawski *et al.*, Physical Review Special Topics - Accelerators and beams **13** (2010) 022803; P. Goslawski, Diploma thesis, Westfälische-Wilhelms Universität Münster (2008).
6. T. Mersmann *et al.*, Physical Review Letters **98**, 242301 (2007).