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Simulation of trajectories in the MAVR High-Resolution Magnetic Spectrometer

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Charged-particle trajectories in the MAVR high resolution magnetic spectrometer are simulated. The latter has been constructed at the U400 accelerator for purifying the incident beam and identifying the products of nuclear reactions induced by the beams of stable and radioactive nuclei. In this paper we present the MAVRPC++ software package, aimed at reconstructing the spectrometer focal plane, optimizing the fields of quadrupole and dipole magnets, and estimating the solid-angle acceptance for secondary particles.

Keywords: spectrometer, MAVR, charged-particle trajectories.

Introduction

The mechanisms of nuclear reactions induced by beams of stable and radioactive nuclei and the properties of nuclei close to the boundaries of the stability region are among the research priorities of the JINR Laboratory of Nuclear Reactions (LNR). Corresponding experiments rely on the U400 and U400M cyclotrons at JINR and on the machines operating at other research centers: GANIL (France), RIKEN (Japan), and Q3D (Germany) [1-3]. All these experiments employ magnetic spectrometers and separators where by the primary beam is purified to a high degree and the reaction products are discriminated with high resolutions in momentum, energy, and mass. The method of magnetic spectrometry (with the MSP-144 analyzer [4]) was also employed at LNP for measuring the binding energies and probing the stability and structure of super-neutron-excessive isotopes of the lightest elements ($^{7-10}$He, $^{9-11}$Li, and $^{12-14}$Be). These measurements relied on the missing-mass technique. Energy levels of the ^{7,8,9}He, ^{10,11}Li, and ^{13}Be nuclides were measured for the first time [2, 3].

The commissioning of the DRIBs radioactive beam system [5] opened up new possibilities for such investigations. Relying on relatively high intensities of radioactive beams and on the good momentum resolution of the MSP-144 spectrometer, studies of ^{6}He induced reactions at energies in the barrier region were initiated. The excitation functions of the ^{6}He-induced fusion and neutron-transfer reactions were measured with a 300-keV precision. Interesting data on deep-subbarrier fusion of the ^{6}He neutron-halo nucleus with heavy nuclei were obtained [6-8].

These measurements are of fundamental importance for nuclear physics and astrophysics and have been followed by similar investigations performed elsewhere. We should emphasize that the aforementioned experiments were carried out in close collaboration with the JINR member laboratories: NPI ASCR (Rez, Czech Republic), IFIN-HH (Bucharest, Romania), and NINP PAS (Krakow, Poland).

Comparison of the main characteristics of the analyzer MAVR with the characteristics of other spectrometers (Table 1) shows that this setup allows to conduct experiments at the world level.

Table 1.
Comparison of the parameters of the analyzer MAVR with the characteristics of other spectrometers.

	MAVR JINR (Dubna)	MSP144 JINR (Dubna)	VAMOS GANIL (Caen)	PRISMA LNL (Legnaro)	MAGNEX LNS (Catania)
Geometry	$Q_vQ_hD_1D_2$	D_1D_2	Q_vQ_hD	Q_vD	Q_vD
Bpmax, Tm	1.5	1.4	1.7	1.2	1.8
Angle, ^{o}	110.7	110.7	45	45	55
Angular Acceptance, mstrd	5	0.49	70	80	55
Dispersion, cm/%	2	1.5	1.8	2	3.68
Energy Resolution ΔE/E	$5{\cdot}10^{-4}$	$5{\cdot}10^{-4}$	$5{\cdot}10^{-4}$	$1{\cdot}10^{-3}$	-
Resolution Z	1/60	1/60	1/50	1/60	-

The MAVR high-resolution magnetic spectrometer will enable us to do the following[9]:

- estimate the degree of nucleon stability for exotic nuclei;
- measure the masses of these nuclei with the missing-mass technique;

- investigate the excited and resonant states of exotic nuclei;
- search for nucleon clusters in light nuclei.

Experimental setup

The MAVR high-resolution magnetic analyzer is comprised of an upgraded system of magnetic optics based on the MSP-144 magnet, a doublet of quadrupole lenses Q1 and Q2 upstream of the magnetic spectrometer, and a detector block located in the analyzer focal plane. MAVR is deployed in the experimental hall of the U400 accelerator.

The target placed at a distance of d_1 = 2576 mm from the front face of the spectrometer's first bending magnet is irradiated by an extracted ion beam. The distances between the target and the upstream quadrupole lens and between the two quadrupoles are r_1 = 307 mm and r_2 = 180 mm, respectively. The quadrupole pair has an effective length of r_{eff} = 350 mm. The distance between the downstream quadrupole lens and the front shutter of the magnet amounts to r_3 = 873 mm. The analyzing magnet consists of two parts, of which the second one generates a magnetic field that is 1.55 times stronger than the first one. The first and second magnets provide bending angles of φ_1 = 60^o and φ_2 = 52^o, respectively, so that for a detected particle the total bending angle amounts to 111^o. The interpole distance equals 47 and 30 mm for the first and second magnets, respectively.

The conceptual scheme of the MAVR spectrometer is in Figure 1.

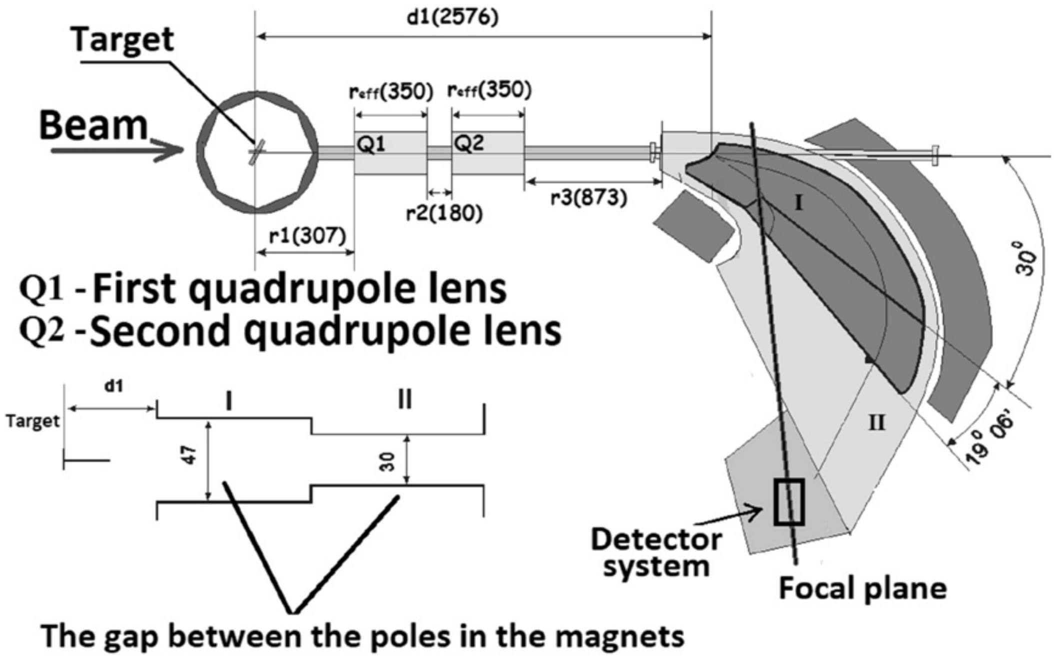

Figure 1. Conceptual scheme of the MAVR high-resolution spectrometer.

With a system of detectors deployed in the spectrometer focal plane, reactions products are detected and precisely discriminated by charge Q, atomic number Z, and mass A by measuring their energy losses (ΔE), times of flight (T), and total energies (E). For this, detectors of different types including position-sensitive chambers and semiconductor strip sensors will be used.

The upgraded magnetic spectrometer features a high energy resolution of $\Delta E/E \approx 5 \cdot 10^{-4}$, a large bending angle of 111^{o}, and a dispersion along focal plane 2 cm/%. Thereby, products of nuclear reactions are detected with a high charge resolution of $\Delta Z/Z \approx 1/60$ essential for efficiently discriminating massive secondary nuclei.

The basic parameters of the MAVR spectrometer are listed in Table 2.

Table 2.
Basic parameters of the MAVR spectrometer.

Interpole distance for the first magnet, mm	47
Interpole distance for the second magnet, mm	30
Maximum magnetic rigidity B_{ρ}, Tm	1.5
Dispersion along focal plane, cm/%	2
Energy resolution ΔE/E	$5{\cdot}10^{-4}$
Mean radius of particle trajectory R, m	1.25
Solid-angle acceptance, msrad up to	5
Particle's total bending angle in the spectrometer, deg	111

The MAVRPC++ software package

Since the spectrometer features a quadrupole-lens doublet, the position of the magnet focal plane depends on the quadrupole field strengths. For this reason, the MAVRPC software package [10] was developed. The MAVRPC software package is aimed at reconstructing the focal-plane position and estimating the spectrometer solid-angle acceptance as functions of the parameters of investigated secondary particles. This software package has been developed on the COSY INFINITY platform [11] aimed at designing optical systems, spectrometers and accelerators in particular. The latter relies on the methods of differential algebra: particle propagation through each element of an optical system is described in terms of a corresponding transition matrix. Since the quadrupole transition matrices depend on their induction gradients, that of the spectrometer as a whole and its focal-plane position also depend on the quadrupole fields.

MAVRPC ++ is an enhanced version of MAVRPC. The main innovation of MAVRPC ++ is that the calculations of the position of the focal plane were made with an accuracy of the 7th order (in MAVRPC, the accuracy of calculations did not exceed the 2nd order, the focal plane was approximated by a straight line). In addition, a function of calculation the dependence of the effective solid angle of the MAVR installation on the relative stiffness of the BP/BP0 particles was added.

Table 3 presents the results of calculations of the focal planes positions of the MAVR analyzer in MAVRPC ++ for a central particle with BP0 = 0.91 Tm for different fields of quadrupoles, and also provides an estimate of the solid angle of the analyzer for each of the options considered. The radius of the central trajectory is R_{ref} = 1.25 m (Figure 2).

Table 3.
Calculations of the focal planes positions of the analyzer MAVR in MAVRPC ++ for the central particle with BP0 = 0.91 Tm.

R_{ref}, m	Q1, T	Q2, T	Ω, msr
1.25	-0.5	0.4	5
1.25	-0.2	0.3	1.9
1.25	-0.1	0.3	4
1.25	-0.1	0.1	2.9
1.25	0.0	0.2	4

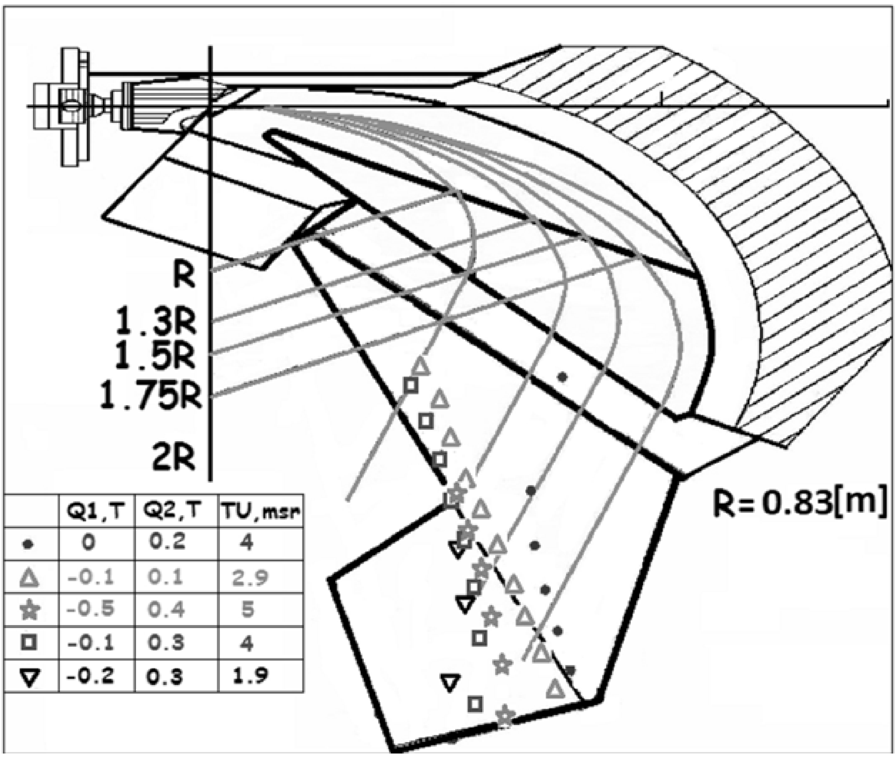

Figure 2. Graphic representation of the reconstructed focal planes of the MAVR analyzer in MAVRPC++ for the central particle with BP0 = 0.91 Tm with different fields of quadrupoles.

Thus, MAVRPC ++ allows you to compare various settings of the MAVR analyzer and select the best options for a specific experiment. In the considered example (table 3), for a central particle with BP0 = 0.91 Tm, the optimal choice of quadrupole fields is: Q1 = -0.5 Tm, Q2 = 0.4 Tm, which corresponds to the solid angle Ω = 5 msr and the central particle hits the detector system. An ordinary standard-size silicon detector (60×60 mm) was considered as a detector system. These calculations show that an increase in solid angle compared with the MSP-144 analyzer (Ω MMP-144 = 0.49 msrd [12]) is expected to be 10 times.

Figure 3 shows the dependence of the effective solid angle of the MAVR facility on the relative rigidity of the particles BP/BP0 (where BP0 is the rigidity of the central particle) for the chosen setting of the fields of installation of MAVR (central particle with BP0 = 0.91 Tm, fields of quadrupoles: Q1 = -0.5 Tm, Q2 = 0.4 Tm).

Figure 3 clearly demonstrates that the selected setting of the spectrometer provides the maximum transmission of particles with BP0 = 0.91 Tm through the

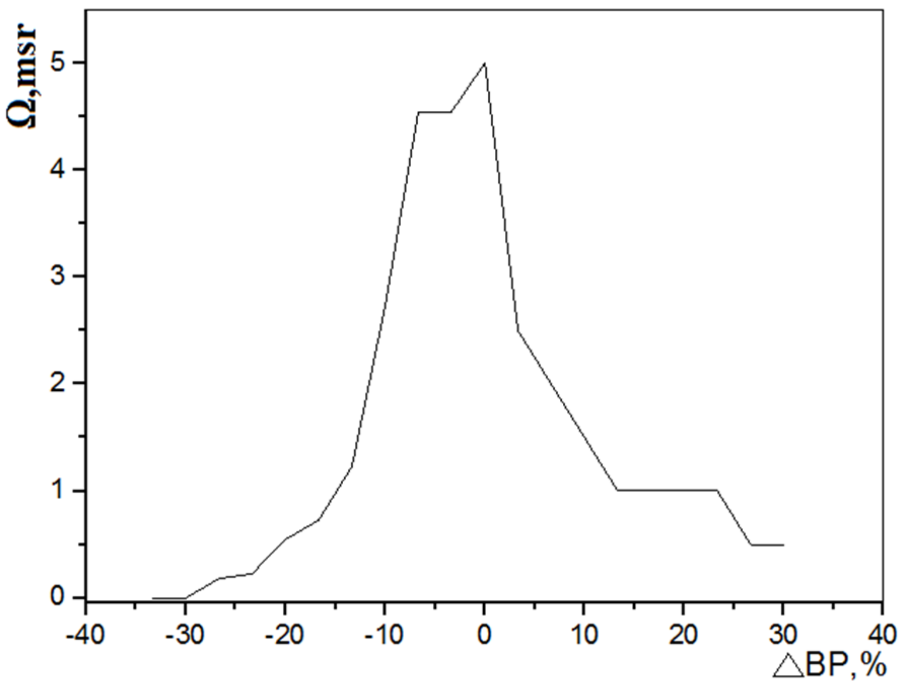

Figure 3. Dependence of the effective solid angle of the MAVR facility on the relative stiffness of the BP/BP0 particles for a 60×60 mm detector system.

spectrometer to a fixed point of the focal plane.

Conclusion

In this paper, charged-particle trajectories in the MAVR high-resolution magnetic spectrometer are simulated using the MAVRPC++ software package. Thereby, the spectrometer energy resolutions are estimated as $\Delta E/E \approx 5 \cdot 10^{-4}$, respectively, and, in the charge of nuclear-reaction products, $\Delta Z/Z \approx 1/60$. The solid angle acceptance of the MAVR spectrometer is found to exceed that of MSP-144 by a factor of up to ten.

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