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Fusion Reactions at the Coulomb Barrier with Neutron-rich Mg Isotopes

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Fusion reactions at energies close to the Coulomb barrier with stable and radioactive Mg beams on ^{28}Si are proposed to be studied employing the REX-ISOLDE accelerator. The γ-spectrometer MINIBALL together with particle detectors will provide a very efficient setup to identify elastic scattered beam particles, fusion products and characteristic γ-rays from evaporation residues. The predicted enhancement of subbarrier fusion for neutron-rich Mg isotopes should be verified. The fusion cross section and the mean angular momentum is expected to be significantly increased by few-nucleon transfer with large positive Q-value. One may expect that the large radii and a possible neutron skin of neutron-rich Mg nuclei may cause even higher subbarrier fusion probabilities.

1 Introduction and Motivation

Subbarrier fusion with stable beams has been extensively studied in order to explain the large enhancements measured with respect to the estimates based on tunneling through a one-dimensional potential barriers. Big differences of 2 orders of magnitude in cross section at the same energy were observed in different but comparable target + projectile combinations. Fusion of heavy ions is treated as a tunneling phenomenon depending on the intrinsic degrees of freedom in addition to the radial separation of the colliding nuclei. The influence of the nuclear deformation, the high sensitivity to the nuclear structure and its excitations and the effect of few nucleon transfer has been observed in precise measurements of the fusion excitation function covering a wide range of $Z_p Z_t$ [1].

The main and new point for the proposed fusion studies with neutron-rich radioactive projectiles is the influence of the increasing neutron excess on the fusion process. The fusion reactions induced by such asymmetric projectiles is expected to be strongly enhanced below the Coulomb barrier by transfer reactions with a large positive Q-value. Moreover, heavier Z=10-14 isotopes could develop a neutron skin, similar to what has already been observed in heavy Na isotopes [2], which may affect the fusion probability. Here detailed theoretical predictions are not yet available.

The understanding of the fusion process with radioactive ion beams is in the early stages and it will hopefully have great ramifications for the production of super-heavy elements. One of the interesting aspects is the possibility of using neutron-rich instable projectiles to synthesize new heavy nuclei on the neutron-rich side. For the ^{208}Pb and ^{209}Bi based cold fusion reactions a significant extension is possible due to Kr, Rb, and Sr beams. In these cases the predicted next magic neutron number N=184 can be crossed and the possibly doubly magic ^{304}120 is within reach. This is the most intriguing perspective for super heavy element research at future RIB facilities.

While fusion studies with radioactive He, Li and Be beams including nuclei with halo- and neutron-skin structure already yielded exciting results, (for a recent review see [3]), up to now only a few experiments with instable projectiles heavier than Be were performed and different results were obtained. The fusion experiment ^{17}F+^{208}Pb was performed at ANL [4]. In comparison with the stable system ^{19}F+^{208}Pb no fusion enhancement was observed for the neutron-deficient case. The systems ^{32,38}S+^{181}Ta were measured at MSU [5]. For the reactions with radioactive ^{38}S the fusion barrier height was 6.8 MeV lower than for the stable ^{32}S case favouring the synthesis of heavy nuclei with a neutron-rich projectile. At RIKEN the fusion of the systems ^{27,29,31}Al+^{197}Au was measured [6]. The data for all three systems do not differ much from each other and no fusion enhancement was observed. A qualitative understanding of this result is given by C. Signorini [3]: The ^{29,31}Al + Au systems do not have positive 2n transfer pick up Q-values. Like in reactions with stable nuclei the positive transfer Q-value remains to be an important condition for fusion enhancement also with instable nuclei.

Recently one of our collaborators V.Yu. Denisov studied in detail the relevance of neutron

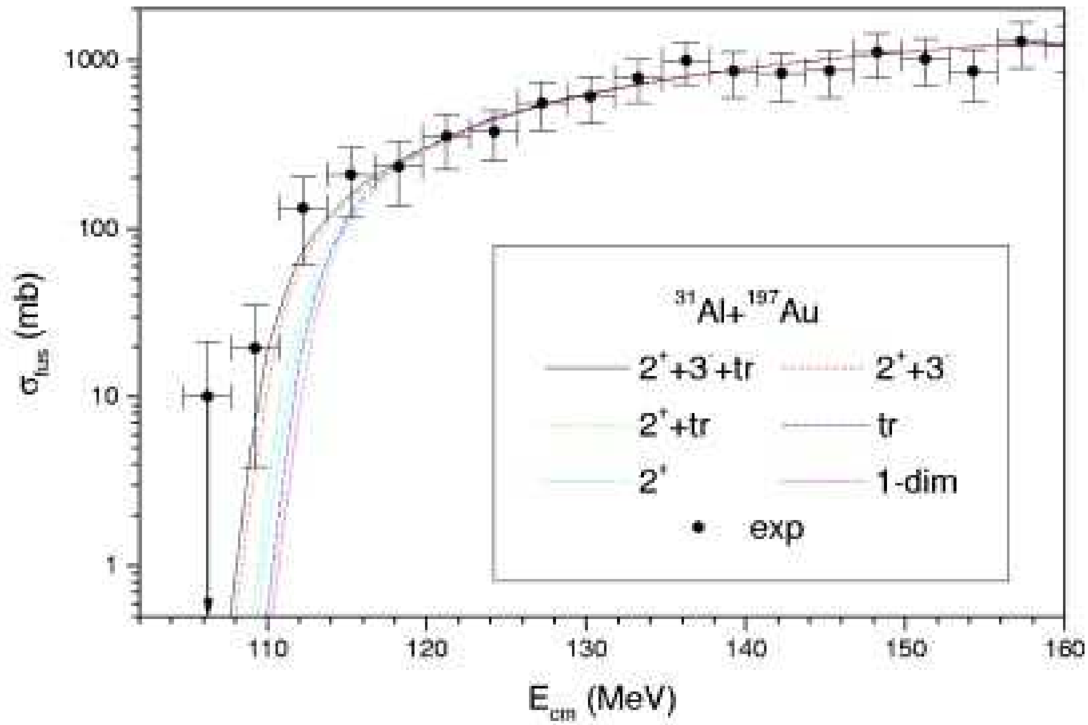

Figure 1: Fusion cross sections for the reactions ^{31}Al+^{197}Au. Experimental data (dots) are taken from [6]. The results of the calculation taking into account both the low-energy 2^+ and 3^- states and the neutrons transfer channel is shown by the black solid curve. The results of the calculation taking into account the individual contributions: coupling to the low-energy 2^+ and 3^- states and the neutrons transfer channel are marked by the dashed curves. The result of the calculation in the one-dimensional WKB approach is shown by the magenta dotted curves.

transfer in fusion reactions within a theoretical model for the description of subbarrier fusion of heavy ions [7]. The model takes into account the coupling to the low-energy surface vibrational states and to the few-nucleon transfer. The model describes rather well the experimental fusion cross section and mean angular momentum for reactions between nuclei near the β-stability line like e.g. ^{40}Ca+^{90,96}Zr where measured data are available [8]. The reaction ^{40}Ca+^{90}Zr can be described when the low-energy surface vibrational 2^+ and 3^- states and the deformations $\beta_{2,3}$ in the colliding nuclei are taken into account. This approach is insufficient for ^{40}Ca+^{96}Zr and underestimates the experimental data at subbarrier energies. Significant enhancement of the subbarrier fusion cross section is obtained by taken into account four transfer channels related to 1-, 2-, 3- and 4-neutron transfer from ^{96}Zr to ^{40}Ca.

The same model reproduces the aforementioned RIKEN cross section data for ^{27,29,31}Al + ^{197}Au very well by including the low-energy surface vibrational states and the few-nucleon transfer (see actual unpublished calculation done by V.Yu. Denisov Fig.1). The qualitative

Reaction	Fusion	2n-transfer	4n-transfer
^{24}Mg + ^{28}Si	12.9 MeV	-10.5 MeV	-28.9 MeV
^{26}Mg + ^{28}Si	18.5 MeV	0.65 MeV	-13.2 MeV
^{28}Mg + ^{28}Si	24.1 MeV	4.1 MeV	1.5 MeV
^{30}Mg + ^{28}Si	31.7 MeV	9.1 MeV	9.9 MeV
^{32}Mg + ^{28}Si	39.1 MeV	11.02 MeV	16.8 MeV

Table 1: Q-values for fusion-, 2n-transfer- and 4n-transfer reactions

argument about the effect of neutron transfer and the positive Q-value is confirmed by the model. The barriers heights of the effective potentials related to 2-, 3- and 4-neutron transfer channels are essentially lower then the potential barrier without neutron transfer. Therefore significant enhancement of the subbarrier fusion cross section is caused by 2-, 3- and 4-neutron transfer channels.

2 Proposed Fusion Reaction Study

The REX ISOLDE accelerator provides the unique experimental opportunity to study not only Coulomb excitation and light particle induced transfer reactions but also fusion reactions with heavy nuclei far from β-stability. Already the first test experiments at Heidelberg and at REX-ISOLDE in November 2001 with 2.2 MeV/u beams on ^{9}Be targets demonstrated that fusion reactions have higher cross sections than transfer reactions and dominate the measured γ-spectra. While Coulomb excitation and light particle induced reactions can be measured also at relativistic beam energies, the proposed fusion reactions are very well suited for reaccelerated ISOL beams with well defined beam energies around the Coulomb barrier. At fragmentation facilities this type of experiments can only be performed after heavy degradation of the beam particles with large energy spreads. The present beam energy of 2.2 MeV/u of the REX ISOLDE accelerator will allow subbarrier fusion experiments with light Na, Mg and Al beams and targets up to Si (Z=14). In the near future the energy upgrade up to 3.1 MeV/u will extend the scope of the intended experiments to heavier targets, especially magic nuclei of Ca and Ni isotopes with their increased binding energy as targets are very important.
The new calculations done by V.Yu. Denisov describe very well the fusion reaction cross section and mean angular momentum for reactions between stable nuclei ^{28,30}Si+^{58,62,64}Ni, ^{40}Ca+^{90,96}Zr and ^{28}Si+^{94,100}Mo and the radioactive beam reactions ^{27,29,31}Al + ^{197}Au. Therefore it is very important and interesting to test the predictive power of the model with other reactions utilizing the very neutron-rich beams available now at ISOLDE.

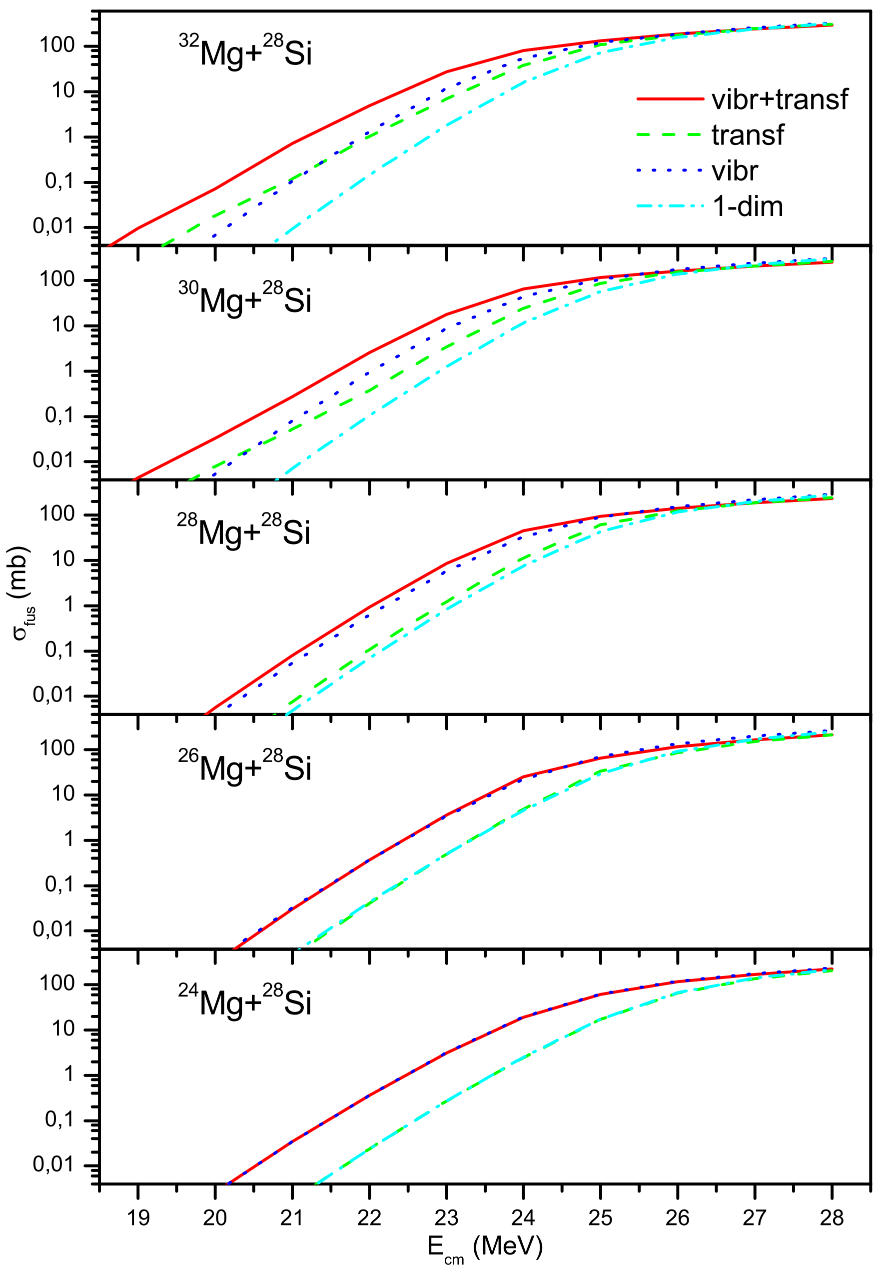

Figure 2: Fusion cross sections for ^{24,26,28,30,32}Mg + ^{28}Si reactions. Subbarrier contributions are enhanced with increasing neutron number in Mg. Red: enhancement due to neutron transfer (until 1n, 2n, 3n and 4n with positive Q-value, negative Q-values for transfer channel are ignored.) and 2+ and 3- vibrational excitations in target and projectile. Green: only neutron transfer contribution. Blue: only 2+ and 3- vibrations in both nuclei. Cyan: 1-dimensional WKB result.

Considering the available ISOLDE beams and their intensities, the actual REX-ISOLDE beam energy and the possible target + projectile combination to observe strong enhanced subbarrier fusion the reactions ^{24,26,28,30,32}Mg + ^{28}Si provide the most promising perspective for a first series of experiments. The main argument for this choice are the high positive Q-values for fusion-, 2n-transfer- and 4n-transfer reactions with radioactive ^{28,30,32}Mg isotopes and the dramatic increase in Q-values for all relevant reactions starting from the two stable isotopes ^{24,26}Mg (see table 1). For the neighbouring Na and Al isotopes as projectiles the situation is less favourable: First the varying ground-state spin values from 3-1/2 $\hbar$ cause complications which are mingled with the interesting enhancement due to deformation and transfer. From the theoretical side these spin related effects are difficult to include. Second as already seen for the Al chain the Q-values are lower.

Most of the Mg isotopes are not spherical and their shapes change from one to another. The ^{22,24}Mg isotopes are well deformed prolate ($\beta_2 = 0.5$), ^{26}Mg is oblate ($\beta_2 =$ -0.3) and $^{28-32}$Mg are expected by theory (see ref.[11]) to be near spherical in the ground state. However, the first excited 2^+ state in ^{32}Mg is extremely deformed and further investigations of ^{28,30}Mg isotopes at REX-ISOLDE (proposal by H. Scheit) will clarify the question of ground state deformations. The deformations of the stable ^{24,26}Mg isotopes have to be considered as possible reason for additional subbarrier fusion enhancement. Therefore, it is possible to evaluate simultaneously two effects - deformation and transfer - in subbarrier fusion in the proposed experiment. The chain of Mg isotopes was studied in recent experiments at GSI and the presence of a neutron skin is also suggested for neutron-rich Mg isotopes like in the heavy sodiums [9, 2]. Such an extended distribution leads to a larger Coulomb barrier radius and hence to a lowered height of the fusion barrier resulting in sub- and above barrier fusion enhancement. However, a neutron skin is not included yet into the interaction potential between two ions in the following calculations.

Within the framework of the model described in ref. [7] preliminary calculations of fusion cross sections and mean angular momentum were performed for the ^{24,26,28,30,32}Mg + ^{28}Si reactions by V. Yu. Denisov. The deformation effect was neglected for ^{24,26}Mg and all isotopes are considered spherical. The 2^+ and 3^- vibrational states are known for ^{24,26}Mg only, i.e. in these cases the experimental energy of the excitations and their deformations are used. The influence of unknown vibrational states in ^{28,30,32}Mg is taken into account by assuming the same parameters of the 2^+ and 3^- vibrational states like for ^{26}Mg. The fusion cross sections for the reactions are shown in Figs. 2. The enhancement of subbarrier fusion cross section due to neutron transfer channel increases with the number of neutrons in Magnesium. For ^{30,32}Mg an increase of more than one order of magnitude above a 1-dim barrier penetration model is predicted. The energy dependence of the mean angular momentum $< L(E) >$ of the compound nucleus formed in the Mg induced fusion reactions in different approaches is shown in Fig. 3. In order to verify the results for the ^{26,28,30}Mg + ^{28}Si systems from Fig. 2 and 3 we propose to measure the fusion cross section and the mean angular momentum at REX-ISOLDE.

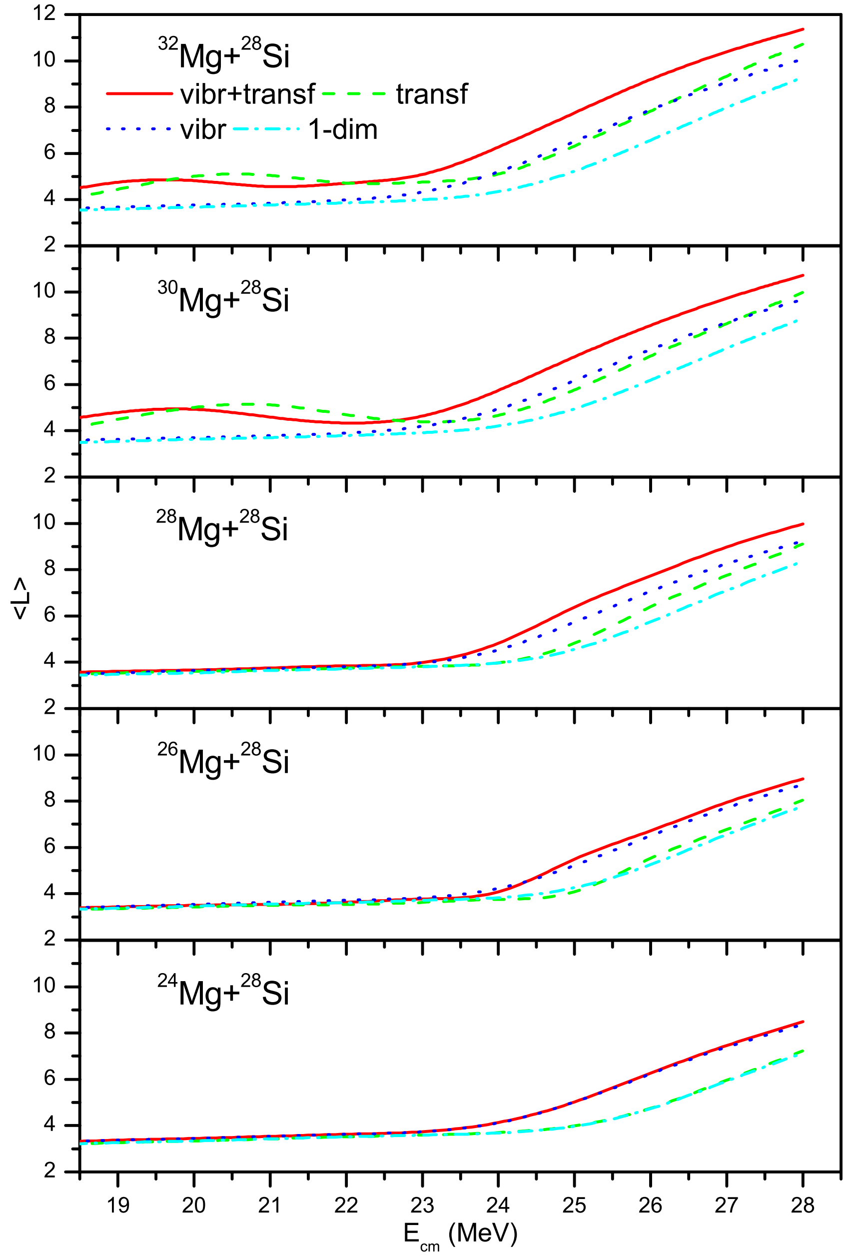

Figure 3: Mean angular momentum for ^{24,26,28,30,32}Mg + ^{28}Si reactions. The notations are the same as in Fig.2.

3 Experimental Considerations

3.1 Setup: MINIBALL and particle detectors

For practical reasons and due to count rate limitations fusion reaction studies with three Mg projectiles on a ^{28}Si target will be proposed: one with a stable ^{26}Mg projectile and two with the even-even unstable ^{28,30}Mg isotopes. The experiment with the stable ^{26}Mg will take only a small fraction of the required beam time and is mainly done (i) to measure all three systems with the same setup in a consistent way, (ii) to setup the detectors in an efficient way and (iii) to cross check the methods for cross section- and angular momentum determination with enough statistic.

The cross section for complete fusion leading to the compound nuclei ^{54,56,58}Fe will be obtained by measuring the intensities of the low lying characteristic γ-rays, emitted from the evaporation residues after particle evaporation. The deexcitation cascades after compound nucleus formation were calculated for the three reactions using the fusion-evaporation code PACE4. As a typical example the results for the ^{28}Si(^{28}Mg,xnypzα) reaction with a bombarding energy of $E_{Lab} = 50$ MeV are shown (see Tab. 2). The compound nucleus ^{56}Fe is created with an excitation energy of 49.1 MeV and populates finally mainly two channels: ^{53}Mn after 2np evaporation with 57 % and the 3n channel ^{53}Fe with 13% . A similar result is obtained by varying the incident energy for the excitation function. For the ^{26}Mg+^{28}Si system the Q-value of the reaction is lower and at the same bombarding energy of $E_{Lab} = 50$ MeV three channels pn, 2np, 2pn collect 75% of the residue yield in ^{51,52}Mn and ^{51}Cr. The dominant reaction channels for ^{30}Mg+^{28}Si at $E_{Lab} = 50$ MeV are 3n, p2n and 4n with ^{55}Mn and ^{54,55}Fe residues. The concentration of the residue yield into two or three main channels will allow to detect the ground state transitions in the well-studied Cr, Mn and Fe isotopes also with low beam intensities and low cross sections.

The MINIBALL array will be used for identification of fusion evaporation channels and cross section determination. The higher multiplicity of the γ-cascade after particle evaporation will provide a higher detection efficiency than only $\approx$10%, which is the MINIBALL efficiency for one γ-ray at 1.33 MeV. As a second observable we want to infer information on the mean angular momentum of the compound nucleus from the γ-array. Here two methods will be employed: first from the individual discrete transitions the populated spins of low lying states can be directly deduced. Second the high solid angle coverage and the granularity of the array (24 individual Ge-detectors), together with the position sensitivity for γ-ray detection, will allow a measurement of the detector multiplicity N_{Det} of the deexcitation cascade starting at high excitation energy below the entry line down to the ground state. The interesting γ-multiplicity is obtained after deconvolution of the measured N_{Det} distribution with the detector response function. For this method its very advantageous that all γ-rays, not only the photo-peak events, contribute to the signal; typically already 250 counts in a N_{Det}-distribution are sufficient for a significant result [15]. The final conversion from measured γ-multiplicity into compound nucleus spin distribution is done by a decomposition

into stretched E2 and statistical E1-transitions and particle spin contributions. The methods of the described analysis procedure are well-established and were applied at various γ-spectrometers e.g. the Heidelberg-Darmstadt Crystal Ball, the Argonne Notre-Dame array or Gammasphere.
The intensity of the radioactive beam of $\approx 10^4 - 10^5$ part/s enables a precise determination of the cross sections by counting the individual incoming beam particles with the Darmstadt Parallel-Plate Avalanche Counter PPAC in transmission and elastic scattered projectiles with the CD-detectors. The fusion products will be measured with a third particle detector in forward direction behind the target, where the fusion products are peaked in a narrow cone due to the kinematics. This detector has to cover a small solid angle e.g. an area of 2 cm radius at a distance of 50 cm from the target, which is sufficient to collect the fusion products after particle evaporation and angular straggling in a ^{28}Si (thickness 0.5 mg/cm^2) target. The fusion products are separated from beam particles, elastically scattered beam and transfer products by their time-of-flight difference. In average the evaporation residue velocity will be 0.92 cm/ns which is half of the beam velocity. A time difference of 46 ns can be easily measured after 50 cm flight distance behind the target with a PPAC- or a silicon detector. The silicon detector will provide another separation of fusion products and other reaction channels by measuring the kinetic energy of the incoming particle. For this purpose a segmented Si strip detector of (size 4 cm x 4 cm) will be provided by University of Munich or in the near future by University of Cologne. The instrumentation and read-out of the Si detector with electronics can be supplied by the available 160 CD electronics channels. The determination of the scattering angles θ and ϕ is not necessary for the forward peaked fusion reactions. A θ-segmentation is sufficient for an angular distribution of elastic scattered projectiles.
The advantages of the combined particle detector setup and the MINIBALL will be a very precise and simultaneous measurement of fusion cross sections, evaporation residue channels and angular momentum distributions. The detection of the individual incoming beam particles together with elastic scattered particles gives the best calibration for the cross section measurement.
Most of the individual measurements will be performed by requiring triple coincidences between the incoming beam particle counter, outgoing fusion product detector and the emitted γ-rays in MINIBALL. The efficiency of the particle-γ trigger will be determined precisely with the abundant stable ^{26}Mg beam. For lower beam intensity with radioactive ions and lower cross sections $\sigma < 50$ mb the trigger on individual γ-transitions with MINIBALL will require a too long measuring period and the measurement will concentrate on a multiplicity distribution. However, in the worst case a cross section measurement is also feasible without γ-ray coincidences employing only the particle detector setup.

Residue	channel	[%]		Residue	channel	[%]
^{54}Fe	2n	6		^{51}Fe	αn, 2p3n	4
^{54}Mn	np	2		^{51}Fe	αp, 3p2n	2
^{54}Cr	2p	1		^{50}Fe	α2n, 2p4n	4
^{53}Fe	3n	13		^{50}Fe	αpn, 3p3n	5
^{53}Mn	2np	57				
^{53}Cr	2pn	6				

Table 2: Yields of residual nuclei from compound nucleus ^{56}Fe after ^{28}Si(^{28}Mg,xnypzα) reaction at E_{CM} = 25 MeV. Calculated with the fusion-evaporation code PACE4.

3.2 Count rates and requested beam time

The excitation function measurement has to cover the cross section range from $\approx$ 500 mb at the barrier down to the $\approx$ 10 mb level in the subbarrier regime. The beam energy has to be changed between $E_{beam} = 43 - 53.5$ MeV three times in steps of $\Delta E_{beam} \approx 3.5$ MeV and a step of $\Delta E_{beam} = 5$ MeV approaching the barrier in order to acquire five data points for the excitation function (this was sufficient e.g. for the ^{17}F experiment [4]). A ^{28}Si target thickness of 0.5 mg/cm^2 is an acceptable compromise considering the energy loss of the beam particles and gain in count rate. The highest ^{28}Mg ISOLDE yield of $3.6 \cdot 10^7$ ions/uC is achieved with Si Carbide targets. A U Carbide ISOLDE target is favourable for ^{30}Mg with $6.0 \cdot 10^5$ ions/uC.
For the count rate estimate the following assumptions have been taken into consideration: The ^{28,30}Mg ISOLDE beam will be accelerated with an efficiency of 5% to the reaction target surrounded by MINIBALL. The particle detection efficiency is estimated to be 90 %, the efficiency for photo peak detection of one (not a γ-cascade) γ-ray with MINIBALL is 10 %. To measure an excitation function five data points at subbarrier energies with cross sections of 500 mb, 200 mb, 100 mb, 50 mb and 20 mb are considered including the time for changes of beam energy. An estimated time of 4 hour per change is taken, based on the good experience during the commissioning run in November 2001. In order to collect at least 50 counts in a low-lying or ground state transition of an evaporation residue nucleus in a particle-gated γ-spectrum the following final beam time is requested:
For the stable ^{26}Mg+^{28}Si reaction we ask for two days or 6 shifts of setup time, including 16 hours for change of beam energies.
The instable ^{28}Mg REX-ISOLDE beam on ^{28}Si target requires 2h, 3h, 6h, 12h and 30h for the five data points and 16 hours for change of beam energies: 9 shifts.
The weak ^{30}Mg REX-ISOLDE beam intensity demands the following beam time for the first four data points with particle γ-coincidences from 500 mb to 50 mb: 12h, 32h, 64h, 120h. The lowest cross section value of 20 mb would require unreasonable long measuring time for the particle-γ-coincidences, here 54h for a particle trigger experiment are necessary to collect 500 fusion evaporation residues. For the ^{30}Mg+^{28}Si reaction we ask for 36 shifts.

The overall requested beam time of this proposal is 51 shifts for all three reactions $^{26,28,30}Mg+^{28}Si$. The length of such a beam time period and the need to change the ISOLDE target may suggest a division into two blocks. A first beam time of 15 shifts may be used to measure the $^{26,28}Mg+^{28}Si$ reactions first. Depending on the feasibility and the achieved results of this experiment the remaining 36 shifts for the $^{30}Mg+^{28}Si$ beam time should be approved.

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